Studies of low-energy K⁻-nucleus/nuclei interactions with light nuclei by AMADEUS

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Abstract. The AMADEUS Collaboration aims to provide unique experimental constraints to the antikaon-nucleon strong interaction in the regime of non-perturbative QCD. The K⁻ nuclear captures, both at-rest and in-flight, are studied using the monochromatic low-momentum kaon beam (p_K ~120 MeV/c) produced at the DAΦNE collider, interacting with the KLOE detector materials. The studies are performed by reconstructing the hyperon-pion and hyperon-nucleon final states. In this work a brief description of AMADEUS results for $\Lambda\pi^-$ and Λp final states is presented.

1 Introduction

The AMADEUS Collaboration [1–4] investigates the low-energy K⁻ induced reactions in light nuclear targets corresponding to components of the KLOE detector [5], in order to

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provide experimental constraints to the non-perturbative QCD in the strangeness sector. It is performed by exploiting the low momentum ($p_K \sim 127$ MeV/c), almost monochromatic, charged kaons produced in the decay of ϕ mesons at-rest at the DAΦNE accelerator [6].

Models of low-energy strong interaction, in the strangeness sector, face difficulties mainly related to the appearance of the broad $\Lambda(1405)$ (I=0) and $\Sigma(1385)$ (I=1) resonances just below the $\bar{\mathrm{K}}$N threshold. To deal with this problem, chiral unitary models [7–13] and phenomenological potential models [14–19] were developed, leading however to contrasting predictions for the $\Lambda(1405)$ parameters and related kaonic nuclear bound states.

The nature of $\Lambda(1405)$ resonance remains still an open issue since experiments result in observation of different masses and widths of this resonance, depending on the production channel, as well as the observed decay mode [20]. In order to understand the line-shape of the $\Lambda(1405)$ in kaon induced reactions the background due to the non-resonant $K^-N \to Y\pi$ reactions has to be taken into account. The position of the $\Lambda(1405)$ reflects the strength of the $\bar{\mathrm{K}}$N interaction, thus influencing the possible formation of more exotic kaonic bound states (for a review see [21]). The phenomenological models [14–16, 18, 19] interpret the I=0 $\Lambda(1405)$ as a pure $\bar{\mathrm{K}}$N bound state, leading to the prediction of deeply bound kaonic nuclear states. According to Chiral models [8–12], however, the $\Lambda(1405)$ emerges as a superposition of two states and, as a consequence the K^-N interaction is much less attractive, which implies the prediction of only slightly bound kaonic nuclear states.

The activities of the AMADEUS Collaboration are centered on the experimental investigations of the low-energy charged kaon-nucleon/nuclei interaction, aiming to unveil the controversial nature of the $\Lambda(1405)$ state, and deepen our understanding of the K^- single- and multi-nucleon interaction processes, and bound states formation.

This article reports on the studies of K^- single-nucleon absorption in ^{4}He leading to the first measurement of the non-resonant contribution in $\mathrm{K}^-\mathrm{N} \to \mathrm{Y}\pi$ reaction [24] below the $\bar{\mathrm{K}}$N threshold which is essential for studies of the $\Lambda(1405)$ resonance properties. Moreover, the investigation of the K^- interactions in ^{12}C nuclei resulting in the first complete characterization of the K^- two-, three- and four-nucleon absorptions (2NA, 3NA and 4NA) in the Λp and Σ^0p final states is presented [25, 26].

2 The measurement of the $K^-n \to \Lambda\pi^-$ non-resonant transition amplitude below the $\bar{\mathrm{K}}$N threshold

The investigation of the $\Lambda(1405)$ properties, produced through the K^-p mechanism in light nuclear targets, requires two biases to be taken into account.

The first bias is the energy threshold imposed by the absorbing nucleon binding energy (for K^- capture at rest on ^{4}He the $\Sigma\pi$ invariant mass threshold is about 1412 MeV, while for ^{12}C it is about 1416 MeV). The access to $\bar{K}N$ sub-threshold region corresponding to the $\Lambda(1405)$ high-mass predicted pole (about 1420 MeV), is possible by exploiting K^-N absorption in-flight [27]. For a mean kaon momentum of 100 MeV/c, the $\Sigma\pi$ invariant mass threshold is shifted upwards by about 10 MeV.

The second bias is related to the non-resonant $K^-N \to Y\pi$ reaction, which was experimentally investigated for the first time in the $K^-n \to \Lambda\pi^-$ process, considering K^-n single nucleon absorptions in ^{4}He [24]. In this work the modulus of non-resonant transition amplitude $|T_{K^-n\to\Lambda\pi^-}|$ at (33±6) MeV below the $\bar{K}N$ threshold was measured by fitting simultaneously the experimentally extracted $\Lambda\pi^-$ invariant mass, momentum and angular distributions with dedicated Monte Carlo simulations. In the fit all the contributing reactions were taken into account: non-resonant processes, resonant processes and the primary production of a Σ followed by the $\Sigma N \to \Lambda N'$ conversion process. The simulations for non-resonant/resonant processes were based on the results of [28]. The non-resonant transition amplitude modulus is equal to $|T_{K^- n\to\Lambda\pi^-}|$=0.334 ± 0.018 $(stat.)\ ^{+0.034}_{-0.058}\ (syst.)$ fm and is shown in Fig. 1 together with the theoretical predictions (see Ref: [29] (P), [30] (KM), [31] (M1,M2), [32] (B2,B4), [33] (BCN)) rescaled for the $K^- n \to \Sigma\pi$ transition probabilities. This measurement can be used to test and constrain the S-wave $K^- n \to \Lambda\pi^-$ transition amplitude calculations.

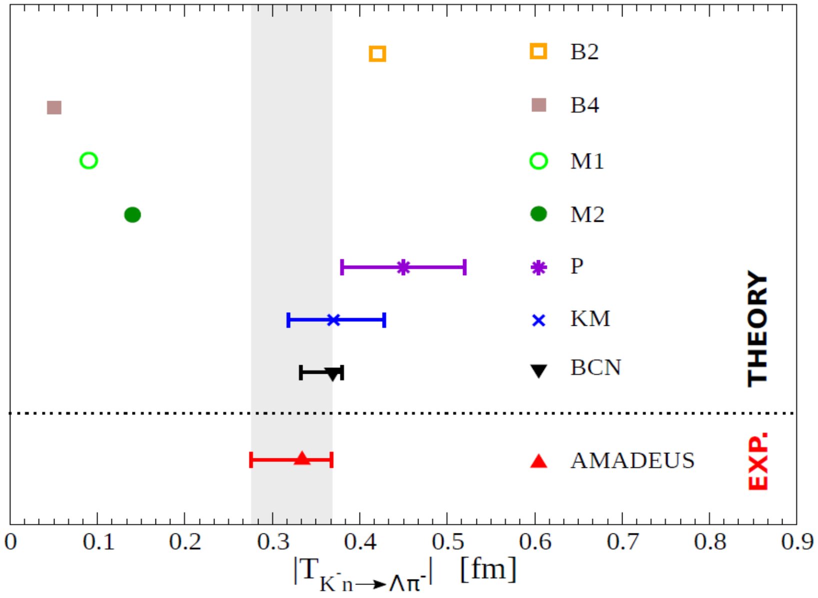

Figure 1. Modulus of the measured non resonant $K^- n \to \Lambda\pi^-$ transition amplitude compared with theoretical calculations, see details in the text. Figure is adapted from Ref. [34].

3 K^- multi-nucleon absorption cross sections and branching ratios in Λp and $\Sigma^0 p$ final states

Recent $\Lambda(\Sigma^0)$p final states investigation in K⁻ capture processes on ^{12}C nuclei [25, 26] by the AMADEUS collaboration results in a complete characterization of the K⁻ two-, three- and four-nucleon absorption (2NA, 3NA and 4NA) processes. The studies were performed [26], based on the phenomenological model for the K⁻ captures at-rest and in-flight on light nuclei described in Refs. [28, 40]. The K⁻ 2NA, 3NA and 4NA branching ratios (BRs) and cross sections for low-momentum kaons in Λp and Σ^0p channels were determined by performing a simultaneous fit of the measured Λp invariant mass, Λp angular correlation, Λ and proton momentum distribution with the corresponding simulated distributions for all the processes contributing to the measured Λp final state, including the primary Σ^0 productions followed by $\Sigma^0 \to \Lambda\gamma$ decay. For the 2NA the contributions of both elastic final state interactions (FSI) of the primary produced hyperon and nucleon with the residual nucleus 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) Λp and Σ^0p productions. The obtained BRs and cross sections are summarized in Table 1.

process	BR (%)	cross section (mb)	@	p_K (MeV/c)
2NA-QF Λp	0.25 ± 0.02 (stat.) $^{+0.01}_{-0.02}$(syst.)	2.8 ± 0.3 (stat.) $^{+0.1}_{-0.2}$ (syst.)	@	128 ± 29
2NA-FSI Λp	6.2 ± 1.4(stat.) $^{+0.5}_{-0.6}$(syst.)	69 ± 15 (stat.) ± 6 (syst.)	@	128 ± 29
2NA-QF Σ^0p	0.35 ± 0.09(stat.) $^{+0.13}_{-0.06}$(syst.)	3.9 ± 1.0 (stat.) $^{+1.4}_{-0.7}$ (syst.)	@	128 ± 29
2NA-FSI Σ^0p	7.2 ± 2.2(stat.) $^{+4.2}_{-5.4}$(syst.)	80 ± 25 (stat.) $^{+46}_{-60}$ (syst.)	@	128 ± 29
2NA-CONV Σ /Λ	2.1 ± 1.2(stat.) $^{+0.9}_{-0.5}$(syst.)	-		
3NA Λpn	1.4 ± 0.2(stat.) $^{+0.1}_{-0.2}$(syst.)	15 ± 2 (stat.) ± 2 (syst.)	@	117 ± 23
3NA Σ^0pn	3.7 ± 0.4(stat.) $^{+0.2}_{-0.4}$(syst.)	41 ± 4 (stat.) $^{+2}_{-5}$ (syst.)	@	117 ± 23
4NA Λpnn	0.13 ± 0.09(stat.) $^{+0.08}_{-0.07}$(syst.)	-		
Global $\Lambda(\Sigma^0)$p	21 ± 3(stat.) $^{+5}_{-6}$(syst.)	-		

Table 1. 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. The Table is adapted from Ref. [26].

The sum of the K^- 2NA BRs is found to be (16.1± 2.9(stat.)$^{+1.0}_{-0.9}$(syst.)) % and is the main 2NA contribution to the global branching ratio shown in Table 1. The missing contribution to the K^- 2NA from other few processes without Λp pair in the final state of the interaction is also estimated combining both the measured branching ratios and the available theoretical information, and amounts to (5.5± 0.1(stat.)$^{+1.0}_{-0.9}$(syst.)) % (for more details see [35]). Including the missing component, the total BR of the K^- 2NA in Carbon is found to be (21.6± 2.9(stat.)$^{+4.4}_{-5.6}$(syst.)) %.

The BR of the Λp QF production in K^- 2NA interaction is found to be smaller than the Σ^0p QF production, the ratio of the BRs in Table 1 is: $R = \frac{BR(K^-(pp)\to\Lambda p)}{BR(K^-(pp)\to\Sigma^0 p)} = 0.7 \pm 0.2(stat.)^{+0.2}_{-0.3}(syst.)$. The ratio of the corresponding phase spaces is instead $R' = 1.22$. This result was interpreted in Ref. [41] and was found to be in agreement with the theoretical calculations (BCN and P models) when the in medium effect due to the Pauli blocking is considered.

The possible contribution of K^-pp bound system in Λp spectra was also investigated. It was found that the signal of the K^-pp bound state formation in K^- induced reactions on carbon completely overlaps with the K^- 2NA-QF process. The two components can be disentangled only for narrow states ($\Gamma < 15$ MeV/c^2) which are excluded by the theoretical calculations. In the further step, in order to compare the spectra with the corresponding FINUDA measurement, back-to-back Λp events were selected ($\cos\theta_{\Lambda p} < -0.8$). As in the previous case, the obtained spectra can be completely described in terms of K^- multi-NA processes.

The presented results demonstrate that the DAΦNE collider is a unique facility for the study of low-energy kaon physics.

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