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 ($p_K \sim 127\text{ MeV}/c$) 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 $\bar{K}^{-}$ 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 $\bar{K}^{-}$ 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 $\phi$-meson decay nearly at-rest, are captured on the nuclei in the materials of the beam pipe setup and of the KLOE detector (H, $^4$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 $\rightarrow$ $\Lambda\pi^-$ 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 $^4$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 $K^-p \rightarrow (\Sigma\pi)^0$ 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 $^4$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 $\sqrt{s} = (33 \pm 6)$ MeV below the $\bar{K}N$ threshold, which is found to be

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

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 $^{12}$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.

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

The \(\Lambda\) 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 \(R' \approx 1.22\). From the BRs in Table I, we measure

\[
R = \frac{\text{BR}(K^-pp \rightarrow \Lambda p)}{\text{BR}(K^-pp \rightarrow \Sigma^0 p)} = 0.7 \pm 0.2(\text{stat.})\(+0.2\)\(-0.3\)(syst.).
\] (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 \(KN\) 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 $K^-\Lambda\pi$ 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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