Studies of K^--nuclei interactions at low-energies by AMADEUS

R. Del Grande[1,2], M. Bazzi[1], A. M. Bragadireanu[3], D. Bosnar[4], M. Cargnelli[5], A. Clozza[1], C. Curceanu[1], L. De Paolis[1,6], L. Fabbietti[7,8], F. Ghio[9,10], C. Guaraldo[1], M. Iliescu[1], M. Iwasaki[11], P. Levi Sandri[1], J. Marton[5], M. Miliucci[1], P. Moskal[12], S. Okada[11], K. Piscicchia[2,1], A. Ramos[13], A. Scordo[1], M. Silarski[12], D. L. Sirghi[1,3], F. Sirghi[1,3], M. Skurzok[1,12], A. Spallone[1], O. Vazquez Doce[7,8], E. Widmann[5], S. Wycech[14], J. Zmeskal[5]

[1] INFN Laboratori Nazionali di Frascati, Frascati, Rome, Italy
[2] CENTRO FERMI - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Roma, Italy
[3] Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Magurele, Romania
[4] Department of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia
[5] Stefan-Meyer-Institut für Subatomare Physik, Wien, Austria
[6] Università degli Studi di Roma Tor Vergata, Rome, Italy
[7] Excellence Cluster Origin and Structure of the Universe, Garching, Germany
[8] Physik Department E12, Technische Universität München, Garching, Germany
[9] INFN Sezione di Roma I, Rome, Italy
[10] Istituto Superiore di Sanità, Rome, Italy
[11] RIKEN, The Institute of Physics and Chemical Research, Saitama, Japan
[12] Institute of Physics, Jagiellonian University, Cracow, Poland
[13] Departament de Fisica Quantica i Astrofisica and Institut de Ciencies del Cosmos, Universitat de Barcelona, Barcelona, Spain
[14] National Centre for Nuclear Research, Warsaw, Poland

E-mail: `raffaele.delgrande@lnf.infn.it`

Abstract. The AMADEUS collaboration is providing unique experimental information on the low-energy strong interaction between K^- and nucleons exploiting the low momentum K^- ($p_K \sim 127$ MeV/c) produced at the DAΦNE collider and using the KLOE detector as active target. The absorption of the K^- in light nuclei (H, ^{4}He, ^{9}Be and ^{12}C) are investigated and hyperon-pion/hyperon-nucleons, emitted in the final state, are reconstructed. In the present work the results obtained from the study of $\Lambda\pi^-$, Λp and Λt correlated production will be presented.

1. Introduction

The AMADEUS collaboration is performing unique studies of the K^- hadronic interaction with nucleons at low-energy, fundamental for understanding of the non-perturbative QCD in the strangeness sector [1].

The antikaon-nucleon ($\bar{\mathrm{K}}$N) strong interaction potential is attractive in nuclear medium due to the existence of the $\Lambda(1405)$ (isospin I=0) and the $\Sigma(1385)$ (I=1) resonances in the energy region below the $\bar{\mathrm{K}}$N threshold. In phenomenological potential models [3, 4, 5, 6, 7] the $\Lambda(1405)$ is interpreted as a pure $\bar{\mathrm{K}}$N bound state with a Binding Energy (BE) of about 27 MeV, in chiral models [8, 9, 10, 11, 12] two states emerge in the neighborhood of the $\Lambda(1405)$ mass, the higher mass state is coupled to the $\bar{\mathrm{K}}$N channel leading to a weaker attraction. From the experimental side the resonance line-shape is found to depend on both the observed $\Sigma\pi$ decay channel and the production mechanism. In K^- induced reactions the non-resonant $\Sigma\pi$ production contribution has to be considered in order to extract information of the resonance properties. In Ref. [13] important information on the hyperon-pion ($\mathrm{Y}\pi$) non-resonant production in I=1 channel, where the $\Sigma(1385)$ resonant contribution is well known, is given. The results obtained in Ref. [13] are summarised in Section 2.

The investigation of the K^- interaction with more than one nucleon is also fundamental. In Refs. [14, 15] it is demonstrated that a phenomenological K^- multi-nucleon absorption term in the K^--nucleus optical potential has to be added to the single nucleon absorption in order to achieve a good fit of the kaonic atoms data along the periodic table. In heavy-ion collisions the K^- multi-nucleon absorption cross sections at low-energy are also crucial for the interpretation of the data [16].

Furthermore the experimental search for exotic bound states between K^- and nucleons, whose existence is related to the strength of the K^--nuclei interaction potential, cannot disregard a comprehensive characterisation of the K^- multi-nucleon absorption processes. In K^- induced reactions the K^- multi-nucleon absorptions overlaps with the K^- bound state formation over a broad range of the phase space [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. In Section 4 the strategy for the investigation of the rare K^- 4NA process will be presented.

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

2. Modulus of the non-resonant $\mathrm{K}^-\mathrm{n} \to \Lambda\pi^-$ amplitude below threshold

The K^-n single nucleon absorptions on ^{4}He, emitting a Λ and a π^- in the final state, are experimentally investigated in Ref. [13] by the AMADEUS collaboration. The aim is to extract information on the non-resonant I=1 $\mathrm{K}^-\mathrm{n} \to \Lambda\pi^-$ process. In this channel the non-resonant transition amplitude ($|T_{\mathrm{K}^-\mathrm{n}\to\Lambda\pi^-}|$) can be extracted since the corresponding resonant counterpart, involving the formation of the $\Sigma^-(1385)$ (I=1), is well known. Such information is crucial for the experimental investigation of the $\Lambda(1405)$ properties because in K^- induced reaction the shape of the non-resonant $\mathrm{Y}\pi$ production in both I=1 and I=0 channels represents one of the main biases to the experimental $\Sigma\pi$ invariant mass spectrum.

In Ref. [13] the experimentally extracted $\Lambda\pi^-$ invariant mass, momentum and angular distributions were simultaneously fitted by using dedicated Monte Carlo simulations for all the contributing reactions: non-resonant processes, resonant processes and the primary production of a Σ followed by the $\Sigma\mathrm{N} \to \Lambda\mathrm{N}'$ conversion process. The simulations of non-resonant/resonant processes were based on the results of [22]. The fit allowed to extract the non-resonant transition amplitude modulus $|T_{\mathrm{K}^-\mathrm{n}\to\Lambda\pi^-}|$ at $\sqrt{s}$ =(33±6) MeV below the $\bar{\mathrm{K}}$N threshold, which is found to be:

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

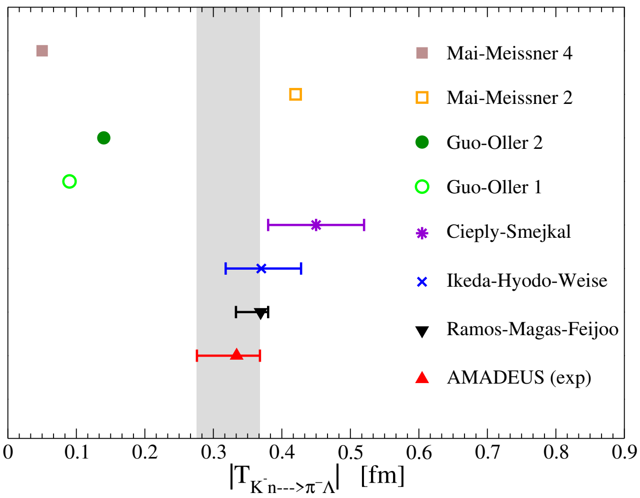

Figure 1. Modulus of the non-resonant amplitude for the $K^-n \to \Lambda\pi^-$ process at 33 MeV below the $\bar{K}N$ threshold obtained by AMADEUS, compared with theoretical predictions: Ramos-Magas-Feijoo [23], Ikeda-Hyodo-Weise [24], Cieply-Smejkal [25], Guo-Oller 1 and 2 [26], Mai-Meissner 2 and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

The result of this analysis (with combined statistical and systematic errors) is shown in Fig. 1 and compared with the theoretical predictions (see Ref: Ramos-Magas-Feijoo [23], Ikeda-Hyodo-Weise [24], Cieply-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.

3. K^- multi-nucleon absorption Branching Ratios and Cross Sections in Λp and Σ^0p channels

The experimental investigation of the K^- 2NA, 3NA and 4NA processes is performed in Refs. [18, 19] exploiting K^- captures in ^{12}C nuclei and reconstructing, respectively, the produced Σ^0p and Λp pairs in the final state.

In Ref. [19] a simultaneous fit of the measured Λp invariant mass, Λp angular correlation, Λ and proton momenta to the simulated distributions for both direct Λ production and Σ^0 production followed by $\Sigma^0 \to \Lambda\gamma$ decay allowed to extract the Branching Ratios (BRs) and cross sections of the K^- absorptions on two, three and four nucleons. The K^- absorption model described in Refs. [29, 22] is used to calculated the K^- nuclear capture for both at-rest and in-flight interactions. 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 1, will be useful for the improvement of microscopical models of the K^-NN absorption and for future generalisation to K^- absorption reaction calculations involving even more than two nucleons.

The BRs in Table 1 give also important information on the $\bar{K}N$ dynamics below the threshold. The Λp direct production in 2NA-QF is expected to be phase space favoured with respect to the corresponding Σ^0p 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 1 we measure

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

The dominance of the Σ^0p channel is then an evidence of the important dynamical effects

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.

Process	Branching Ratio (%)	σ (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.) $\pm$ 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.) $\pm$ 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.)	-		

involved in the measured processes [30].

The possible contribution of a K^-pp bound state, decaying into a Λp pair, was investigated. The 2NA-QF is found to completely overlap with the possible K^-pp signal, 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.

4. K^- four nucleon absorption in the Λt channel

The Λ-triton correlated production in K^- absorption in ^{4}He and ^{12}C nuclei is presently under investigation by the AMADEUS collaboration with the aim to extract the contribution of the K^- 4NA process. The experimental search for a Λ and a triton in the final state of K^- induced reactions with ^{4}He and two light solid targets (^{6,7}Li and ^{9}Be) was already performed in Refs. [32, 33] and global yields for the Λt production were extracted, including not only 4NA but also the dominant single nucleon absorption, FSI and conversion processes. Moreover in Ref. [32] the selected events were found to be kinematically compatible with both Λt and Λdn production.

The key events selection criterion for the analysis performed by the AMADEUS collaboration consists in the triton detection using the mass measurement by Time Of Flight (TOF), this allows to select a pure sample of Λt events. A simultaneous fit of the measured Λt invariant mass, angular correlation and Λt momentum to the MC simulated distributions of all contributing processes is performed. BRs and cross sections at $p_K \simeq 100$ MeV/c for the K^- 4NA in ^{12}C and in ^{4}He are finally extracted.

Acknowledgements

We acknowledge the KLOE/KLOE-2 Collaboration for their support and for having provided us the data and the tools to perform the analysis presented in this paper. We acknowledge the CENTRO FERMI - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", for the project PAMQ. Part of this work was supported by Austrian Science Fund (FWF): [P24756-

N20]; Austrian Federal Ministry of Science and Research BMBWK 650962/0001 VI/2/2009; the Croatian Science Foundation under the project IP-2018-01-8570; Minstero degli Affari Esteri e della Cooperazione Internazionale, Direzione Generale per la Promozione del Sistema Paese (MAECI), Strange Matter project and the EU STRONG-2020 project (grant agreement No 824093); Polish National Science Center through grant No. UMO-2016/21/D/ST2/01155; Ministry of Science and Higher Education of Poland grant no 7150/E-338/M/2018.

References

[1] Curceanu C et al. [AMADEUS Collaboration] 2015 *Acta Phys. Polon.* B **46** no.1 203.
[2] Tanabashi M et al. (Particle Data Group) 2018 *Phys. Rev.* D **98** 030001.
[3] Akaishi Y and Yamazaki T 2002 *Phys. Rev.* C **65** 044005.
[4] Ikeda Y and Sato T 2007 *Phys. Rev.* C **76** 035203.
[5] Wycech S and Green A M 2009 *Phys. Rev.* C **79** 014001.
[6] Revai J and Shevchenko N V 2014 *Phys. Rev.* C **90** 034004.
[7] Maeda S, Akaishi Y and Yamazaki T 2013 *Proc. Jpn. Acad.* B **89** 418.
[8] Dote A, Hyodo T and Weise W 2009 *Phys. Rev.* C **79** 014003.
[9] Barnea N, Gal A and Liverts E Z 2012 *Phys. Lett.* B **712** 132.
[10] Ikeda Y, Kamano H and Sato T 2010 *Prog. Theor. Phys.* **124** 533.
[11] Bicudo P 2007 *Phys. Rev.* D **76** 031502.
[12] Bayar M and Oset E 2013 *Nucl. Phys.* A **914** 349.
[13] Piscicchia K, Wycech S, Fabbietti L et al. 2018 *Phys. Lett.* B **782** 339.
[14] Friedman E and Gal A 2017 *Nucl. Phys.* A **959** 66–82.
[15] Hrtánková J and Mareš J 2017 *Phys. Rev.* C **96** 015205.
[16] Metag V, Nanova M and Paryev E Ya 2017 *Prog. Part. Nucl. Phys* **97** 199–260.
[17] Suzuki T et al. 2008 *Mod. Phys. Lett.* A **23** 2520–2523.
Magas V K, Oset E, Ramos A and Toki H 2006 *Phys. Rev.* C **74** 025206.
Magas V K, Oset E and Ramos A, *Phys. Rev.* C **77** 065210.
[18] Vazques Doce O, Fabbietti L et al. 2016 *Phys. Lett.* B **758** 134.
[19] Del Grande R, Piscicchia K, Vazquez Doce O et al. 2019 *Eur. Phys. J.* C **79** no.3 190.
[20] Bossi F et al. 2008 *Riv. Nuovo Cim.* **31** 531.
[21] Gallo A et al. 2006 *Conf. Proc.* **C060626** 604.
[22] Piscicchia K, Wycech S and Curceanu C 2016 *Nucl. Phys.* A **954** 75.
[23] Feijoo A, Magas V and Ramos A 2019 *Phys. Rev.* C **99** no. 3 035211.
[24] Ikeda Y, Hyodo T and Weise W 2012 *Nucl. Phys.* A **881** 98.
[25] Cieplý A and Smejkal J 2012 *Nucl. Phys.* A **881** 115.
[26] Guo Z H and Oller J A 2013 *Phys. Rev.* C **87** 035202.
[27] Mai M and Meißner U G 2015 *Eur. Phys. J.* A **51** 30.
[28] Feijoo A, Magas V K and Ramos A 2019 *AIP Conf. Proc.* **2130** no. 1 040013.
[29] Del Grande R, Piscicchia K and Wycech S 2017 *Acta Phys. Pol.* B **48** 1881.
[30] Hrtánková J and Ramos A 2019 arXiv:1910.01336 submitted to *Phys. Rev.* C.
[31] Agnello M et al. 2005 *Phys. Rev. Lett.* **94** 212303.
[32] Roosen R and Wickens J H 1981 *Il Nuovo Cim.* A Series 11 Volume **66** Issue 1 101.
[33] Agnello M et al. 2008 *Phys. Lett.* B **669** 229.