Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Studies of low-energy K^- hadronic interactions with light nuclei by AMADEUS

To cite this article: R Del Grande *et al* 2020 *J. Phys.: Conf. Ser.* **1526** 012024

Studies of low-energy K^- hadronic interactions with light nuclei 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 aims to provide precise experimental information on the K^- strong interaction with nucleons in the low-energy regime. The step 0 of AMADEUS consists in the re-analysis of the data collected with the KLOE detector at the DAΦNE collider during the 2004/2005 data taking campaign. The absorptions of low-momentum K^-s in the nuclei contained in the detector and the beam pipe setup (H, ^{4}He, ^{9}Be and ^{12}C) are investigated. Information on the K^- single and multi-nucleon interactions are extracted from the study of the $\Lambda\pi^-$ and Λp correlated production in the final state.

1. Introduction

The AMADEUS collaboration studies the K^- absorptions in light nuclei (H, ^{4}He, ^{9}Be and ^{12}C) at low-energy with the aim to extract precise experimental information on the strong interaction between antikaons and nucleons in the non-perturbative QCD regime [1].

The existence of the resonances $\Lambda(1405)$ (isospin $I = 0$) and $\Sigma(1385)$ ($I = 1$) in the energy region below the $\bar{K}N$ threshold and the strong coupling between the $\bar{K}N$ and $\Sigma\pi$ channels make the chiral perturbation theory not applicable to the low-energy strangeness $S = -1$ sector [2, 3]. To overcome the problem chiral approaches to the $\bar{\mathrm{K}}$N interaction, based on coupled channels SU(3) dynamics, and phenomenological potential models are used. The most precise experimental constraint to the models is provided by the $\mathrm{K^-p}$ scattering length extracted from the SIDDHARTA measurements [4, 5]. In chiral models [6, 7, 8, 9, 10] the $\Lambda(1405)$ emerges dynamically as superposition of two poles in the energy region of the resonance, the position of the poles in the complex energy plane is model dependent [11], while in phenomenological potential models a single pole ansatz is used [12, 13]. 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 $\mathrm{K^-}$ induced reactions the non-resonant $\Sigma\pi$ production contribution has to be considered in order to extract information on the resonance properties. In [14] 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 by AMADEUS in [14] are summarised in Section 2.

Furthermore the modelling of the $\mathrm{K^-}$ interaction with single nucleons cannot reproduce all the experimental data. In [15, 16] it was demonstrated that the contribution due to the interaction of the $\mathrm{K^-}$ with more than one nucleon has to be included in the theoretical models in order to achieve a good fit of the kaonic atoms data along the periodic table of the elements. In heavy-ion collisions the data are interpreted by means of transport model calculations in which the low-energy cross sections of $\mathrm{K^-}$ multi-nucleon captures in nuclei represent a fundamental input [17]. In $\mathrm{K^-}$ induced reactions the search for exotic bound states between antikaons and nucleons, whose existence was predicted in [18, 12], cannot disregard a complete characterisation of the $\mathrm{K^-}$ multi-nucleon absorption processes due to the overlap with the bound states formation over a broad range of the phase space [19]. A comprehensive study of the $\mathrm{K^-}$ absorption on two, three and four nucleons (2NA, 3NA and 4NA) is performed by AMADEUS in [20, 21]. The details of the data analysis reported in [21] will be given in Section 3.

AMADEUS takes advantage of the low-momentum and monochromatic $\mathrm{K^-}$s ($p_{\mathrm{K}} \sim 127$ MeV/c) produced at the DAΦNE collider [22] from the ϕ-meson decay nearly at-rest and exploits the KLOE detector [23] as active target. The $\mathrm{K^-}$ absorptions at-rest and in-flight in the nuclei contained in the detector setup (H, ^{4}He, ^{9}Be and ^{12}C) are investigated and the emitted hyperon-pion ($\mathrm{Y}\pi$) and hyperon-nucleon/nuclei (YN) pairs in the final state are reconstructed. In the present work the data collected by the KLOE collaboration during the 2004/2005 data campaign, corresponding to 1.74 fb^{-1} total integrated luminosity, are analysed by AMADEUS.

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

The experimental investigation of the $\Lambda(1405)$ properties is challenging. In stopped $\mathrm{K^-}$ reactions with light nuclei the measured $\Sigma\pi$ invariant mass spectrum is affected by two main biases: (i) due to the absorption of the $\mathrm{K^-}$ in nuclei the phase space of the final states is reduced with respect to the $\mathrm{K^-}$ single nucleon absorption in free-space, the energy threshold is then shifted from 1432 MeV to lower energies (1412 MeV in ^{4}He and 1416 MeV in ^{12}C); (ii) the shape of the non-resonant $\mathrm{K^-p} \to (\Sigma\pi)^0$ reactions has to be taken into account.

In [14] the $\mathrm{K^-n}$ single nucleon absorptions on ^{4}He are investigated in order to extract information on the non-resonant $\mathrm{K^-n} \to \Lambda\pi^-$ process. In this channel the resonant counterpart is represented by the formation of the well known $\Sigma^-(1385)$ ($I = 1$). The corresponding non-resonant transition amplitude ($|T_{\mathrm{K^-n}\to\Lambda\pi^-}|$) can be extracted and used to test the theoretical predictions below threshold. In [14] 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 [24]. The fit allowed to extract

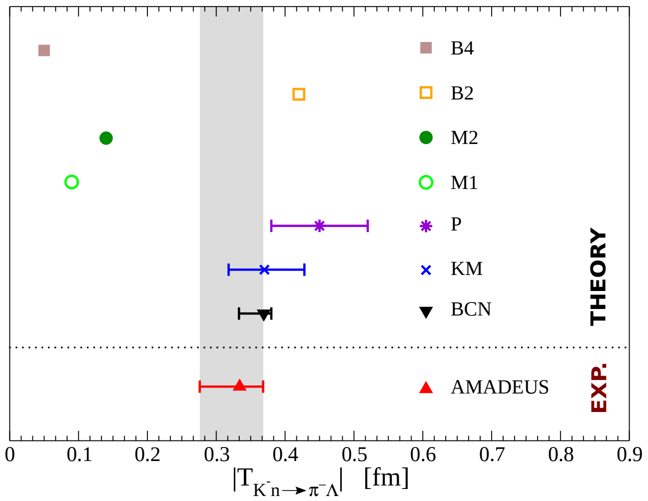

Figure 1. Modulus of the non-resonant amplitude for the $K^-n \to \Lambda\pi^-$ process at 33 MeV below the K^-n threshold obtained by AMADEUS, compared with theoretical predictions: Barcelona (BCN) [10], Kyoto-Munich (KM) [6], Prague (P) [7], Murcia (M1 and M2) [8], Bonn (B2 and B4) [9]. The plot in the Figure is adapted from [25].

the modulus of the non-resonant transition amplitude at $\sqrt{s}$ =(33±6) MeV below the K^-n threshold, which is found to be:

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

The result of this analysis (with combined statistical and systematic errors) is shown in Fig. 1 and compared with the theoretical predictions (see Ref: Barcelona (BCN) [10], Kyoto-Munich (KM) [6], Prague (P) [7], Murcia (M1 and M2) [8], Bonn (B2 and B4) [9]). 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

The K^- 2NA, 3NA and 4NA processes are investigated by the AMADEUS collaboration in [20, 21], by reconstructing Λp and Σ^0p pairs emitted in K^- hadronic interactions with ^{12}C nuclei. In [21] 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 Branching Ratios (BRs) and cross sections of the K^- absorptions on two, three and four nucleons. The K^- absorption model described in [26, 24] is used to calculate the K^- nuclear capture for both at-rest, assuming the absorption from the atomic 2p state, and in-flight interactions. 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 are reported in Table 1.

The BRs in Table 1 give also important information on the K^- dynamics in nuclear medium. 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

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

In [27] it is shown that the dominance of the Σ^0p channel is an evidence of the important in-medium effects, in particular the Pauli blocking, involved in the measured processes.

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.) ± 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.)	-		

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 [28]. 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.

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] Kaiser N, Siegel P B and Weise W 1995 *Nucl. Phys.* A **594** 325.
[3] Lee C H, Jung H, Min D P and Rho M 1994 *Phys. Lett.* B **326** 14.
[4] Bazzi M et al. 2011 *Phys. Lett.* B **704** 113.
[5] Curceanu C et al. 2019 *Rev. Mod. Phys.* **91** 025006.
[6] Ikeda Y, Hyodo T and Weise W 2012 *Nucl. Phys.* A **881** 98.
[7] Cieplý A and Smejkal J 2012 *Nucl. Phys.* A **881** 115.
[8] Guo Z H and Oller J A 2013 *Phys. Rev.* C **87** 035202.
[9] Mai M and Meißner U G 2015 *Eur. Phys. J.* A **51** 30.
[10] Feijoo A, Magas V and Ramos A 2019 *Phys. Rev.* C **99** no. 3 035211.

[11] Cieplý A, Mai M, Meißner U G and Smejkal J 2016 *Nuclear Physics* A **954** 17-40.
[12] Akaishi Y and Yamazaki T 2002 *Phys. Rev.* C **65** 044005.
[13] Shevchenko N V 2012 *Phys. Rev.* C **85** 034001.
[14] Piscicchia K, Wycech S, Fabbietti L et al. 2018 *Phys. Lett.* B **782** 339.
[15] Friedman E and Gal A 2017 *Nucl. Phys.* A **959** 66–82.
[16] Hrtánková J and Mareš J 2017 *Phys. Rev.* C **96** 015205.
[17] Metag V, Nanova M and Paryev E Ya 2017 *Prog. Part. Nucl. Phys* **97** 199–260.
[18] Wycech S 1986 *Nucl. Phys.* A **450** 399c.
[19] 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.
[20] Vazques Doce O, Fabbietti L et al. 2016 *Phys. Lett.* B **758** 134.
[21] Del Grande R, Piscicchia K, Vazquez Doce O et al. 2019 *Eur. Phys. J.* C **79** no.3 190.
[22] Gallo A et al. 2006 *Conf. Proc.* **C060626** 604.
[23] Bossi F et al. 2008 *Riv. Nuovo Cim.* **31** 531.
[24] Piscicchia K, Wycech S and Curceanu C 2016 *Nucl. Phys.* A **954** 75.
[25] Feijoo A, Magas V K and Ramos A 2019 *AIP Conf. Proc.* **2130** no. 1 040013.
[26] Del Grande R, Piscicchia K and Wycech S 2017 *Acta Phys. Pol.* B **48** 1881.
[27] Hrtánková J and Ramos A 2019 arXiv:1910.01336 submitted to *Phys. Rev.* C.
[28] Agnello M et al. 2005 *Phys. Rev. Lett.* **94** 212303.