Recent Experimental Results on the Low-energy K[^]-Interaction with Nucleons by AMADEUS

(AMADEUS Collaboration) Del Grande, R.; Bazzi, M.; Bragadireanu, A.M.; Bosnar, D.; Cargnelli, M.; Curceanu, C.; De Paolis, L.; Fabbietti, L.; Fiorini, C.; Ghio, F.; ...

Source / Izvornik: Acta Physica Polonica B, 2020, 51, 121 - 127

Journal article, Published version Rad u časopisu, Objavljena verzija rada (izdavačev PDF)

https://doi.org/10.5506/APhysPolB.51.121

Permanent link / Trajna poveznica: https://urn.nsk.hr/urn:nbn:hr:217:324863

Rights / Prava: Attribution 4.0 International/Imenovanje 4.0 međunarodna

Download date / Datum preuzimanja: 2025-03-27



Repository / Repozitorij:

Repository of the Faculty of Science - University of Zagreb





RECENT EXPERIMENTAL RESULTS ON THE LOW-ENERGY K^- INTERACTION WITH NUCLEONS BY AMADEUS*

R. DEL GRANDE^{a,b}, M. BAZZI^a, A.M. BRAGADIREANU^c, D. BOSNAR^d
M. CARGNELLI^e, C. CURCEANU^a, L. DE PAOLIS^{a,f}, L. FABBIETTI^{g,h}
C. FIORINI^{i,j}, F. GHIO^{k,l}, C. GUARALDO^a, R.S. HAYANO^m, M. ILIESCU^a
M. IWASAKIⁿ, P. LEVI SANDRI^a, J. MARTON^e, M. MILIUCCI^a
P. MOSKAL^o, S. OKADAⁿ, K. PISCICCHIA^{b,a}, A. RAMOS^P, A. SCORDO^a
M. SILARSKI^o, D.L. SIRGHI^{a,c}, F. SIRGHI^{a,c}, M. SKURZOK^{a,o}
A. SPALLONE^a, O. VAZQUEZ DOCE^{g,h}, E. WIDMANN^e, S. WYCECH^q
J. ZMESKAL^e

^aINFN Laboratori Nazionali di Frascati, Frascati, Rome, Italy ^bCENTRO FERMI — Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Roma, Italy ^cHoria Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH) Măgurele, Romania ^dDepartment of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia ^eStefan-Meyer-Institut für Subatomare Physik, Wien, Austria ^fUniversità degli Studi di Roma "Tor Vergata", Rome, Italy ^gExcellence "Cluster Origin and Structure of the Universe", Garching, Germany ^hPhysik Department E12, Technische Universität München, Garching, Germany ⁱPolitecnico di Milano, Dip. di Elettronica, Informazione e Bioingegneria Milano, Italy ^jINFN Sezione di Milano, Milano, Italy ^kINFN Sezione di Roma I, Rome, Italy ¹Istituto Superiore di Sanità, Rome, Italy ^mThe University of Tokyo, Tokyo, Japan ⁿRIKEN, The Institute of Physics and Chemical Research, Saitama, Japan ^oInstitute of Physics, Jagiellonian University, Kraków, Poland ^pDepartament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, Barcelona, Spain ^qNational Centre for Nuclear Research, Warszawa, Poland (Received October 7, 2019)

Recent results obtained by the AMADEUS Collaboration on the experimental investigation of the K^- low-energy interaction with light nuclei

^{*} Presented at the 3rd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics, Kraków, Poland, June 23–28, 2019.

are summarised. The step 0 of AMADEUS consists in the analysis of the data collected at the DA Φ NE 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, ⁴He, ⁹Be and ¹²C) and hyperon–pion/hyperon–nucleons, emitted in the final state, are reconstructed. From the study of $A\pi^-$ and Ap correlated production, important information on the $\bar{K}N$ strong interaction in the non-perturbative QCD regime are extracted.

 $\rm DOI:10.5506/APhysPolB.51.121$

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^- ($p_K \sim 127 \text{ MeV/}c$), produced at the DA Φ NE 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, ⁴He, ⁹Be and ¹²C) used as active target. The analysed data sample allows to investigate both atrest ($p_K \sim 0 \text{ MeV/}c$) 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 ⁴He and 1416 MeV in ¹²C) 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 ⁴He. 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 $A\pi^-$ 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 $\Sigma N \to AN'$ conversion process. The simulations of nonresonant/resonant processes were based on the results of [22]. The analysis allowed the extraction of the non-resonant transition amplitude modulus $|T_{K^-n\to A\pi^-}|$ at $\sqrt{s} = (33\pm 6)$ MeV below the $\bar{K}N$ threshold, which is found to be

$$|T_{K^-n \to A\pi^-}| = \left(0.334 \pm 0.018 \text{ (stat.)}_{-0.058}^{+0.034} \text{ (syst.)}\right) \text{ fm}.$$
 (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 $K^-n \to A\pi^-$ 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 Ap and $\Sigma^0 p$ pairs emitted in K^- hadronic interactions with ¹²C 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 Ap invariant mass, Ap angular correlation, A and proton momenta using the simulated distributions for both direct A production and Σ^0 production followed by $\Sigma^0 \to A\gamma$ decay. The K^- nuclear capture was calculated for both atrest 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 A 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]	0	$p_K \; [{\rm MeV}/c]$
$2NA$ -QF Λp	$0.25 \pm 0.02 (\text{stat.})^{+0.01}_{-0.02} (\text{syst.})$	$2.8 \pm 0.3 (\text{stat.})^{+0.1}_{-0.2} (\text{syst.})$	0	128 ± 29
$2NA$ -FSI Λp	$6.2 \pm 1.4 (\text{stat.})^{+0.5}_{-0.6} (\text{syst.})$	$69\pm15(\text{stat.})\pm6(\text{syst.})$	0	128 ± 29
$2NA$ -QF $\Sigma^0 p$	$0.35 \pm 0.09 (\text{stat.})^{+0.13}_{-0.06} (\text{syst.})$	$3.9 \pm 1.0 (\text{stat.})^{+1.4}_{-0.7} (\text{syst.})$	0	128 ± 29
$2NA$ -FSI $\Sigma^0 p$	$7.2 \pm 2.2 (\text{stat.})^{+4.2}_{-5.4} (\text{syst.})$	$80\pm25(\text{stat.})^{+46}_{-60}(\text{syst.})$	0	128 ± 29
2NA-CONV \varSigma/Λ	$2.1 \pm 1.2 (\text{stat.})^{+0.9}_{-0.5} (\text{syst.})$			—
$3NA \Lambda pn$	$1.4 \pm 0.2 (\text{stat.})^{+0.1}_{-0.2} (\text{syst.})$	$15\pm2(\text{stat.})\pm2(\text{syst.})$	0	117 ± 23
$3NA \ \Sigma^0 pn$	$3.7 \pm 0.4 (\text{stat.})^{+0.2}_{-0.4} (\text{syst.})$	$41 \pm 4 (\text{stat.})^{+2}_{-5} (\text{syst.})$	0	117 ± 23
$4NA \ \Lambda pnn$	$0.13 \pm 0.09 (\text{stat.})^{+0.08}_{-0.07} (\text{syst.})$	_		—
Global $\Lambda(\Sigma^0) p$	$21 \pm 3(\text{stat.})^{+5}_{-6}(\text{syst.})$			

The Ap 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

$$\mathcal{R} = \frac{\text{BR}(K^- pp \to \Lambda p)}{\text{BR}(K^- pp \to \Sigma^0 p)} = 0.7 \pm 0.2 \text{(stat.)}_{-0.3}^{+0.2} \text{(syst.)}.$$
 (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 $\bar{K}N$ dynamics below the threshold [30]. The possible contribution of a K^-pp bound state, decaying into a Ap 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 Ap production was performed by selecting $\cos \theta_{Ap} < -0.8$ 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.

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 the Austrian Science Fund (FWF): [P24756-N20]; the Austrian Federal Ministry of Science and Research BMBWK 650962/0001VI/2/2009; the Croatian Science Foundation, under project 8570; Minstero degli Affari Esteri e della Cooperazione Internazionale, Direzione Generale per la Promozione del Sistema Paese (MAECI), Strange Matter project; the National Science Centre, Poland (NCN) through grant No. UMO-2016/21/D/ST2/01155; EU STRONG-2020 (grant agreement 824093).

REFERENCES

- C. Curceanu et al. [AMADEUS Collaboration], Acta Phys. Pol. B 46, 203 (2015).
- [2] M. Tanabashi et al. [Particle Data Group], Phys. Rev. D 98, 030001 (2018).
- [3] Y. Akaishi, T. Yamazaki, *Phys. Rev. C* 65, 044005 (2002).
- [4] Y. Ikeda, T. Sato, *Phys. Rev. C* 76, 035203 (2007).
- [5] S. Wycech, A.M. Green, *Phys. Rev. C* **79**, 014001 (2009).
- [6] J. Revai, N.V. Shevchenko, *Phys. Rev. C* **90**, 034004 (2014).
- [7] S. Maeda, Y. Akaishi, T. Yamazaki, Proc. Jpn. Acad. B 89, 418 (2013).
- [8] A. Dote, T. Hyodo, W. Weise, *Phys. Rev. C* **79**, 014003 (2009).
- [9] N. Barnea, A. Gal, E.Z. Liverts, *Phys. Lett. B* **712**, 132 (2012).
- [10] Y. Ikeda, H. Kamano, T. Sato, Prog. Theor. Phys. 124, 533 (2010).
- [11] P. Bicudo, *Phys. Rev. D* **76**, 031502 (2007).
- [12] M. Bayar, E. Oset, *Nucl. Phys. A* **914**, 349 (2013).

- [13] K. Piscicchia et al., Phys. Lett. B 782, 339 (2018).
- T. Suzuki et al., Mod. Phys. Lett. A 23, 2520 (2008); V.K. Magas, E. Oset,
 A. Ramos, H. Toki, Phys. Rev. C 74, 025206 (2006); V.K. Magas, E. Oset,
 A. Ramos, Phys. Rev. C 77, 065210 (2008).
- [15] O. Vazques Doce et al., Phys. Lett. B 758, 134 (2016).
- [16] V. Metag, M. Nanova, E.Ya. Paryev, Prog. Part. Nucl. Phys. 97, 199 (2017).
- [17] E. Friedman, A. Gal, Nucl. Phys. A 959, 66 (2017).
- [18] J. Hrtánková, J. Mareš, *Phys. Rev. C* 96, 015205 (2017).
- [19] R. Del Grande et al., Eur. Phys. J. C 79, 190 (2019).
- [20] F. Bossi et al., Riv. Nuovo Cim. **31**, 531 (2008).
- [21] A. Gallo et al., Conf. Proc. C060626, 604 (2006).
- [22] K. Piscicchia, S. Wycech, C. Curceanu, Nucl. Phys. A 954, 75 (2016).
- [23] A. Feijoo, V. Magas, A. Ramos, *Phys. Rev. C* 99, 035211 (2019).
- [24] Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A 881, 98 (2012).
- [25] A. Cieplý, J. Smejkal, Nucl. Phys. A 881, 115 (2012).
- [26] Z.H. Guo, J.A. Oller, *Phys. Rev. C* 87, 035202 (2013).
- [27] M. Mai, U.-G. Meißner, Eur. Phys. J. A 51, 30 (2015).
- [28] A. Feijoo, V.K. Magas, A. Ramos, AIP Conf. Proc. 2130, 040013 (2019).
- [29] R. Del Grande, K. Piscicchia, S. Wycech, Acta Phys. Pol. B 48, 1881 (2017).
- [30] J. Hrtánková, A. Ramos, arXiv:1910.01336 [nucl-th], submitted to Phys. Rev. C.
- [31] M. Agnello et al., Phys. Rev. Lett. 94, 212303 (2005).