Frontiers | Frontiers in Physics

TYPE Mini Review
PUBLISHED 31 July 2023
DOI 10.3389/fphy.2023.1237644

OPEN ACCESS

EDITED BY
Kanchan Khemchandani,
Federal University of São Paulo, Brazil

REVIEWED BY
Zilong Chang,
Indiana University, United States

*CORRESPONDENCE
Magdalena Skurzok,
magdalena.skurzok@uj.edu.pl

RECEIVED 09 June 2023
ACCEPTED 29 June 2023
PUBLISHED 31 July 2023

CITATION
Skurzok M, Cargnelli M, del Grande R, Fabbietti L, Guaraldo C, Marton J, Moskal P, Piscicchia K, Scordo A, Silarski M, Sirghi DL, Vazquez Doce O, Zmeskal J, Wycech S, Branchini P, Czerwiński E, Kang X, Mandaglio G, Martini M, Selce A and Curceanu C (2023), A review of the low-energy K⁻-nucleus/nuclei interactions with light nuclei AMADEUS investigations. *Front. Phys.* 11:1237644. doi: 10.3389/fphy.2023.1237644

A review of the low-energy K^--nucleus/nuclei interactions with light nuclei AMADEUS investigations

Magdalena Skurzok[1,2]*, Michael Cargnelli[3], Raffaele del Grande[4,5], Laura Fabbietti[4,6], Carlo Guaraldo[5], Johann Marton[3], Paweł Moskal[1,2], Kristian Piscicchia[7,5], Alessandro Scordo[5], Michał Silarski[1,2], Diana Laura Sirghi[5,8], Oton Vazquez Doce[5], Johann Zmeskal[3], Sławomir Wycech[9], Paolo Branchini[10], Eryk Czerwiński[1,2], Xiaolin Kang[11], Giuseppe Mandaglio[12,13], Matteo Martini[14,5], Andrea Selce[5] and Catalina Curceanu[5]

[1]Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland, [2]Center for Theranostics, Jagiellonian University, Kraków, Poland, [3]Stefan-Meyer-Institut für Subatomare Physik, Vienna, Austria, [4]Physik Department E62, Technische Universität München, Garching, Germany, [5]Instituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, Frascati, Italy, [6]Excellence Cluster "Origin and Structure of the Universe", Garching, Germany, [7]Centro Ricerche Enrico Fermi—Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Roma, Italy, [8]Horia Hulubei National Institute of Physics and Nuclear Engineering, Magurele, Romania, [9]Department of Theoretical Physics, National Centre for Nuclear Research, Warsaw, Poland, [10]INFN Sezione di Roma Tre, Roma, Italy, [11]Department of Physics, China University of Geosciences, Wuhan, China, [12]Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra dell'Università di Messina, Messina, Italy, [13]INFN Sezione di Catania, Catania, Italy, [14]Dipartimento di Scienze e Tecnologie Applicate, Università "Guglielmo Marconi", Roma, Italy

The AMADEUS Collaboration conducts research aimed to experimentally investigate the low-energy K^- hadronic interactions with light nuclei like hydrogen, helium, and carbon, in order to provide new constraints to the antikaon-nucleon strong interaction studies in the non-perturbative quantum chromodynamics regime. K^- nuclear absorption, both at-rest and in-flight, are explored using the unique low-momentum and monochromatic kaon beam from the DAΦNE collider interacting with the KLOE detector components, a detector characterized by high acceptance and excellent position and momentum resolutions. This paper presents an overview of the AMADEUS results.

KEYWORDS

strangeness, kaon absorption, antikaon interactions in nuclear matter, strong interaction, cross section

1 Introduction

The AMADEUS (Anti-kaonic Matter At DAΦNE: An Experiment with Unraveling Spectroscopy) Collaboration performed research of the low-energy K^--nucleon/nuclei interactions in light nuclear targets for over a decade [1–3]. The primary objective of these studies is an investigation of the poorly known $\Lambda(1405)$ resonance and a deeper understanding of the K^- single- and multi-nucleon absorption processes, both at-rest and in-flight, including the possible formation of kaonic bound states.

The investigation of the in-medium modification of the $\bar{K}N$ interaction is of fundamental importance for the low-energy Quantum Chromodynamic (QCD) in the strangeness sector. Chiral Perturbation Theory (ChPT), an Effective Field Theory (EFT) that successfully describes interactions involving πN, $\pi\pi$ and NN in the low-energy regime [4, 5] is not applicable to the sector with s quarks due to the broad Λ(1405) and Σ(1385) resonances emerging just below the $\bar{K}N$ threshold. The resonances appearance causes an attractive $\bar{K}N$ interaction in the far subthreshold region, whereas it looks repulsive at threshold, as demonstrated by the SIDDHARTHA measurements of the K^-p scattering length [6].

Two main theoretical approaches have been developed to overcome these difficulties, namely, phenomenological potential models based on the $\bar{K}N$ and NN interactions [7–13] and chiral unitary models involving the non-perturbative Chiral SU(3) dynamics [14–20]. The two models, constrained by the existing scattering data, describe the $\bar{K}$ dynamics above the threshold very well, however, a large difference appears in the subthreshold extrapolations. In particular, significantly weaker attraction is predicted by the chiral SU(3) models than by the phenomenological potential approach which leads to contrasting predictions for the Λ(1405) (I = 0) resonance and related kaonic nuclear bound states. Although the Particle Data Group (PDG) [21] lists the Λ(1405) as a four-star resonance (spin 1/2, isospin I = 0, strangeness $S = -1$), decaying into $(\Sigma\pi)^0$ through the strong interaction, its nature remains still an open issue. According to the phenomenological potential models, the Λ(1405) is a pure strongly attractive $\bar{K}N$ bound state with a mass of about 1,405 MeV/c^2, binding energy of about 30 MeV and a width of 40 MeV/c^2 [7, 13]. Conversely, the chiral models [14–20] predict that Λ(1405) occurs as a superposition of two states, a high-mass state predominantly coupled to the $\bar{K}N$ production channel and a low-mass state mainly coupled to the Σπ channel which are located around 1,420 MeV/c^2 and at 1,380 MeV/c^2, respectively. The two different theoretical scenarios for Λ(1405) reflect the strength of the $\bar{K}N$ interaction and thus influence the possibility of K^- multi-nucleon bound states formation. Deeply bound nuclear states with narrow widths and large binding energies (up to 100 MeV/c^2) are predicted by phenomenological models as a consequence of the strongly attractive $\bar{K}N$ interaction, while SU(3) models result in much less attractive K^-N interaction, which leads to the prediction of slightly bound kaonic nuclear states. Till now, the bound kaonic nuclear states have been searched for in several experiments, using two main approaches: proton-proton and heavy ion collisions (DISTO [22]) as well as in-flight and at-rest K^- interactions in light nuclei (FINUDA [23] and KEK-PS E549 [24, 25] experiments). The first K^-pp bound kaonic nuclear system signal has been currently observed and investigated at J-PARC in the ^{3}He(K^-, Λp)n reaction [25].

Recently the ALICE Collaboration confirmed the couple-channel character of the $\bar{K}N$ interaction [26] indicating that the $(\Sigma\pi)^0$ invariant mass spectral shape depends on the decay channel (since the isospin interference term contributes to $\Sigma^\pm\pi^\mp$ cross section with opposite sign and vanishes for $\Sigma^0\pi^0$) as well as on the production channel. In this case, $\bar{K}N$ absorption represents the golden channel for examining the predicted high mass pole of the Λ(1405). Moreover, experimental studies of spectral shape and yield of non-resonant contribution in hyperon–pion final states, allow to constraint the chiral predictions which are strongly model dependent. This has been performed by investigating the single-nucleon absorption $K^-n \rightarrow \Lambda\pi^-$ channel [27].

Investigation of K^- multi-nucleon absorption contributions plays a very important role in the determination of the K^--nucleus optical potential. Existing K^- single-nucleon optical potentials, combined with phenomenologically determined K^- multi-nucleon absorption term (based on global absorption bubble chamber data) do not reproduce the kaonic atoms data along the periodic table of the elements [28, 29]. Therefore, it is crucial to improve the theoretical model by providing complete characteristics of the absorption processes, by extracting the two-, three-, and four-nucleon absorptions (2NA, 3NA, and 4NA). The first comprehensive measurement of K^- multi-nucleon absorptions, including a contribution of the possible K^-pp bound state, has been completed [30].

The purpose of the article is to provide an overview of the current status of the research performed by AMADEUS collaboration. It begins with an introduction of the experimental facility, namely, the DAΦNE accelerator and the KLOE detector. Thereupon, K^- single- and multi-nucleon absorption studies and their impact on the field are discussed, which is followed by Conclusions.

2 Experimental facility

The AMADEUS studies are based on an experimental data sample, corresponding to 1.74 fb^{-1} integrated luminosity, collected with the KLOE detection system [31, 32], installed at the double electron-positron ring of the DAΦNE collider [33] located at the National Laboratory in Frascati of INFN (Italy).

The DAΦNE facility (so-called ϕ meson factory) was designed to work at the center of mass energy of the ϕ meson. The acceleration complex deliver low-momentum (~127 MeV/c) monochromatic charged kaon beam, characterized by a very small hadronic background, originating from the ϕ-meson decays (BR(K^+K^-) = (48.9 ± 0.5)%) which, in turn, is produced in e^+e^- collisions (beam energies of 0.51 GeV). The back-to-back topology of the kaons pair production allows to extrapolate non-identified charged kaon tracks.

The KLOE detector system has a 4π geometry and surrounds the DAΦNE interaction region (geometrical acceptance of 98%). The detection setup consists of two basic components: a large cylindrical Drift Chamber (DC) [31, 34] and an electromagnetic calorimeter (EMC) consisting of groved lead with scintillating fibers [31, 35]. The detection system was immersed in a 0.52 T magnetic field along the beam axis, provided by a superconducting solenoid.

The DC, designed for tracking and identification of charged particles, containing a total of about 52,000 wire, was filled with a mixture of helium (90%) and isobutane (10%) C_4H_{10}. Its inner radius, outer radius, and length were equal to 0.25, 2, and 3.3 m, respectively. The DC entrance wall was built of 750 μm layer of low-density carbon fiber and 150 μm layer of aluminum. The momenta of charged particles were determined with excellent relative accuracy of $\frac{\sigma(p)}{p} = 0.4\%$. The spatial resolution of the particle tracks reconstruction was of $\sigma_{\rho\phi}$ ~ 200 μm in the transverse and of σ_z ~ 2 mm along the z-axis, while the accuracy of decay vertices reconstruction was about 1 mm.

The EMC composed of a cylindrical barrel with an inner radius of 2 m and two end-caps was dedicated to neutral particles detection. It also provided Time-of-Flight (TOF) information for the charged particles. The volume ratio of lead-scintillating fibers (lead/fibers/glue = 42:48:10) was optimized to achieve high light yield and high efficiency for photons in the 20–300 MeV/c energy range. The cluster position resolution along the fibers was $\sigma_{\parallel} = \frac{1.4cm}{\sqrt{(E/1GeV)}}$, while in the orthogonal direction it was $\sigma_{\perp} = 1.4$ cm. The energy and time resolutions for photon clusters are given by $\frac{\sigma_E}{E_\gamma} = \frac{0.057}{\sqrt{(E_\gamma/1GeV)}}$ and $\sigma_t = \frac{57ps}{\sqrt{(E_\gamma/1GeV)}} \oplus 100$ ps, respectively.

3 Single- and multi-nucleon K$^-$ absorption studies

Since the Λ(1405)'s resonance line shape is expected to depend on both, the production mechanism and the observed decay channel [26], experimental investigation of its properties is challenging. Additionally, extraction of the shape of the Λ(1405) invariant mass in reactions induced by negatively charged kaons (K$^-$) is complicated by two biases. The first bias arises from the threshold of the $\Sigma\pi$ invariant mass, which is limited by the last nucleon binding energy. This threshold is approximately 1,412 MeV/c^2 for K$^-$ capture at rest on ^{4}He and around 1,416 MeV/c^2 on ^{12}C. Therefore, to verify the existence of the predicted high mass pole of the Λ(1405), which is expected to be located at approximately 1,420 MeV/c^2, it is necessary to explore the K$^-$ absorption in flight. As shown in [36], the experimental $\Sigma^0\pi^0$ invariant mass threshold for K$^-$ captures in ^{12}C in flight ($p_K \sim$ 100 MeV/c) is shifted upwards by about 10 MeV with respect to the capture at-rest, thus opening the access to the energy range of interests. The $\Sigma^0\pi^0$ is the so-called "golden decay channel" since it provides a clear Λ(1405) signature in the I = 0 isospin.

Another crucial bias impacting the $(\Sigma\pi)^0$ invariant mass spectrum is associated with the non-resonant contribution, which needs to be subtracted in order to extract the shape and investigate the characteristics of the Λ(1405) resonance. Chiral SU(3) meson-baryon coupled channels interaction models (Barcelona (BCN) [37], Prague (P) [38], Kyoto-Munich (KM) [39], Murcia (M1,M2) [40], Bonn (B2,B4) [41]) provide the K$^-$n → $\Lambda\pi/\Sigma\pi$ scattering amplitudes, which, however, strongly differ in the $\bar{K}$N subthreshold region. To determine the appropriate model for explaining the observed spectra of $\Sigma^0\pi^0$, the K$^-$n → $\Lambda\pi^-$ process was investigated by AMADEUS for the single-nucleon K$^-$ absorption in ^{4}He [27]. The non-resonant transition amplitude, below the $\bar{K}$N threshold, was extracted for the first time for the K$^-$n → $\Lambda\pi^-$ channel, based on the well known resonant part corresponding to the formation of Σ^-(1385) (I = 1). The multidimensional fit of experimental distributions ($\Lambda\pi^-$ invariant mass, momentum, and angular spectrum) with dedicated Monte Carlo simulations for the contributing processes (non-resonant and resonant reactions, the primary production of a Σ followed by the ΣN → ΛN' conversion process, the contamination of K$^-$^{12}C) was performed. The Monte Carlo simulations are based on the phenomenological K$^-$-nucleus absorption model developed in Ref. [42]. The non-resonant transition amplitude modulus was found to be $|A_{K^-n\to\Lambda\pi^-}| =$ (0.334 ± 0.018 stat. $^{+0.034}_{-0.058}$ syst.) fm at (33 ± 6) MeV/c^2 below the $\bar{K}$N threshold. A measurement at $\sqrt{s} \sim 33$ MeV/c^2 below threshold was possible due to the binding energy of the absorbing nucleon as well as to the recoil energy of the K$^-$n pair with respect to the residual ^{3}He nucleus. The AMADEUS experimental result together with the theoretical predictions rescaled for the K$^-$n → $\Sigma\pi$ transition probabilities, is shown in Figure 1.

The obtained result enables to test the chiral predictions in the subthreshold region which allow constraining the corresponding

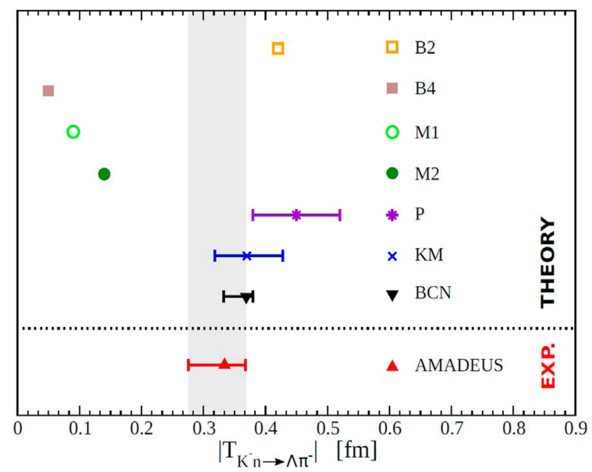

FIGURE 1
Modulus of the measured non resonant K$^-$n → $\Lambda\pi^-$ transition amplitude (with combined statistical and systematic errors) compared with theoretical calculations, see details in the text. Figure is adapted from [43].

non-resonant background for I = 0 channel $(\Sigma\pi)^0$ and hence to determine the Λ(1405) properties.

Apart from single-nucleon capture studies, AMADEUS conducted research specifically focused on K$^-$ absorptions on two or more nucleons. The investigation is highly significant for the determination of K$^-$-nucleus/nucleon optical potential which has a strong impact on various sectors of physics, like nuclear and particle physics as well as astrophysics [44–46]. A detailed characterization of the K$^-$ two-, three- and four-nucleon absorption processes (2NA, 3NA, and 4NA) in K$^-$ capture on ^{12}C nuclei was obtained by investigating $\Lambda(\Sigma^0)$p decay channels [30, 47]. A comprehensive study was performed [30] based on the phenomenological model for the K$^-$ captures at-rest and in-flight on light nuclei [42, 48]. The simultaneous fit of the experimental Λp invariant mass, Λp angular correlation, Λ and proton momentum spectra with the corresponding simulated distributions of the contributing processes (including the Σ^0 productions followed by $\Sigma^0 \to \Lambda\gamma$ decay and for the 2NA: 1) the Quasi-Free (QF) processes, 2) elastic Final State Interaction (FSI) processes and 3) inelastic FSI processes due to conversion (ΣN →ΛN′)), allowed to extract the K$^-$ 2NA, 3NA and 4NA branching ratios (BRs) and cross sections for low-momentum kaons in Λp and Σ^0p final states. The obtained BRs and cross sections are summarized in Table 1.

The determined global BR (sum of 2NA, 3NA, and 4NA BRs) (21 ± 3 (stat.)$^{+5}_{-6}$(syst.)) % aligns with the K$^-$ multi-nucleon absorption BRs measured in bubble chamber experiments [49, 50]. Combining the experimental BRs for processes leading to Λp pair production (16.1 ± 2.9 (stat.)$^{+1.0}_{-0.9}$(syst.))% [30] with a component corresponding to processes without Λp in the final state (5.5 ± 0.1 (stat.)$^{+1.0}_{-0.9}$(syst.))% [51] (determined based on theoretical and experimental information [49, 52]), the total BR for K$^-$ 2NA in ^{12}C was found to be (21.6 ± 2.9 (stat.)$^{+4.4}_{-5.6}$(syst.))% [51].

The performed studies show that the experimental BR of the Λp QF production in K$^-$ 2NA interaction is lower than that of Σ^0p QF production: $R = \frac{BR(K^-(pp)\to\Lambda p)}{BR(K^-(pp)\to\Sigma^0 p)} = 0.7 \pm 0.2\,(stat.)^{+0.2}_{-0.3}\,(syst.)$ indicating a dominance of Σ^0p final state, which in contradiction

TABLE 1 Branching ratios (for the K⁻ captured at-rest) and cross sections (for the K⁻ captured 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 [30].

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.)	—	

to the ratio of corresponding phase spaces $R' = 1.22$. This result was found to be consistent with theoretical calculations of Barcelona and Prague groups when considering the in-medium effect caused by the Pauli blocking [52].

The potential contribution of the K^-pp bound system to the Λp spectra was explored revealing the entire overlap of the signal associated with the formation of the K^-pp cluster in K^--induced reactions on carbon with the K^- 2NA-QF process [30]. Repeating the analysis in the FINUDA-like measurement [23] conditions (selection of back-to-back Λp events ($\cos\theta_{\Lambda p} < -0.8$)) yielded the same results (BRs are in agreement with those obtained from entire data sample), indicating that if the bound system exists, it cannot be distinguished from the two-nucleon capture process within this type of analysis.

4 Conclusion

In this paper, the results obtained by the AMADEUS collaboration in studying the low-energy K^- interactions with light nuclei inducing single- and multi-nucleon absorptions, were reviewed. The investigation of K^--nucleons/nuclei interactions is fundamental for a better understanding of the non-perturbative quantum chromodynamics QCD in the strangeness sector.

By conducting studies on the K^-n single nucleon absorption in ^{4}He, it was possible to provide the first characterization of the non-resonant $K^-N \rightarrow Y\pi$ production below the $\bar{K}N$ threshold which is crucial for investigating the properties of the puzzling $\Lambda(1405)$ resonance. Additionally, investigations of low-energy K^- capture on a solid carbon target led to a comprehensive understanding of the two-, three-, and four-nucleon absorptions in the Λp and Σ^0p final states, including their branching ratios (BRs) and cross sections. Furthermore, it was discovered that the potential contribution from a K^-pp bound state completely overlaps with the K^- two-nucleon quasi-free process. The presented results demonstrate that the DAΦNE collider is a unique research facility with outstanding capabilities for studying kaon physics at low energies.

The AMADEUS Collaboration is currently completing studies of K^- 4NA in the Λt golden channel and analyses related to $K^-p \rightarrow \Sigma^0 \pi^0 (\Lambda\, \pi^0)$ cross section determination for kaon momentum below 100 MeV/c [53] which will provide additional new experimental constraints to the $\bar{K}N$ strong interaction.

Author contributions

The manuscript was initially drafted by MAS, and later edited and contributed to by CC and KP. AS, KP, RG, OV, and MIS carried out simulations and data analysis. The results were discussed and analyzed by all authors. All authors contributed to the article and approved the submitted version.

Funding

We acknowledge the Centro Ricerche Enrico 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]; Austrian Federal Ministry of Science and Research BMBWK 650962/0001 VI/2/2009; the Croatian Science Foundation, Under Project 8570; Polish National Science Center through Grant No. UMO-2016/21/D/ST2/01155; the SciMat and qLife Priority Research Areas budget under the program Excellence Initiative–Research University at the Jagiellonian University; EU Horizon 2020 STRONG2020-No. 824093 Project.

Acknowledgments

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.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

1. Skurzok M, Bazzi M, Bragadireanu M, Bosnar D, Cargnelli M, Clozza A, et al. Investigation of the low-energy K⁻ hadronic interactions with light nuclei by AMADEUS. *Int J Mod Phys E* (2022) 31:08. doi:10.1142/S0218301322400018

2. Curceanu C, Piscicchia K, Bazzi M, Berucci C, Bosnar D, Bragadireanu A, et al. Unprecedented studies of the low-energy negatively charged kaons interactions in nuclear matter by AMADEUS. *Acta Phys Polon B* (2015) 46:203. doi:10.5506/APhysPolB.46.203

3. Del Grande R, Piscicchia K, Cargnelli M, Fabbietti L, Marton J, Moskal P, et al. On the K⁻ absorptions in light nuclei by AMADEUS. *Few-body Syst* (2021) 62:1. doi:10.1007/s00601-020-01589-7

4. Bernard V, Kaiser N, Meisner UG. Aspects of chiral pion-nucleon physics. *Nucl Phys A* (1997) 615:483–500. doi:10.1016/S0375-9474(97)00021-3

5. Scherer S, Schindler MR. A primer for chiral perturbation theory. *Lect Notes Phys* (2012) 830:1–338. doi:10.1007/978-3-642-19254-8

6. Bazzi M, Beer G, Bombelli L, Bragadireanu A, Cargnelli M, Corradi G, et al. A new measurement of kaonic hydrogen X-rays. *Phys Lett B* (2011) 704:113–7. doi:10.1016/j.physletb.2011.09.011

7. Akaishi Y, Yamazaki T. Nuclear K⁻ bound states in light nuclei. *Phys Rev C* (2002) 65:044005. doi:10.1103/PhysRevC.65.044005

8. Ikeda Y, Sato T. Strange dibaryon resonance in the K⁻NN - πYN system. *Phys Rev C* (2007) 76:035203. doi:10.1103/PhysRevC.76.035203

9. Wycech S, Green AM. Variational calculations for K⁻-few-nucleon systems. *Phys Rev C* (2009) 79:014001. doi:10.1103/PhysRevC.79.014001

10. Shevchenko NV, Gal A, Mares J. Faddeev calculation of a K⁻pp quasi-bound state. *Phys Rev Lett* (2007) 98:082301. doi:10.1103/PhysRevLett.98.082301

11. Révai J, Shevchenko NV. Faddeev calculations of the KNN system with chirally-motivated KN interaction. II. The K⁻pp quasibound state. *Phys Rev C* (2014) 90:034004. doi:10.1103/PhysRevC.90.034004

12. Maeda S, Akaishi Y, Yamazaki T. Strong binding and shrinkage of single and double an external file that holds a picture, illustration, etc. Object name is pjab-89-418-i001.jpg nuclear systems (K−pp, K−ppn, K−K−p and K−K−pp) predicted by Faddeev-Yakubovsky calculations. *Proc Jpn Acad B* (2013) 89:418–37. doi:10.2183/pjab.89.418

13. Akaishi Y, Yamazaki T. (K⁻, π^-) production of nuclear K⁻ bound states in proton-rich systems via Λ* doorways. *Phys Lett B* (2002) 535:70–6. doi:10.1016/S0370-2693(02)01738-0

14. Dote A, Hyodo T, Weise W. Variational calculation of the pp K^- system based on chiral SU(3) dynamics. *Phys Rev C* (2009) 79:014003. doi:10.1103/PhysRevC.79.014003

15. Dote A, Inoue T, Myo T. Fully coupled-channel study of K^-pp resonance in a chiral SU(3)-based potential. *Phys Lett B* (2018) 784:405–10. doi:10.1016/j.physletb.2018.08.029

16. Barnea N, Gal A, Liverts EZ. Realistic calculations of KNN, KNNN, and KKNN quasibound states. *Phys Lett B* (2012) 712:132–7. doi:10.1016/j.physletb.2012.04.055

17. Ikeda Y, Kamano H, Sato T. Energy dependence of FormulaN interactions and resonance Pole of strange dibaryons KN interactions and resonance Pole of strange dibaryons. *Prog Theor Phys* (2010) 124:533–9. doi:10.1143/PTP.124.533

18. Bicudo P. Large degeneracy of excited hadrons and quark models. *Phys Rev D* (2007) 76:094005. doi:10.1103/PhysRevD.76.094005

19. Bayar M, Oset E. The KNN system revisited including absorption. *Nucl Phys A* (2013) 914:349–53. doi:10.1016/j.nuclphysa.2013.02.005

20. Sekihara T, Oset E, Ramos A. On the structure observed in the in-flight ^{3}He(K⁻, Λp)n reaction at J-PARC. *Prog Theor Exp Phys* (2016) 2016:123D03. doi:10.1093/ptep/ptw166

21. Workman RL, Burkert VD, Crede V, Klempt E, Thoma U, Tiator L, et al. Review of particle physics. *Prog Theor Exp Phys* (2022) 2022. doi:10.1093/ptep/ptac097

22. Maggiora M, Kienle P, Suzuki K, Yamazaki T, Alexeev M, Amoroso A, et al. DISTO data on K⁻pp. *Nucl Phys A* (2010) 835:43–50. doi:10.1016/j.nuclphysa.2010.01.173

23. Agnello M, Beer G, Benussi L, Bertani M, Bianco S, Botta E, et al. Evidence for a kaon-bound state K⁻pp produced in K⁻ absorption reactions at rest. *Phys Rev Lett* (2005) 94:212303. doi:10.1103/PhysRevLett.94.212303

24. Suzuki T, Iio M, Itahashi K, Iwasaki M, Matsuda Y, Ohnishi H, et al. YN correlations from the stopped K⁻ reaction on ^{4}He. *Mod Phys Lett* (2008) A23:2520–3. doi:10.1142/S021773230802971X

25. Ajimura S, Asano H, Beer G, Berucci C, Bhang H, Bragadireanu M, et al. "K⁻pp", a $\bar{K}$ meson nuclear bound state, observed in ^{3}He(K⁻,p)n reactions. *Progr Theor Exp Phys* (2018) 789:620–5. doi:10.1016/j.physletb.2018.12.058

26. Acharya S, Adamová D, Adhya S, Adler A, Adolfsson J, Aggarwal M, et al. Scattering studies with low-energy kaon-proton femtoscopy in proton-proton collisions at the LHC. *Phys Rev Lett* (2020) 124:092301. doi:10.1103/PhysRevLett.124.092301

27. Piscicchia K, Wycech S, Fabbietti L, Cargnelli M, Curceanu C, Del Grande R, et al. First measurement of the K⁻n → $\Lambda\pi^-$ non-resonant transition amplitude below threshold. *Phys Lett B* (2018) 782:339–45. doi:10.1016/j.physletb.2018.05.025

28. Hrtánková J, Mares J. K⁻ nuclear states: Binding energies and widths. *Phys Rev C* (2017) 96:015205. doi:10.1103/PhysRevC.96.015205

29. Friedman E, Gal A. K⁻N amplitudes below threshold constrained by multi-nucleon absorption. *Nucl Phys A* (2017) 959:66–82. doi:10.1016/j.nuclphysa.2016.12.009

30. Del Grande R, Piscicchia K, Vazquez Doce O, Cargnelli M, Curceanu C, Fabbietti L, et al. K^- multi-nucleon absorption cross sections and branching ratios in Lambda p and Sigma0 p final states. *Eur Phys J C* (2019) 79:190. doi:10.1140/epjc/s10052-019-6694-7

31. Lee-Franzini J, Franzini P. A flavor of KLOE. *Acta Phys Polon B* (2007) 38:2703–30.

32. Bossi F, De Lucia E, Lee-Franzini J, Miscetti S, Palutan M, Collaboration K. Precision kaon and hadron physics with KLOE. *Rivista Del Nuovo Cimento* (2008) 31:531–623. doi:10.1393/ncr/i2008-10037-9

33. Gallo A, Alesini D, Biagini ME, Biscari C, Boni R, Boscolo M, et al. DAFNE status report. *Conf Proc* (2006) C060626:604–6.

34. Adinolfi M, Ambrosino F, Andryakov A, Antonelli A, Antonelli M, Bacci C, et al. The tracking detector of the KLOE experiment. *Nucl Instrum Meth* (2002) A488:51–73. doi:10.1016/S0168-9002(02)00514-4

35. Adinolfi M, Ambrosino F, Antonelli A, Antonelli M, Anulli F, Barbiellini G, et al. The KLOE electromagnetic calorimeter. *Nucl Instrum Meth* (2002) A482:364–86. doi:10.1016/S0168-9002(01)01502-9

36. Piscicchia K, Cargnelli M, Curceanu C, Del Grande R, Fabbietti L, Guaraldo C, et al. Low energy antikaon-nucleon/nuclei interaction studies by AMADEUS. *Acta Phys Polon B Proc Suppl* (2018) 11:609. doi:10.5506/aphyspolbsupp.11.609

37. Feijoo A, Magas V, Ramos A. *S*=1 meson-baryon interaction and the role of isospin filtering processes. *Phys Rev C* (2019) 99:035211. doi:10.1103/PhysRevC.99.035211

38. Cieply A, Smejkal J. Chirally motivated KN amplitudes for in-medium applications. *Nucl Phys A* (2012) 881:115–26. doi:10.1016/j.nuclphysa.2012.01.028

39. Ikeda Y, Hyodo T, Weise W. Chiral SU(3) theory of antikaon-nucleon interactions with improved threshold constraints. *Nucl Phys A* (2012) 881:98–114. doi:10.1016/j.nuclphysa.2012.01.029

40. Guo ZH, Oller JA. Meson-baryon reactions with strangeness -1 within a chiral framework. *Phys Rev C* (2013) 87:035202. doi:10.1103/PhysRevC.87.035202

41. Mai M, Meißner UG. Constraints on the chiral unitary $\bar{K}$ N amplitude from $\pi\Sigma K^+$ photoproduction data. *Eur Phys J A* (2015) 51:30. doi:10.1140/epja/i2015-15030-3

42. Piscicchia K, Wycech S, Curceanu C. On the K⁻^{4}He → $\Lambda\pi^{-3}$He resonant and non-resonant processes. *Nucl Phys A* (2016) 954:75–93. doi:10.1016/j.nuclphysa.2016.05.007

43. Feijoo A, Magas VK, Ramos A. The constraining effect of isospin filtering processes in low energy meson-baryon interactions. *AIP Conf Proc* (2019) 2130: 040013. doi:10.1063/1.5118410

44. Fuchs C. Strangeness production in heavy ion reactions at intermediate energies. *Prog Part Nucl Phys* (2004) 53:113–24. doi:10.1016/j.ppnp.2004.02.023

45. Weise W. Topics in low-energy QCD with strange quarks. *Hyperfine Interact* (2015) 233:131–40. doi:10.1007/s10751-015-1129-9

46. Tolos L, Fabbietti L. Strangeness in nuclei and neutron stars. *Progr Part Nucl Phys* (2020) 112:103770. doi:10.1016/j.ppnp.2020.103770

47. Vázquez Doce O, Fabbietti L, Cargnelli M, Curceanu C, Marton J, Piscicchia K, et al. K^- absorption on two nucleons and ppK^- bound state search in the Σ^0p final state. *Phys Lett B* (2016) 758:134–9. doi:10.1016/j.physletb.2016.05.001

48. Del Grande R, Piscicchia K, Wycech S. Formation of $\Sigma\pi$ pairs in nuclear captures of K^- mesons. *Acta Phys Polon B* (2017) 48:1881. doi:10.5506/APhysPolB.48.1881

49. Vander Velde-Wilquet C, Sacton J, Wickens JH, Tovee DN, Davis DH. Determination of the branching fractions for K^- -meson absorptions at rest in carbon nuclei. *Il Nuovo Cimento A* (1977) 39:538–47. doi:10.1007/bf02771028

50. Del Grande R, Piscicchia K, Cargnelli M, Curceanu C, Fabbietti L, Marton J, et al. Total branching ratio of the k^- two-nucleon absorption in 12c. *Phys Scripta* (2020) 95: 084012. doi:10.1088/1402-4896/ab9ed3

51. Katz P, Bunnell K, Derrick M, Fields T, Hyman LG, Keyes G. Reactions of K^- stopping in helium. *Phys Rev D* (1970) 1(5):1267–76. doi:10.1103/physrevd.1.1267

52. Hrtánková J, Ramos A. Single- and two-nucleon antikaon absorption in nuclear matter with chiral meson-baryon interactions. *Phys Rev C* (2020) 101(3):035204. doi:10. 1103/PhysRevC.101.035204

53. Piscicchia K, Skurzok M, Cargnelli M, Del Grande R, Fabbietti L, Marton J, et al. *First simultaneous* $K^-p \rightarrow (\Sigma^0, \Lambda)\pi^0$ *cross sections measurements at 98 MeV/c* (2022). arXiv: 2210.10342.