

## Search for Deeply Bound Kaonic Nuclear States in AMADEUS experiment\*

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We briefly report on the search for Deeply Bound Kaonic Nuclear States  
with AMADEUS in the  $\Sigma^0 p$  channel and future perspectives.

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## 1. Introduction

The existence or not of the Deeply Bound Kaonic Nuclear States (DBKNS) is, currently, one of the hottest topics in nuclear and hadronic strangeness physics, both from experimental and theoretical points of view. The existence of bound kaonic nuclear states of  $K^-$ , also called kaonic nuclear clusters, was firstly predicted in 1986 [1]. The position of the  $\Lambda(1405)$  reflects the strength of the  $\bar{K}N$  interaction, thus influencing the possible formation of  $\bar{K}$  multi-nucleon bound states. Accordingly recent theoretical calculations, based on different approaches, deliver a wide range of bindings and widths for the di-baryonic kaonic bound state  $ppK^-$  [2, 3, 4, 5, 6, 7] while the experimental results are contradictory [8, 9, 10, 11, 12, 13, 14]. Moreover, the extraction of  $ppK^-$  signal in  $K^-$  absorption experiments is strongly affected by the yield and the shape of the competing  $K^-$  multi-nucleon absorption processes. Therefore, in order to clarify this issue, experimental data are needed. This research is very important in understanding the fundamental laws of the Nature and Universe. It can have important consequences in various sectors of physics, like nuclear and particle physics, as well as astrophysics. The binding of the kaon in nuclear medium may impact on models describing the structure of neutron stars (Equation of State of neutron stars) [15, 16] including binaries which are expected to be sources of the gravitational waves. Investigation of stable forms of strange matter like DBKNS in extreme conditions would be helpful for a better understanding of elementary kaon-nucleon interaction for low energies in the non-perturbative quantum chromodynamics (QCD) and would contribute to solve crucial problems in hadron physics: hadron masses (related to the chiral symmetry breaking), hadron interactions in nuclear medium and the structure of the dense nuclear matter.

The AMADEUS group has developed a method having a high chance for discovery of DBKNS corresponding to  $K^-pp$ ,  $K^-ppn$  and  $K^-ppnn$  kaonic nuclear clusters and their decays to  $\Sigma^0/\Lambda p$ ,  $\Sigma^0/\Lambda d$  and  $\Sigma^0/\Lambda t$ , respectively. The method is based on the exclusive measurement of the momentum, angular and invariant mass spectra for correlated  $\Sigma^0/\Lambda p$ ,  $\Sigma^0/\Lambda d$ ,  $\Sigma^0/\Lambda t$  pairs [17]. Possible DBKNS may be produced with  $K^-$  stopped in helium or carbon and then decaying into considered decay channels. The AMADEUS experiment is conceived to perform a systematic investigation of the low-energy  $\bar{K}N$  interaction, taking advantage of the kaons beams delivered by the DAΦNE collider [18]. The ongoing AMADEUS analyses refer to two data samples. One is represented by the data collected by the KLOE [19] collaboration during the 2004/2005 data taking, corresponding to  $\sim 1.74 \text{ fb}^{-1}$ . The KLOE detector [20] is used as an active target, the hadronic interaction of negative kaons with the materials of the apparatus being in-

vestigated; in particular  $K^-{}^9\text{Be}$  absorptions in the DAΦNE Beryllium thin cylindrical layer and the DAΦNE aluminated beryllium pipe,  $K^-{}^{12}\text{C}$  and  $K^-{}^{\text{H}}$  absorptions in the KLOE Drift Chamber [21] (DC) inner wall (aluminated carbon fiber),  $K^-{}^4\text{He}$  in the DC gas. Extremely rich experimental information is contained in this sample, with  $K^-$  hadronic captures both at-rest and in-flight [22]. In order to increase the statistics and as an essential interpretation tool, a high purity carbon target (graphite) was realized in summer 2012 and installed inside the KLOE detector, between the beam pipe and the DC inner wall. The geometry of the target was optimized to maximize the kaon stopping power. The total collected integrated luminosity is  $\sim 90 \text{ pb}^{-1}$ . Up to now we analysed a sample of  $37 \text{ pb}^{-1}$  reconstructed data. The adopted procedure is to exclusively measure the correlated  $\Sigma^0/\Lambda p$ ,  $\Sigma^0/\Lambda d$  and  $\Sigma^0/\Lambda t$  pairs, searching for  $K^-pp$ ,  $K^-ppn$  and  $K^-ppnn$  multi-nucleon, and related bound states, production. In the next section we present briefly results of data analysis devoted to  $\Sigma^0 p$  channel. Detailed description can be found in Ref. [23].

## 2. $\Sigma^0 p$ data analysis

The analysis presented below is focused on studies of  $K^-$  absorption processes inside the Drift Chamber (DC) carbon wall leading to  $\Sigma^0 p$  final state [23]. Selection of  $\Lambda(1116)$  hyperons being the signature of the  $K^-$  hadronic interaction in  ${}^{12}\text{C}$  was the first aim of the data analysis. As were identified via reconstruction of their decay vertex  $\Lambda \rightarrow p + \pi^-$  (BR = 63.8%). The protons and negatively charged pions selection and identification was done using the  $dE/dx$  information in DC installed around the interaction point and the momentum of the track. The proton-pion invariant mass was determined under the  $p$  and  $\pi^-$  mass hypothesis. The constructed  $p\pi^-$  invariant mass resulted in a value of  $1115.753 \pm 0.002 \text{ MeV}/c^2$  and a statistical error of  $0.5 \text{ MeV}/c^2$ . Then,  $\Lambda$ -proton vertex was searched for and  $K^-$  absorption processes inside the DC wall were selected based on radial position  $\rho_{\Lambda p}$ . The identification of  $\Sigma^0$  candidates was carried out through their decay into  $\Lambda\gamma$  pairs where  $\gamma$  quanta were identified in Calorimeter [24]. Afterwards, simultaneous global fit to  $\Sigma^0 p$  invariant mass, the  $\cos(\theta_{\Sigma^0 p})$ , the  $\Sigma^0$  and the proton momenta was performed in order to extract contributions from the different absorption processes like 2 Nucleon Absorption (2NA), with final state interaction (FSI) or without (QF), 3NA and 4NA. For this purpose Monte Carlo simulations of the absorption processes in  ${}^{12}\text{C}$  have been carried out. The final fit is presented in Fig. 1. It delivered the contribution of the different absorption processes. The fit results in the first measurement of the 2NA free from FSI which was found to be 12% of the total absorption cross-section. Contribution from the  $K^-pp$  bound

state was included in the second fit of the experimental data. Breit-Wigner shape was used to simulate the bound state contribution, scanning a grid of possible bindings ( $15\text{-}75\text{ MeV}/c^2$  in steps of  $15\text{ MeV}/c^2$ ) and widths ( $30\text{-}70\text{ MeV}/c^2$  in steps of  $20\text{ MeV}/c^2$ ). The best value of the total reduced  $\chi^2$  was achieved for the hypothesis of a binding energy of  $45\text{ MeV}/c^2$  and width  $30\text{ MeV}/c^2$  and are shown in Fig. 2. The  $K^-pp$  yield extracted from the fit is  $K^-pp/K_{stop}^- = (0.044 \pm 0.009_{stat} \pm 0.005_{syst}) \cdot 10^{-2}$ . However, F-Test carried out to compare the two models: with and without  $K^-pp$  bound state, results in  $1\sigma$  significance for the best fit which doesn't allow to claim observation of the bound state.

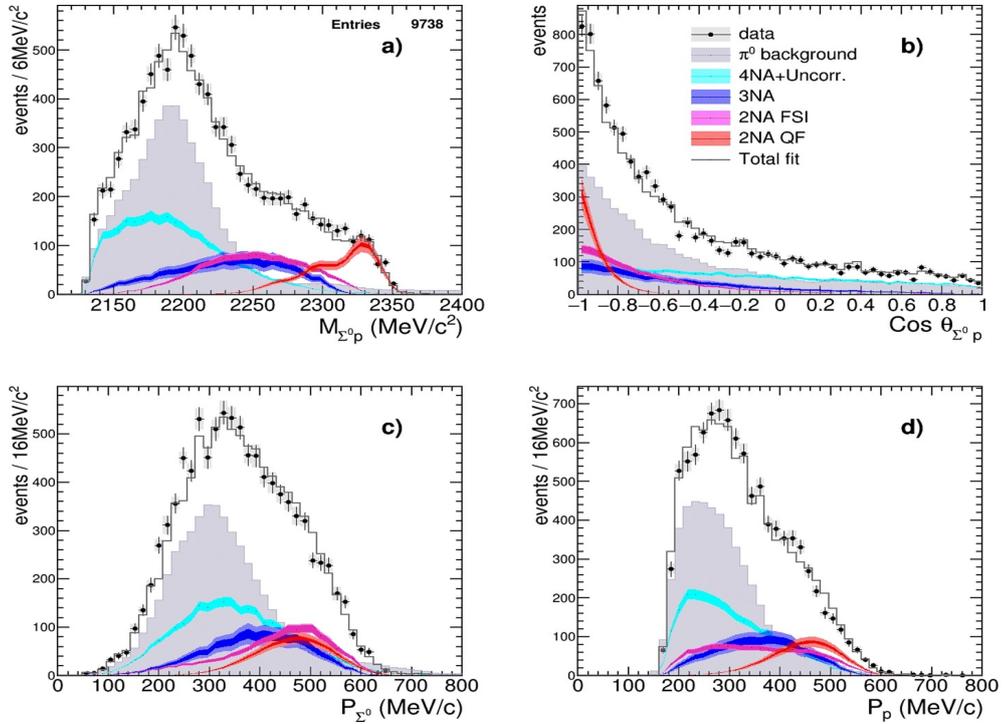


Fig. 1. The simultaneous fit to the  $\Sigma^0 p$  invariant mass (a),  $\cos(\Sigma^0 p)$  (b),  $\Sigma^0$  momentum (c) and proton momentum distributions (d) performed for kaons stopped in DC wall. The colors represent the following fit contributions:  $\pi^0$  background (grey), 4NA with uncorrelated production of the  $\Sigma^0 p$  final state (cyan), 3NA (blue), 2NA-FSI (magenta) and 2NA-QF (red). The light-coloured bands correspond to the fit errors while the darker bands represent the symmetrised systematic errors. The grey line shows the overall fit. Figure is adopted from [23].

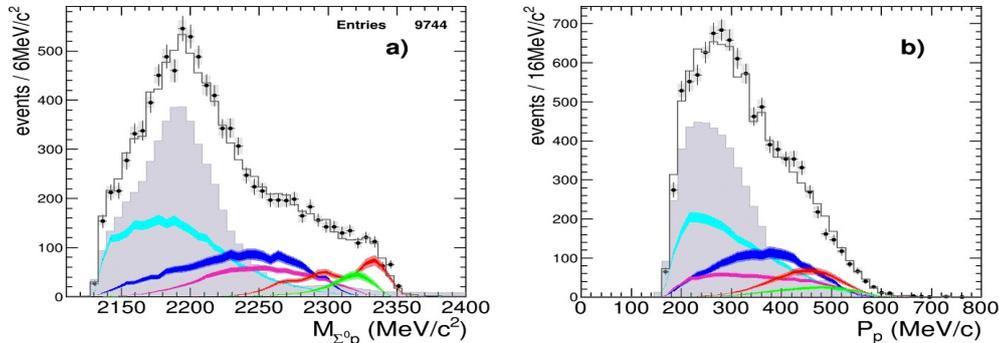


Fig. 2. The simultaneous fit to the  $\Sigma^0 p$  invariant mass (a) and proton momentum distributions (b) performed for kaons stopped in DC wall. Green color represents  $K^- pp$  signal while different contributions are marked as in Fig. 1. The black line shows the overall fit. Figure is adopted from [23].

### 3. Summary and conclusion

One of the AMADEUS's goal is to search for Deeply Bound Kaonic Nuclear States by studies of  $K^-$  absorption processes in various targets. In this work investigation of  $\Sigma^0 p$  final state was presented. It results in the extraction of contributions from various few nucleon absorption processes. Contribution from possible  $K^- pp$  bound state was determined, however the significance of the result is not sufficient to claim the observation of a bound system. Presently, the analysis is in progress for other channels like  $\Lambda p$ ,  $\Lambda d$  and  $\Lambda t$ . Moreover, a feasibility study [25, 26] is ongoing for the realization of a dedicated AMADEUS experimental setup, in order to deepen and extend the low energy anti-kaon nuclei interaction studies and obtain fundamental input for the understanding of the QCD with strangeness.

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## REFERENCES

- [1] S. Wycech, *Nucl. Phys. A* **450**, 399c (1986).
- [2] T. Yamazaki, *et al.*, *Phys. Rev. C* **76** 045201 (2007).
- [3] S. Wycech, *et al.*, *Phys. Rev. C* **79**, 014001 (2009).
- [4] N. Barnea, *et al.*, *Phys. Lett. B* **712**, 132 (2012).
- [5] E. Oset, *et al.*, *Nucl. Phys. A* **881**, 127 (2012).
- [6] A. Dote, T. Hyodo, W. Weise, *Phys. Rev. C* **79**, 014003 (2009).
- [7] Y. Ikeda, T. Sato, *Phys. Rev. C* **79**, 035201 (2009).
- [8] G. Agakishiev, *et al.*, *HADES Coll.*, *Phys. Lett. B* **742**, 242 (2015).
- [9] M. Agnello, *et al.* (*FINUDA Coll.*), *Phys. Rev. Lett.* **94**, 212303 (2005).
- [10] T. Yamazaki, *et al.*, *Phys. Rev. Lett.* **104**, 132502 (2010).
- [11] Y. Ichikawa, *et al.*, *Prog. Theor. Exp. Phys.* **021D01** (2015).
- [12] A. O. Tokiyasu *et al.*, *Phys. Lett. B* **728**, 616 (2014).
- [13] L. Fabbietti, *et al.*, *Nucl. Phys. A* **914**, 60 (2013).
- [14] T. Hashimoto, *et al.*, *Prog. Theor. Exp. Phys.* **061D01** (2015).
- [15] A. E. Nelson and D. B. Kaplan, *Phys. Lett B* **192**, 193 (1987).
- [16] A. Scordo, *al.*, *AIP Conf. Proc.* **1735**, 080015 (2016).
- [17] C. Curceanu, *et al.*, *Acta Phys. Polon. B* **46**, 203 (2015).
- [18] G. V. Vignola, *et al.*, *Conf. Proc. C* 930517 (1993) 1993.
- [19] F. Bossi, *et al.*, *KLOE coll.: Riv. Nuovo Cim.* **31**, 531 (2008).
- [20] F. Ambrosino, *et al.*, *NIM A* **534**, 403 (2004).
- [21] M. Adinolfi, *et al.*, [*KLOE Collaboration*], *Nucl. Inst. Meth. A* **488**, 51 (2002).
- [22] K. Piscicchia, *et al.*, *PoS Bormio2013*, 034 (2013).
- [23] O. Vazques Doce, *et al.*, *Phys. Lett. B* **758**, 134 (2016).
- [24] M. Adinolfi, *et al.* [*KLOE Collaboration*], *Nucl. Inst. Meth. A* **482**, 386 (2002).
- [25] M. Bazzi, *et al.*, *Nuclear Instruments and Methods in Physics Research A* **671**, 125 (2012).
- [26] M. Bazzi, *et al.*, *Journal of Instrumentation* 8(05) January 2013.