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Investigating the low-energy K^- interactions in nuclear matter with AMADEUS

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Abstract. The AMADEUS collaboration studies low-energy K^- interactions with light nuclei in order to clarify some aspects related to the behaviour of hadrons containing strangeness in nuclear medium. One of the main topics is the quest about the possible formation of Kaonic Nuclear Clusters (KNC), which depends on the strength of the anti-kaons interaction with nucleons. In kaonic absorption experiments, the search for KNC is strictly connected with the measurement of the yields of the so-called multi-nucleon absorption processes. In this paper, the study of Σ^0p correlated production from K^- absorption in ^{12}C, using the KLOE 2004-2005 data set, is reported. The yield of the two nucleon absorption (2NA), when the produced Σ^0 and p particles are free from any final state interaction process, was measured for the first time. The contribution of a ppK^- bound state was also tested. The best fit is obtained for a ppK^-

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state with a binding energy of 45 MeV and a width of 30 MeV, but the statistical significance is at the level of 1σ only.

1. Introduction

The AMADEUS (Anti-kaonic Matter At DAΦNE: An Experiment with Unraveling Spectroscopy) [1] collaboration investigates low-energy negative kaons induced reactions in light nuclear targets in order to provide experimental constraints to the non-perturbative QCD in the strangeness sector.

The study of $\bar{\text{K}}$N interaction has a special interest to understand the interplay between the spontaneous and explicit chiral symmetry breaking (induced by the large strange quark mass) and its role in the origin of hadron masses [2]. The existence of the Λ(1405) state only few MeV below the $\bar{\text{K}}$N threshold is related to the attractive antikaon-nucleon interaction, thus chiral perturbation theory is not applicable. Effective Lagrangian techniques as well as phenomenological potential models were developed to deal with this problem [3–10], leading to contrasting predictions for the Λ(1405) parameters and the related possibility for $\bar{\text{K}}$ multi-nucleon bound states. The Λ(1405) is experimentally found to exhibit different masses and widths, depending on the production channel as well as the chosen $(\Sigma\pi)^0$ observed decay. A detailed discussion regarding the theoretical and experimental determination of the Λ(1405) properties can be found in [11]. Calculations of the Binding Energy (BE) and the Width (Γ) of the ppK$^-$ state lead to different results, depending on the theoretical approach [12–19]. A strong experimental effort was devoted to the search for a ppK$^-$ state, but a clear evidence is still missing [20–26].

The broad program of the AMADEUS collaboration is devoted to a complete experimental investigation of the $\bar{\text{K}}$ behaviour in light nuclear matter, ranging from the measurement of hyperon resonances properties [27–29] to the search for $\bar{\text{K}}$-multi-N bound states. As will be outlined in the following sections, the extraction of bound state signal, in kaon induced reactions, strongly depends on an accurate description of K$^-$ multi-nucleon absorption processes, overlapping over a broad range of the allowed phase space [30, 31].

This contribution reports on the investigation of K$^-$ absorptions in ^{12}C nuclei, searching for Σ^0 proton correlated production. The aim of the analysis is to disentangle the different K$^-$ multi-nucleon absorption processes in order to extract the corresponding yields. A systematic search for signal of ppK$^-$ bound state was performed. Σ^0p is the golden decay channel of an eventual ppK$^-$ state, being free from the ΣN→ ΛN' conversion processes which strongly affect the competing Λp decay. In Sec. 2, we will introduce the features of the DAΦNE accelerator and the KLOE detector. In Sec. 3 the event selection procedure is described; results and conclusions are discussed in Secs. 4 and 5, respectively.

2. DAΦNE and KLOE

AMADEUS takes advantage of the DAΦNE (Double Annular Φ-factory for Nice Experiments) collider [32], which is a double rings e$^+$ e$^-$ collider, designed to work at the Center of Mass (CM) energy of the ϕ meson, which decays into K$^+$ K$^-$ pairs with a Branching Ratio of BR($\phi \to$ K$^+$ K$^-$) = 0.489 ± 0.005. Kaons are produced back-to-back with an almost monochromatic momentum of $p_{\text{K}} \sim 127$ MeV/c.

The KLOE (K LOng Experiment) [33] detector consists in a large cylindrical Drift Chamber (DC) [34] and a fine sampling lead-scintillating fibres calorimeter [35], all immersed in an axial magnetic field of 0.52 T, provided by a superconducting solenoid. The KLOE 4π geometry allows to cover almost the whole solid angle around the DAΦNE interaction point, therefore the acceptance is of ∼ 98 %. The DC has an inner radius of 0.25 m, an outer radius of 2 m and a length of 3.3 m. The DC entrance wall composition is 750 μm of carbon fibre and 150 μm of aluminium foil. Dedicated GEANT Monte Carlo (MC) simulations [36] of the KLOE apparatus were performed to estimate the percentages of K^- absorptions in the materials of the DC entrance wall (the K^- absorption physics were treated by the GEISHA package [37]). Out of the total number of kaons interacting in the DC entrance wall, about 81% results to be absorbed in the carbon fibre component and the residual 19% in the aluminium foil. The KLOE DC is filled with a mixture of helium and isobutane (90% in volume ^{4}He and 10% in volume C_4H_{10}). The chamber is characterised by excellent position and momentum resolutions. Tracks are reconstructed with a resolution in the transverse $R-\phi$ plane of $\sigma_{R\phi} \sim 150\,\mu$m and a resolution along the z-axis of $\sigma_z \sim$ 2mm. The transverse momentum resolution for low momentum tracks ((50 $< p <$ 300) MeV/c) is $\frac{\sigma_{p_T}}{p_T} \sim 0.4\%$. The KLOE calorimeter is composed of a cylindrical barrel and two end-caps. The volume ratio (lead/fibres/glue=42:48:10) is optimised for a high light yield and a high efficiency for photons in the range (20-300) MeV/c. The position of the cluster along the fibres can be obtained with a resolution $\sigma_\parallel \sim 1.4\,\mathrm{cm}/\sqrt{E/(1\mathrm{GeV})}$. The resolution in the orthogonal direction is $\sigma_\perp \sim 1.3$ cm. The energy and time resolutions for photon clusters are given by $\frac{\sigma_E}{E_\gamma} = \frac{0.057}{\sqrt{E_\gamma/(1\mathrm{GeV})}}$ and $\sigma_t = \frac{57\,\mathrm{ps}}{\sqrt{E_\gamma/(1\mathrm{GeV})}} \oplus 100$ ps.

The analysis presented below refers to a total integrated luminosity of $\mathcal{L} = 1.74$ pb^{-1}, from the 2004/2005 KLOE data taking campaign.

3. Events selection

The Σ^0p correlated events selection starts from the reconstruction of a $\Lambda(1116)$ particle through its charged decay $\Lambda \to$ p + π^- that occurs with a Branching Ratio (BR) of BR=63.9 $\pm$ 0.5 %, where the error contain both the statistic and systematic uncertainties. The proton and negative pion tracks are identified using both the dE/dx information from the DC wires and the measured energy release in the calorimeter. Details about p - π^- particle identification and vertex reconstruction can be found in [27, 38]. The measured pπ^- invariant mass is $m_{\mathrm{p}\pi^-} = 1115.723 \pm 0.002$ stat MeV/c^2 with a resolution of $\sigma = 0.5$ MeV/c^2. The systematic error is under evaluation. The hadronic interaction vertex is reconstructed through a backward extrapolation of the Λ path and an extra-proton track (with the same selection requirements optimized for the proton from Λ decay). The resolution achieved for the radial coordinate of the Λp vertex ($\rho_{\Lambda\mathrm{p}}$) is 1.2 mm. Σ^0 candidates are identified through their decay into $\Lambda\gamma$ pairs. After the Λp pair, the photon selection is carried out via its identification in the calorimeter [39]. In order to select K^- captures in ^{12}C the cut $\rho_{\Lambda\mathrm{p}}$=(25 $\pm$ 1.2) cm was applied, optimised by means of MC simulations and a study of the Λ decay path.

4. Results

A simultaneous fit of the measured invariant mass $m_{\Sigma^0\mathrm{p}}$, angular correlation $\cos(\theta_{\Sigma^0\mathrm{p}})$, Σ^0 momentum P_{Σ^0} and proton momentum P_p was performed to the following simulated processes:

1. K^- + "pp" $\to \Sigma^0$ + p (2NA),
2. K^- + "ppn" $\to \Sigma^0$ + p + n (3NA),
3. K^- + "ppnn" $\to \Sigma^0$ + p + n + n (4NA),

where 2NA, 3NA and 4NA refers to the number of nucleons involved in the multi-nucleon K^- absorptions. The interacting nucleon are bound in the Carbon nucleus. Final State Interactions (FSI) of the Σ^0 or p particles, produced in 2NA processes, with the residual nucleus, were also considered.

Two background sources are considered whose shapes were obtained from experimental data samples:

4. $K^- + A \to \Sigma^0(\pi) + p + R$,
5. $K^- + A \to \Lambda + p + \pi^0 + R$,

where R represents the residual nucleus. Process number 4 corresponds to the uncorrelated production of a Σ^0 and of a proton, in this case the proton originates from the fragmentation of the residual nucleus. Process number 5 describes Σ^0 misidentification when a $\Lambda\pi^0$ pair is produced. We refer to [39] for more details. The fit is shown in Fig. 1 and the obtained results are summarised in Table 1, where the yields of each contribution are normalised to the total number of stopped negative kaons. The best fit delivers a reduced χ^2 of 0.85.

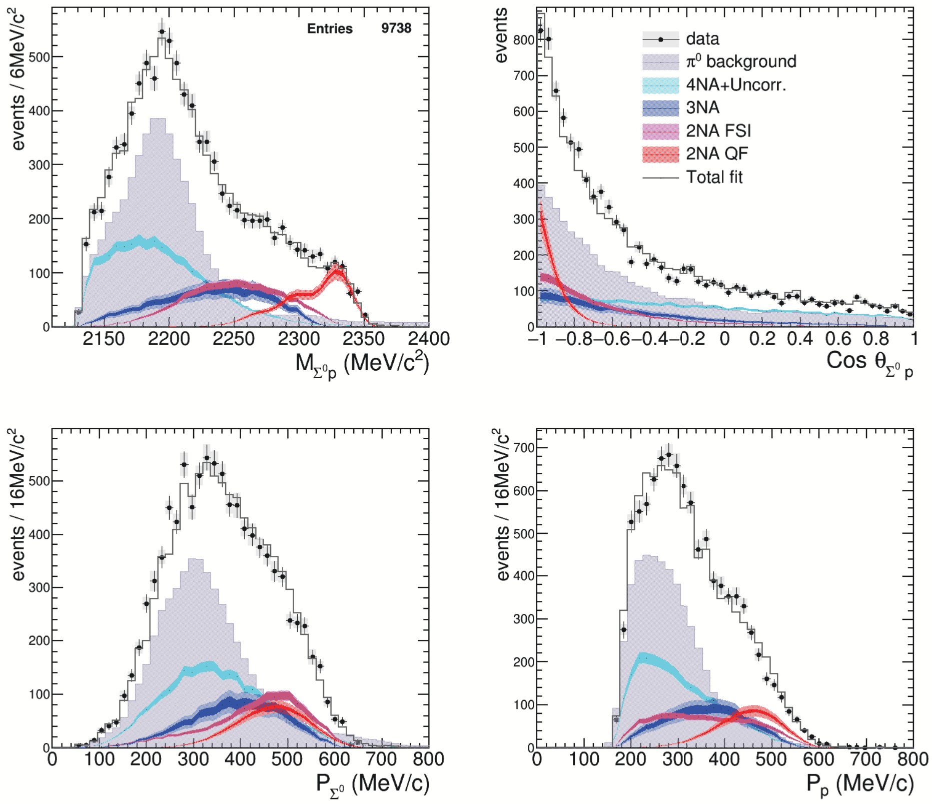

Figure 1. Fit of the Σ^0p invariant mass, $\cos(\theta_{\Sigma^0 p})$, Σ^0 and proton momenta is shown. Data points are represented by black circles, the systematic errors by boxes, coloured histograms correspond to the simulated processes (light-coloured bands show the statistical errors and the darker bands represent the symmetrised systematic errors). The gray line is the total fit.

The 2NA production probability in ^{12}C, when the produced Σ^0 and p particles are free form any FSI process (2NA-QF), was measured for the first time, with good precision. A second fit was performed to include the contribution of a ppK$^-$ bound state, decaying into Σ^0p. The ppK$^-$ mass was sampled according to a Breit-Wigner distribution. The event kinematic is obtained by imposing total energy and momentum conservation for the ppK$^-$-R system. Binding Energy (BE) and Width (Γ) were varied on a grid of values, $\Delta(\text{BE}) = (15 \div 75)\,\text{MeV/c}^2$ and $\Delta(\Gamma) = (30 \div 70)\,\text{MeV/c}^2$ in steps of 15 and 20 MeV/c^2, respectively. The best fit (reduced $\chi^2 = 0.807$) is obtained for a ppK$^-$ candidate with a binding energy of 45 MeV/c^2 and a width of 30 MeV/c^2. Out of the four simultaneously fitted distributions, the Σ^0p invariant mass and proton momentum distributions are displayed in Fig. 2 a) and b), respectively. The ppK$^-$

Table 1. Yields of the various Σ^0p production processes normalised to the number of stopped K^- in the DC wall. The statistical and systematic errors are also shown.

Process	yield / $K^-_{stop} \times 10^{-2}$	$\sigma_{stat} \times 10^{-2}$	$\sigma_{syst} \times 10^{-2}$
2NA-QF	0.127	± 0.019	$^{+0.004}_{-0.008}$
2NA-FSI	0.272	± 0.028	$^{+0.022}_{-0.023}$
Tot 2NA	0.399	± 0.033	$^{+0.023}_{-0.032}$
3NA	0.274	± 0.069	$^{+0.044}_{-0.021}$
Tot 3 body	0.546	± 0.074	$^{+0.048}_{-0.033}$
4NA + bkg.	0.773	± 0.053	$^{+0.025}_{-0.076}$

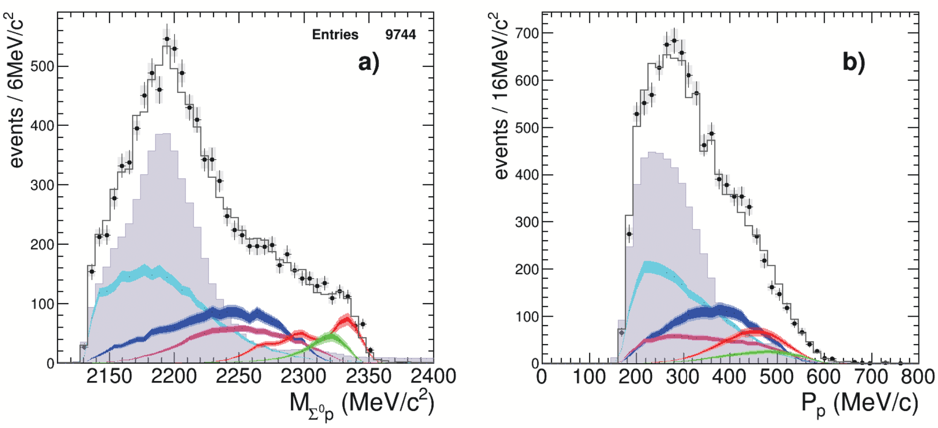

Figure 2. Experimental distributions of the Σ^0p invariant mass and proton momentum together with the results of the global fit including the ppK$^-$. The contributing distributions are labelled as in Fig. 1. The green curve represent the ppK$^-$ signal.

bound state contribution is shown in green. The resulting yield normalised to the number of stopped K^- is $ppK^-/K^-_{stop} = (0.044 \pm 0.009 \;\; \mathrm{stat}^{+0.004}_{-0.005} \; \mathrm{syst}) \times 10^{-2}$. An F-test was performed in order to estimate the significance of the measured bound state component with respect to a statistical fluctuation, i.e. the null hypothesis. The ppK$^-$ signal was found to be significant at the level of 1σ only. Although the measured spectra are compatible with the hypothesis of a bound state contribution, the significance of the result is not sufficient to claim the discovery of this state.

5. Conclusions

The main goals of the analysis described in this work consisted in the extraction of the relative yields of the K^- multi-nucleon absorption processes and the search for ppK$^-$ state signal. A sample of K^- captures in ^{12}C was selected and the Σ^0p final state was chosen because free from conversion (one of the main background sources of the Λp channel). We isolated the contribution of the free 2NA (2NA-QF) processes, without FSI, from the fit of the KLOE 2004-2005 data, using simulations to reproduce the kinematic shapes for the multi-nucleon absorption processes and the experimental data samples for the backgrounds. The yield of the 2NA process, when the produced Σ^0 and p particles are free form any FSI, was measured for the first time. A search for a ppK$^-$ bound state contribution was carried out with a scan in binding energies and widths ($\Delta(\mathrm{BE}) = (15 \div 75)\,\mathrm{MeV/c^2}$ and $\Delta(\Gamma) = (30 \div 70)\,\mathrm{MeV/c^2}$ in steps of 15 and 20 $\mathrm{MeV/c^2}$, respectively). The best value of the reduced χ^2 is achieved for a binding energy of 45 $\mathrm{MeV/c^2}$ and a width of 30 $\mathrm{MeV/c^2}$. The corresponding yield is $\mathrm{ppK^-}/\mathrm{K^-_{stop}} = (0.044 \pm 0.009\ \mathrm{stat}^{+0.004}_{-0.005}\mathrm{syst}) \times 10^{-2}$. In order to extract the significance of the $\mathrm{ppK^-}$ signal an F-test was performed. A significance of 1σ only was obtained for the measured $\mathrm{ppK^-}$ yield, which is not sufficient to claim the observation of this state.

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