Experimental results on multi-nucleonic K⁻ absorptions in light nuclei

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Abstract. The AMADEUS collaboration studied the K⁻ absorptions at low momentum in light nuclei leading to Σ^0p final state. Those events were recorded by the KLOE detector, used as an active target, installed in the the DAΦNE collider. The results show that it is possible to isolate the process where the K⁻ is absorbed by two nucleons and the decay products are emitted without any further final state interactions among other contributions involving more than two nucleons. Further, the possible contribution of a ppK⁻ bound state was investigated. The best fit gives space to a yield of ppK⁻/K$^-_{stop}$ = $(0.044 \pm 0.009$ stat$^{+0.004}_{-0.005}$ syst$) \times 10^{-2}$ corresponding to a binding energy and a width of 45 and 30 MeV/c^2, respectively. A statistical analysis of this result shows although that its significance is only at the level of 1σ.

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XIIth Quark Confinement & the Hadron Spectrum

1 Introduction

The strangeness sector in the low energy regime of the study of QCD has one of its main focus on the study of the strength and behaviour of the antikaon-nucleon potential. Many efforts from the theoretical and experimental point of view have been put forward in the last decades in order to describe the interaction of antikaons with nucleons and its implications on the possible formation of a superdense state of matter with strangeness content. A very interesting result is the prediction of the existence of the kaonic clusters [1] [2] that would mean in practice the trap of a antikaon inside a light nucleus allowing the formation of a very dense cold state of matter. A recent claim of the observation of the ppK^- bound state [3] is currently under theoretical investigation [4]. On the strength of the antikaon nucleon potential would depend as well the possibility (currently ruled out by the measurement of 2 solar masses neutron star candidates [5]) of a phase transition that would allow the formation of a kaonic condensate inside neutron stars [6] [7]. For the study of the antikaon-nucleon interaction, differently to what occurs with the kaon, the presence of below (close to) threshold resonances, like the very debated $\Lambda(1405)$ [8], prevents for a perturbative description of the dynamics of the antikaon-nucleon interaction dynamics. Different theoretical models have been used, from phenomenological approaches to optical potential descriptions. Generally those models are based on chiral $SU(3)$ Lagrangians and the use of coupled channel methods are demanded in order to describe the data [9]. Among the data used as input for models are: the shift and width due to the strong interaction in the kaonic hydrogen (recently measured with high precision by SIDDHARTA), the scattering cross sections, the invariant shape of the below threshold resonances and K-p hadronic branching ratios.

The AMADEUS collaboration [10] [11] study the low-energy K$^-$ interactions with light nuclei (H, ^{4}He, ^{9}Be and ^{12}C). The attractive behaviour of the K$^-$-nucleon potential is intimately related to the rather large cross-sections for antikaon absorption processes on nucleons that should be understood quantitatively. One of the main questions when dealing with the absorption processes is the specific contribution of processes involving two, three or more nucleons, for which several reactions have been investigated to extract this information but could not draw any quantitative conclusion on the contribution of the different processes. The interpretation of these results requires an accurate description of the single and multi-nucleon absorption processes that a K$^-$ would undergo when interacting with light nuclei. AMADEUS takes advantage of the DAΦNE collider at the LNF-INFN in Frascati, which provides a unique source of monochromatic low-momentum kaons and exploits the KLOE detector as an active target, in order to obtain excellent acceptance and resolution data for the K$^-$ nuclear capture, both at-rest and in-flight. From the analysis of the KLOE 2004-2005 data set, both the strength of the K$^-$ binding in nuclei and the $\Sigma(1385)$ and $\Lambda(1405)$ resonances properties can be extracted by analysing, respectively, the Λ/Σ-p,d,t channels and the decay channels $\Lambda/\Sigma - \pi$. Here we report on the study of the Σ^0p final state produced in absorption processes of K$^-$ on two or more nucleons, occurring in the KLOE Drift Chamber (DC) entrance wall which is composed by solid carbon, and on the search for a signature of the ppK$^- \rightarrow \Sigma^0$+p kaonic bound state. A more detailed description of the analysis procedures can be found in [12].

2 The DAΦNE collider and the KLOE detector

DAΦNE [13] (Double Anular Φ-factory for Nice Experiments) is a double ring $e^+ e^-$ collider, designed to work at the center-of-mass energy of the ϕ particle $m_\phi = (1019.456 \pm 0.020)$ MeV/c^2. The ϕ meson decay produces charged kaons (with BR(K$^+$ K$^-$) = 48.9 ± 0.5%) with low momentum ($\sim$ 127 MeV/c) which is ideal either to stop them, or to explore the products of the low-energy nuclear absorptions of K$^-$s. The KLOE detector [14] is centered around the interaction region of DAΦNE and is characterised by a $\sim 4\pi$ geometry and an acceptance of $\sim$ 98%; it consists of a large cylindrical

Drift Chamber (DC) and a fine sampling lead-scintillating fibers calorimeter, all immersed in an axial magnetic field of 0.52 T, provided by a superconducting solenoid. The DC [15] 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 MonteCarlo simulations 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). 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}) and 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 $\sigma_z \sim 2$ mm. 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 [16] is composed of a cylindrical barrel and two endcaps, providing a solid angle coverage of 98%. 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 $\sigma_\parallel \sim 1.4$ cm/ $\sqrt{E(\text{GeV})}$. The resolution in the orthogonal direction is $\sigma_\perp \sim 1.3$ cm. The energy and time resolutions for photon clusters are given by $\sigma_E/E_\gamma = 0.057/\sqrt{E_\gamma(\text{GeV})}$ and $\sigma_t = 54$ ps/ $\sqrt{E_\gamma(\text{GeV})}$ respectively. The AMADEUS step 0 consists in the 2004-2005 KLOE collected data analysis, that corresponds to a total integrated luminosity of 1.74 fb^{-1}, for which the dE/dx information of the reconstructed tracks is available (dE/dx represents the truncated mean of the ADC collected counts due to the ionisation in the DC gas). An important contribution of in-flight K$^-$ nuclear captures, in different nuclear targets from the KLOE materials, was evidenced and characterised, enabling to perform invariant mass spectroscopy of in-flight K$^-$ nuclear captures [17].

3 The Λ(1116) selection

The presence of a hyperon always represents the signature of a K$^-$ hadronic interaction inside the KLOE setup materials. Most of the analyses introduced in at the beginning then start with the identification of a Λ(1116), through the reconstruction of the $\Lambda \rightarrow p + \pi^-$ (BR = 63.9 ±0.5%) decay vertex. A minimum track length of 30 cm is required, and a common vertex is searched for all the p$-\pi^-$ pairs in each event. When found, the common vertex position is added as an additional constraint for the track refitting. The module of the momentum and the vector cosines are redefined for both tracks, taking into account for the energy loss in the gas and the various crossed materials (signal and field wires, DC wall, beam pipe) when tracks are extrapolated back through the detector. As a final step for the identification of Λ decays, the vertices are cross-checked with quality cuts using the minimum distance between tracks (minimum distance < 3.2 cm) and the chi-square of the vertex fit. A spatial resolution below 1 mm is achieved for vertices found inside the DC volume (evaluated with Monte Carlo). A gaussian fit on the invariant mass M$_{p\pi^-}$, calculated under the p and π^- mass hypothesis, gives a mass of 1115.723 ± 0.003 MeV/c^2 and an excellent resolution (σ) of 0.3 MeV/c^2, confirming the unique performances of KLOE for charged particles (the systematics, depending on the momentum calibration of the KLOE setup, are presently under evaluation).

4 Σ^0p analysis

After the Λ search, a common vertex between the Λ candidate and an additional proton track is searched for. The obtained resolution on the radial coordinate for the Λp vertex is 12 mm, while its

invariant mass resolution is found to be, from MC studies, equal to 1.1 MeV/c^2. The Σ^0 candidates are identified through their decay into $\Lambda\gamma$ pairs. After the reconstruction of a Λp pair, the photon selection is carried out via its identidication in the EMC. More details are given in [12]. Then, the Σ^0p invariant mass, opening angle, and the individual Σ^0 and proton momenta distributions are considered simultaneously in a global fit to extract the contributions of the various absorption processes. The processes that are taken into account in the fit of the experimental data are:

- K$^-$A $\rightarrow \Sigma^0 - (\pi)p_{spec}(A')$

- K$^-$pp $\rightarrow \Sigma^0$−p (2NA)

- K$^-$ppn $\rightarrow \Sigma^0$−p−n (3NA)

- K$^-$ppnn $\rightarrow \Sigma^0$−p−n−n (4NA)

where A is the atomic number of the target nucleus, p_{spec} is the spectator proton, A' is the atomic number of the residual nucleus and 2/3/4NA stands for 2/3/4-nucleons absorption. This list includes the K$^-$ absorption on two nucleons with and without final state interaction (FSI) for the Σ^0p state and processes involving more than two nucleons in the initial state. These contributions are either extracted from experimental data samples or modelled via simulations. Two kinds of background contribute to the analysed Σ^0p final state: the machine background and the events with $\Lambda\pi^0$p in the final state. Both are quantified using experimental data [12]. The obtained fit is shown in figure 1 and the results are summarised in table 4.

Table 1. Production probability of the Σ^0p final state for different intermediate processes normalised to the number of stopped K$^-$ in the DC wall. The statistical and systematic errors are shown as well [12].

Process	yield / K$^-_{stop}$ × 10^{-2}	σ_{stat} × 10^{-2}	σ_{syst} × 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	$^{+0.025}_{-0.076}$

The final fit results deliver the contributions of the different channels to the analysed Σ^0p final state. The best fit delivers a reduced chi-square of 0.85. The emission rates extracted from the fit are normalised to the total number of stopped antikaons. The fit results lead to the first measurements of the genuine 2NA-QF for the final state Σ^0p in reactions of stopped K$^-$ on targets of ^{12}C and ^{27}Al. This contribution is found to be only 9% of the total absorption cross-section. The last step of the analysis consists in the search of the ppK$^-$ bound state produced in K$^-$ interaction with nuclear targets, decaying into a Σ^0p pair. The ppK$^-$ are simulated similarly to the 2NA-QF process but sampling the mass of the ppK$^-$ state with a Breit-Wigner distribution, rather than the Fermi momenta of the two nucleons in the initial state. The event kinematic is obtained by imposing the momentum conservation of the ppK$^-$ residual nucleus system. Different values for the binding energy and width varying within $15 - 75$ MeV/c^2 and $30 - 70$ MeV/c^2 in steps of 15 and 20 MeV/c^2, respectively, are tested. This range has been selected according to several theoretical predictions present in literature and taking into account the experimental resolution. The global fit is repeated adding the ppK$^-$. The best fit (χ^2/ndf= 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, respectively. Figure 2 shows the results of the best fit for the Σ^0p invariant mass and proton momentum distributions where the ppK$^-$ bound state contribution is shown in green.
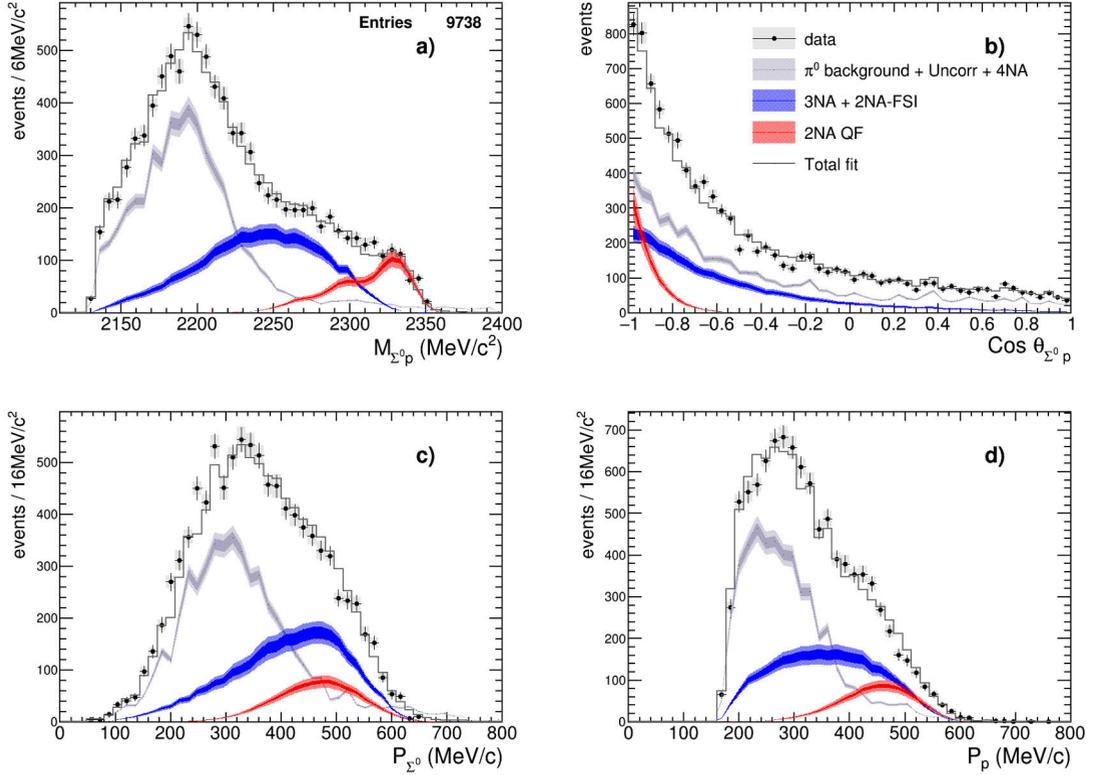
Figure 1. Experimental distributions of the $\Sigma^0 p$ invariant mass, $\cos(\theta_{\Sigma^0 p})$, Σ^0 and proton momentum together with the results of the global fit. The experimental data after the subtraction of the machine background are shown by the black circles, the systematic errors are represented by the boxes and the coloured histograms correspond to the fitted signal distributions where the light-coloured bands show the fit errors and the darker bands represent the symmetrised systematic errors. The gray line show the total fit distributions (see [12] for details).

The resulting yield normalised to the number of stopped K^- is ppK^-/K^-_{stop} = (0.044 ± 0.009 stat$^{+0.004}_{-0.005}$ syst)$\times 10^{-2}$. The F-test conducted to compare the simulation models with and without the ppK^- signal gave a significance of the result of only 1σ for the ppK^- yield result [12]. This shows that although the measured spectra are compatible with the hypothesis of a contribution of a deeply bound state, the significance of the result is not sufficient to claim the discovery of this state.

5 Conclusions

We have presented the analysis of the K^- absorption on ^{12}C leading to the $\Sigma^0 p$ final state measured with the KLOE spectrometer. The tracking capability and comprehensive particle identification capability of the KLOE detector allows to reconstruct the $\Sigma^0 p$ final state and extract a clean experimental sample. Several kinematic variables of the studied final state have been fitted simultaneously by a simulated cocktail containing several reactions including processes where the K^- absorption occurs on two or more nucleons. The fit results shows that it is possible to isolate with a good precision
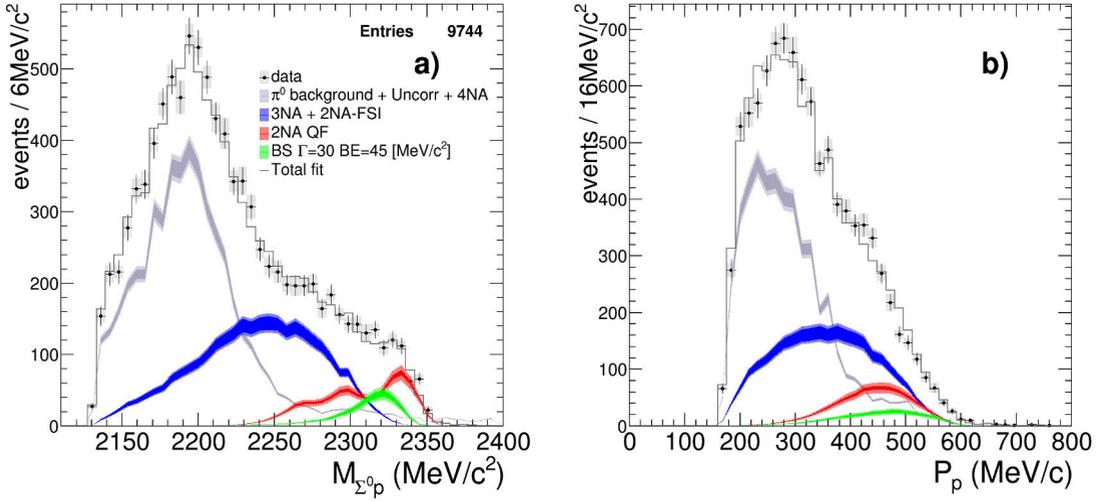
Figure 2. Experimental distributions of the Σ^0p invariant mass, $\cos(\theta_{\Sigma^0 p})$, Σ^0 and proton momentum together with the results of the global fit including the ppK$^-$. The different contributions are labeled as in Figure 2 and the green histograms represent the ppK$^-$ signal.

processes where the K^- is absorbed by two nucleons and the decay products are emitted without any further final state interactions among them from other contributions (2NA-QF). We can conclude that the contribution of the FSI-free two-nucleons K^- absorption for momenta lower than 120 MeV/c is much smaller in comparison with other processes. A second fit of the experimental data has been carried out including the simulation of a kaonic bound state (ppK$^-$) decaying into the Σ^0p final state. A systematic scan of possible binding energies and widths varying within 15-75 MeV and 30-70 MeV, respectively, has been carried out and the best value of the total reduced χ^2 has been achieved for the hypothesis of a ppK$^-$ with a binding energy of 45 MeV and a width of 30 MeV. The corresponding ppK$^-$ yield extracted from the fit is ppK$^-$/K$^-_{stop}$ = $(0.044 \pm 0.009 \text{ stat}^{+0.004}_{-0.005} \text{ syst}) \times 10^{-2}$. A f-test has been conducted to compare the null-hypothesis, not including the ppK$^-$ signal, and the fit with the signal in order to extract the significance of the result. A significance of only 1 σ has been obtained for this result, since the improvement of the fit with the ppK$^-$ is mainly due to the fact that additional degrees of freedom in the fit improves the total χ^2. This result shows that although the measured spectra are compatible with the hypothesis of a contribution of the channel $ppK^- \to \Sigma^0 + p$, the significance of the result is not sufficient to claim the discovery of the state.

Acknowledgments

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