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Investigation of the low energy kaons hadronic interactions in light nuclei by AMADEUS

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Abstract. The AMADEUS experiment has the aim to perform studies of the low energy hadronic interactions of negatively charged kaons with nucleons and nuclei, which are fundamental to solve longstanding open questions in the non-perturbative QCD in the strangeness sector. The DAΦNE collider provides a unique source of monochromatic low-momentum kaons, whose nuclear interaction with the materials of the KLOE detector (used as an active target) provide us excellent acceptance and resolution data for K^- capture on H, ^{4}He, ^{9}Be and ^{12}C, both at-rest and in-flight. AMADEUS step 0 consisted in the analysis of the 2004-2005 KLOE data. A second step consisted in the implementation in the central region of the KLOE detector of a pure graphite target, providing a high statistic sample of $K^- \ ^{12}C$ nuclear captures at rest. For the future, new setups for various dedicated targets are under preparation.
The aim of such investigations is to face the major open questions in hadron nuclear physics in the strangeness sector, such as the nature of the $\Lambda(1405)$ state and the resonant versus non-resonant yield in nuclear K^- capture, the possible existence of kaonic nuclear clusters, strongly related to a quantitative understanding of single versus multi-nucleon K^- absorption.

1 Introduction

The AMADEUS experiment [1, 2] is dealing with the study of the low-energy interactions of the negatively charged kaons with light nuclei. Such type of physics, extremely important for the understanding of the non-perturbative QCD in the strangeness sector, has important consequences, going

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from hadron and nuclear physics to astrophysics. In this context, our investigation proceeds along two lines of research, both intimately connected with the antikaon-nucleon potential: the strength of the K^- binding in nuclei and the in-medium modification of the Σ^* and Λ^* resonances properties.

The investigation of the absorptions of K^- inside the KLOE Drift Chamber (DC) was originally motivated by the prediction of the formation of deeply bound kaonic nuclear states [3]. Their binding energies and widths could be determined by studying their decays into baryons and nucleons. In particular, the dibarionic state K^-pp is expected to decay into Λp.

From the experimental point of view, two main approaches have been used for studying the K^-pp cluster: p-p and heavy ion collisions [4] [5], and in-flight or stopped K^- interactions in light nuclei. For the second, data has been published by the FINUDA [6] and KEK-PS E549 collaborations [7]. The interpretation of both results is far from being conclusive, and it requires an accurate description of the single and multi-nucleon absorption processes that a K^- would undergo when interacting with light nuclei.

On the other side, the unique quality of the 2004-2005 KLOE data, offers the opportunity to explore Σ^* and Λ^* resonances properties and their behaviour in nuclear environment. Moreover, the non-resonant versus resonant formation transition amplitudes could be measured, for the first time, for different isospin states, for a broad range of light nuclei. Of particular interest is the case of the $\Lambda(1405)$ state, which we are investigating through its decay into $\Sigma^0\pi^0$ and $\Sigma^+\pi^-$. The $\Lambda(1405)$ is generally accepted to be a spin $1/2$, isospin $I = 0$ and strangeness $S = -1$ negative parity baryon resonance ($J^P = 1/2^-$) assigned to the lowest $L = 1$ supermultiplet of the three-quark system, together with its spin-orbit partner, the ($J^P = 3/2^-$) $\Lambda(1520)$. Such state decays only into $(\Sigma\pi)^0$ ($I = 0$) through the strong interaction. Despite the fact that the $\Lambda(1405)$ is currently listed as a four-stars resonance in the table of the Particle Data Group (PDG) [8], its intimate nature still remains an open issue [9].

A complete review of the broad theoretical and experimental literature is not possible here (see, however, [10]). The $\Lambda(1405)$ production in $\overline{K}N$ reactions is of particular interest due to the prediction, in chiral unitary models [11–13], of two poles emerging in the scattering amplitude (with $S = -1$ and $I = 0$) in the region of the $\Lambda(1405)$ mass. One pole is located at higher energy with a narrow width, and is mainly coupled to the $\overline{K}N$ channel, while a second lower mass and broader pole is dominantly coupled to the $\Sigma\pi$ channel [14]. Both contribute to the final experimental invariant mass distribution [13, 15]. Moreover, the $\Sigma^0\pi^0$ channel, which is free from the $I = 1$ contribution and from the isospin interference term, represents the golden decay channel for such state.

2 The DAΦNE collider and the KLOE detector

DAΦNE [16] (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 $m_\phi = (1019.456 \pm 0.020)\,\mathrm{MeV/c^2}$. The ϕ meson decay produces charged kaons (with $\mathrm{BR}(K^+K^-) = 48.9 \pm 0.5\%$) with low momentum ($\sim 127\,\mathrm{MeV/c}$) which is ideal either to stop them, or to explore the low-energy nuclear absorption processes of K^-s.

The KLOE detector [17] is centered around the interaction region of DAΦNE and is characterized by a $\sim 4\pi$ geometry and an acceptance of $\sim 98\%$. It consists of a large cylindrical 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 [18] has an inner radius of 0.25 m, an outer radius of 2 m and a length of 3.3 m. Its entrance wall composition is 750 μm of carbon fibre and 150 μm of aluminum foil.

Dedicated GEANT MC 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 fraction of captured kaons, about 81% results to be absorbed in the carbon fibre component and the residual 19% in the aluminum foil. The KLOE DC is filled with a mixture of helium and isobutane (90% in volume ^4He and 10% in volume C_4H_{10}).

The chamber is characterized by excellent position and momentum resolutions. Tracks are reconstructed with a resolution in the transverse $R - \phi$ plane of $\sigma_{R\phi} \sim 200\,\mu$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 [19] is composed of a cylindrical barrel and two endcaps, providing a solid angle coverage of 98%. The position of the cluster along the fibres can be obtained with a resolution $\sigma_{\parallel} \sim 1.4\,\mathrm{cm}/\sqrt{E(\mathrm{GeV})}$. The resolution in the orthogonal direction is $\sigma_{\perp} \sim 1.3$ cm. The energy and time resolutions for photon clusters are given by $\frac{\sigma_E}{E_\gamma} = \frac{0.057}{\sqrt{E_\gamma(\mathrm{GeV})}}$ and $\sigma_t = \frac{57\,\mathrm{ps}}{\sqrt{E_\gamma(\mathrm{GeV})}} \oplus 100$ ps.

As a step 0 of AMADEUS, we analysed the 2004-2005 KLOE collected data, 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 ionization in the DC gas). Signals from K^- absorption (at rest and with momenta lower than 127 MeV/c) have been investigated for a sample of 70% of the overall statistic collected by the KLOE experiment in 2004-2005, which amounts to 1.4 fb^{-1}. An important contribution of in-flight K^- nuclear captures, in different nuclear targets from the KLOE materials, was evidenced and characterized, enabling to perform invariant mass spectroscopy of the in-flight K^- nuclear captures [20].

3 Preliminary results of the data analyses

3.1 The $\Lambda(1116)$ selection

The presence of a $\Lambda(1116)$ always represents the signature of K^- hadronic interaction with the KLOE setup materials. Λs are identified through the reconstruction of the (BR = 63.9 ±0.5%) decay vertex $\Lambda \rightarrow p + \pi^-$.

Proton and pion tracks are identified and clearly separated using the dE/dx information (measured with the truncated mean of the ADC counts from the hit wires in the Drift Chamber) and the momentum of the track. In figure 1 left the function used for the selection of protons is displayed in red. It has to be noticed that the selection of protons also includes some heavier particles (deuterons or tritons); such contamination in the final sample of selected $\Lambda\pi^-$ events is less than 0.1%.

A minimum track length of 30 cm is required, and a common vertex is searched for all the proton-π^- 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. In addition protons are required to have a momentum $p > 130$ MeV/c, in order to remove the contamination from two body kaon decays ($K^+ \rightarrow \pi^+\pi^0$), when the charge of the π^+ is misidentified.

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 Drift Chamber volume (evaluated with Monte Carlo). The invariant mass $m_{p\pi^-}$, calculated under the p and π^- mass hypothesis, is represented in figure 1 right. The Gaussian fit gives a mass of 1115.723 ± 0.003 MeV/c^2 and an excellent sigma of 0.3 MeV/c^2.

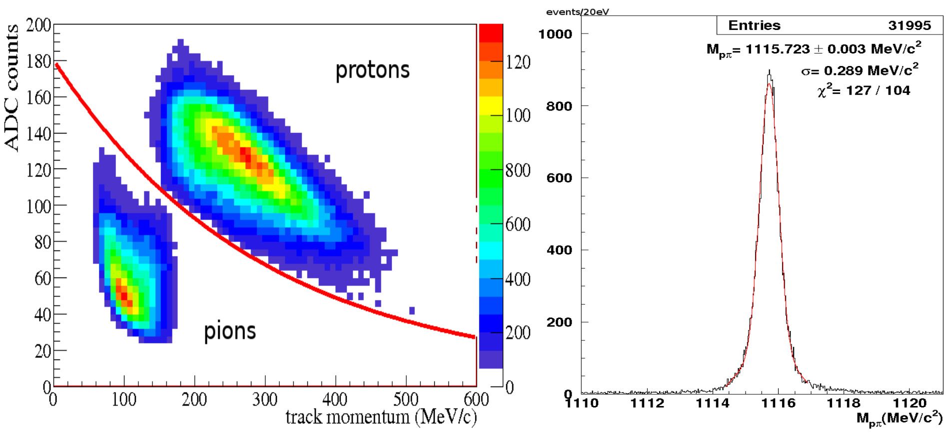

Figure 1. Left: dE/dx (in ADC counts) vs. momentum for the selected proton (up) and pion (down) tracks in the final selection. The proton selection functions is displayed in red. Right: $m_{p\pi^-}$ invariant mass spectrum for the final selected pion-proton pairs.

3.2 Λp correlation study

An extra proton correlated with the Λ decay vertex is searched for following the same prescription described in Sec. 3.1. The primary interaction vertex is then found extrapolating backwards the Λ path and the extra proton track. The resolution in the Λp invariant mass is increased by improving the reconstruction of the proton four-vector; moreover, the material where the absorption takes place can be more precisely determined. The invariant mass distribution for the final selected Λp inclusive events is shown in figure 2 left for K^- captures in the KLOE DC volume. The enhancement characterizing the low invariant mass region is expected to be populated mainly by events coming from the single nucleon absorption. In this case the kaon interacts with one nucleon, producing an hyperon-pion pair. The extra detected proton is a fragment of the residual nucleus [21] (thus initially not participating in the interaction) or comes from the Σ/Λ nuclear conversion process [22] taking place in the residual nucleus. As anticipated in Sec. 1 the knowledge of the shape of the Λp invariant mass spectrum, for the single and multi-nucleon absorption processes, is of great importance in the search for the kaonic bound clusters.

The dominant contribution to the low invariant mass region of figure 2 left comes from the mesonic processes, and can be better characterized. A negatively charged pion correlated with the primary absorption vertex is searched for, following the same procedure used for the identification of the extra proton. This extra pion is found in approximately 1/6 of the total Λp events. The invariant mass for this subsample is represented by the dashed line in figure 2 left, with an arbitrary normalization, in order to be compared with the full spectrum. With the requirement of the presence of a pion track, the contribution from the high energy tail loses strength, when compared with the inclusive selection.

The interpretation of the KLOE data will allow both qualitative and quantitative characterizations of the K^- single and multi-nucleon absorption processes to be added to the p-p and heavy ion collisions informations. From the lambda-baryon channel analyses the fraction of single versus multi-nucleon absorption processes can be extracted in ^4He and ^{12}C, the rates of nuclear Σ/Λ conversion, for the given energy range, can be obtained as well. Such analyses can give strength to models in which

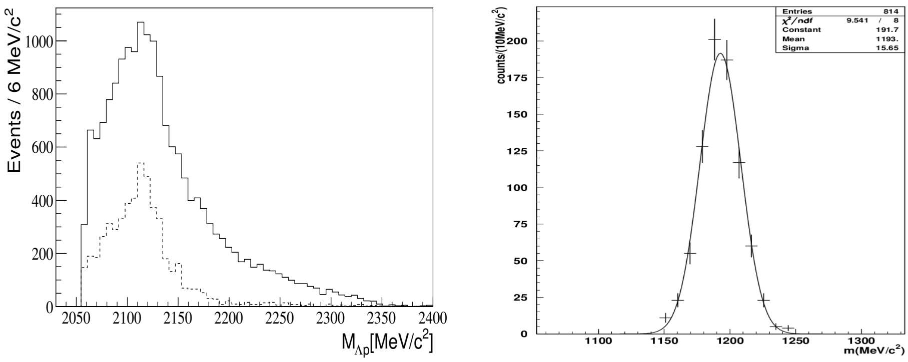

Figure 2. Left: Λp invariant mass for the inclusive Λp selection (continuous line) and for events with an extra π^- detected (dashed line, arbitrary normalization). Right: $m_{\Lambda\gamma3}$ invariant mass distribution, together with a Gaussian fit.

the interaction takes place on a free proton or to those with a bound proton, and will give important inputs to the sub threshold modification of the antikaon-nucleon interaction.

3.3 The $\Sigma^0\pi^0$ identification

The selection of $\Sigma^0\pi^0$ events proceeds, after the $\Lambda(1116)$ identification, with the search for three additional photon clusters in time from the decay vertex position of the $\Lambda(1116)$ ($\mathbf{r}_\Lambda$). To this end a pseudo-chisquare minimization is performed ($\chi_t^2 = (t_i - t_j)^2/\sigma_t^2$) searching for three neutral clusters in the calorimeter ($E_{cl} > 20$ MeV). t_i represents the i-*th* cluster time subtracted by the time of flight in the speed of light hypothesis. According to dedicated MC simulations a cut was optimized on this variable $\chi_t^2 \leq 20$. Once the three candidate photon clusters are chosen, their assignment to the π^0 and Σ^0 decays is based on a second pseudo-chisquare minimization ($\chi^2_{\pi\Sigma}$). $\chi^2_{\pi\Sigma}$ involves both the π^0 and Σ^0 masses, it is calculated for each possible combination and the minimizing triplet is selected. The $\chi^2_{\pi\Sigma} \leq 45$ cut was optimized based on MC simulations. According to true MC information the algorithm has an efficiency of $(98 \pm 1)\%$ in recognizing photon clusters and an efficiency of $(78 \pm 1)\%$ in distinguishing the correct triplet. A check is performed on the clusters energy and distance to avoid the selection of splitted clusters (single clusters in the calorimeter erroneously recognized as two clusters) for π^0s.

As a preliminary result, in figure 2 right the obtained invariant mass $m_{\Lambda\gamma3}$ (for absorptions in the DC volume) together with a Gaussian fit is shown. The resolution in the $m_{\Lambda\gamma3}$ invariant mass is $\sigma_{m_{\Lambda\gamma3}} \sim 15$ MeV/c^2. The data analysis is ongoing.

4 Conclusions and perspectives

The broad experimental program of AMADEUS, dealing with the non-perturbative QCD in the strangeness sector, is supported by the quest for high precision and statistics measurements, able to set more stringent constraints on the existing theoretical models. We demonstrated the capabilities of the KLOE detector to perform high quality physics (taking advantage of the unique features of the DAΦNE factory) in the open sector of strangeness nuclear physics. Our investigations, presently spread on a wide spectrum of physical processes, represent one of the most ambitious and systematic efforts in this field.

We are presently ongoing with the data analyses, both for the 2004-2005 KLOE data, and for the the dedicated carbon-target data collected in 2012. In parallel, from the experimental point of view, we are considering the preparation of a dedicated setup, to explore more in detail and with an even higher precision, low-energy kaons interactions with targets going from hydrogen and helium, to lithium and beryllium.

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