Physics Letters B 758 (2016) 134–139

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

K^- absorption on two nucleons and ppK^- bound state search in the $\Sigma^0 p$ final state

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ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form 21 April 2016
Accepted 1 May 2016
Available online 4 May 2016
Editor: V. Metag

ABSTRACT

We report the measurement of K^- absorption processes in the $\Sigma^0 p$ final state and the first exclusive measurement of the two nucleon absorption (2NA) with the KLOE detector. The 2NA process without further interactions is found to be 9% of the sum of all other contributing processes, including absorption on three and more nucleons or 2NA followed by final state interactions with the residual nucleons. We also determine the possible contribution of the ppK^- bound state to the $\Sigma^0 p$ final state. The yield of ppK^-/K^-_{stop} is found to be $(0.044 \pm 0.009\, stat^{+0.004}_{-0.005}\, syst) \cdot 10^{-2}$ but its statistical significance based on an F-test is only 1σ.

1. Introduction

The study of the $\bar{K}$-nucleus interaction at low energies is of interest not only for quantifying the meson–baryon potential with strange content [1], but also because of its impact on models describing the structure of neutron stars (NS) [2]. The $\bar{K}$-nucleus potential is attractive, as theory predicts [3] and kaonic atoms confirm [4], and this fact leads to the formulation of hypotheses about antikaon condensates inside the dense interior of neutron stars. Although recently measured heavy NS [5] constrain the equation of state of the latter as being rather stiff and hence degrees of freedom other than neutrons are disfavoured and theoretical calculations about nuclear systems with high multiplicity of antikaons present upper limits that disfavour the appearance of a condensate [6], experimental studies of the antikaon behaviour in nuclear matter are needed. The study of antikaons production in heavy-ion reactions at moderate energies ($E_{KIN} \approx$ GeV), with maximal reached baryon densities of $\rho \approx (3\text{–}4) \cdot \rho_0$ (with ρ_0 being the normal nuclear matter density) was carried out to find evidence of a strong attractive potential between antikaons within dense nuclear matter [7]. However, the statistics collected so far [8] does not allow for any conclusive statement about the role played by kaons within dense nuclear matter. In this context it is crucial that the theoretical models used to interpret the data properly include both the rather large cross-sections for antikaon absorption processes on nucleons and the presence of the $\Lambda(1405)$ resonance [1].

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http://dx.doi.org/10.1016/j.physletb.2016.05.001

Indeed, an antikaon produced within nuclear matter can undergo absorption upon one or more nucleons and the measurement of such processes is not yet exhaustive, even at normal nuclear densities [9,10]. Absorption processes also play an important role in the understanding of kaonic atoms, where a substantial multi-nucleon component is put forward by some theoretical models [11]. The $\Lambda(1405)$ link to the antikaon–nucleon interaction resides in the fact that theory describes this resonance as generated dynamically from the coupling of the $\bar{K}$–N and the Σ–π channels [12]. Hence the $\Lambda(1405)$ can be seen, at least partially, as a $\bar{K}$–N bound state. Despite of several experimental measurements [13], not even the vacuum properties of the $\Lambda(1405)$ are yet pinned down precisely and those can also be modified at finite baryonic densities, with major implications for the $\bar{K}$ dynamics in the medium.

Following the line of thought employed to interpret the $\Lambda(1405)$, one or more nucleons could be kept together by the strong attractive interaction between antikaons and nucleons, and then so-called kaonic bound states as ppK$^-$ or ppnK$^-$ might be formed. The observation of such states and the measurement of their binding energies and widths would provide a quantitative measurement of the $\bar{K}$-nucleon interaction in vacuum, providing an important reference for the investigation of the in-medium properties of $\bar{K}$. For the di-baryonic kaonic bound state ppK$^-$, theoretical predictions deliver a wide range of binding energies and widths [14] and experimental results are contradictory [15]. For the search of such states in K$^-$-absorption experiments, the competing multi-nucleonic absorption plays a fundamental role.

This work focuses on the analysis of the Σ^0p final state produced in absorption processes of K$^-$ on two or more nucleons and the search for a signature of the $ppK^- \rightarrow \Sigma^0 + p$ kaonic bound state. The chosen Σ^0p final state is free from the ambiguities present in the analysis of the Λp state considered in previous works [10]. Moreover, this study represents the first attempt of combining a quantitative understanding of the absorption processes and contributing background sources with the test of different hypotheses for the ppK$^-$ bound state properties.

2. Σ^0p selection and interpretation

The analysed data corresponds to a total integrated luminosity of 1.74 fb^{-1} collected in 2004–2005 with the KLOE detector [16] located at the DAΦNE e$^+$e$^-$ collider [17]. There, ϕ mesons are produced nearly at rest, providing an almost monochromatic source of K$^-$ with a momentum of ~ 127 MeV/c.

The data here presented was taken by the KLOE Collaboration and provided to the authors for an independent analysis. The KLOE detector consists of a large acceptance cylindrical drift chamber (DC) of 3 m length and 2 m radius surrounded by an electromagnetic calorimeter (EMC) inside an axial magnetic field of 0.52 T. The DC provides a spatial resolution of 150 μm and 2 mm in the radial and longitudinal coordinates, respectively, and a transverse momentum resolution of $\sigma_{p_T}/p_T \sim 0.4\%$ for large angle tracks. The EMC is composed of barrel and end-cap modules covering 98% of the solid angle with energy and time resolutions of $\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$ and $\sigma_t = 54$ ps$/\sqrt{E(\text{GeV})}$, respectively. The DC entrance wall is composed of 750 μm carbon fibre with inner and outer layers of aluminium of 100 μm thickness. The number of stopped K$^-$ in this wall is calculated by combining the experimental K$^+$ tagging efficiency, the luminosity information and a Monte Carlo simulation to determine the rate of K$^-$ stopped in the DC wall. The decay nearly at rest of the ϕ meson allows to tag K$^-$ events by the identification of a K$^+$ track in the opposite hemisphere of the DC. The extracted total number of stopped K$^-$ is equal to $(3.25 \pm 0.06) \cdot 10^8$. This value is used to normalise the measured yields of the different absorption processes. Both in flight and at rest K$^-$ absorptions can occur and a weight of 50% is assigned to each process for the normalisation.

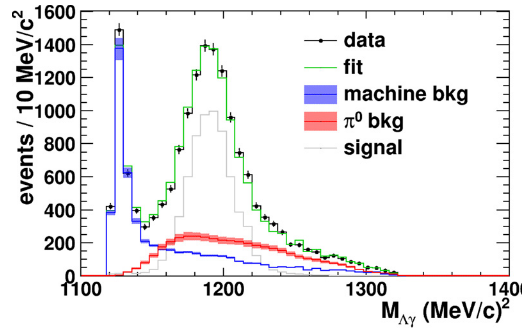

Fig. 1. (Colour online.) $\Lambda\gamma$ invariant mass distribution. The black symbols represent the experimental data, the blue and the red histograms are the contribution from the machine background and events that contain a $\Lambda\pi^0$p in the final state, respectively. The gray histogram shows the simulated Σ^0 signal and the green one the overall fit to the data (see text for details).

The starting point for the selection of K$^-$ absorption processes leading to Σ^0p final state is the identification of a $\Lambda(1116)$ hyperon through its decay into protons and negative pions (BR = 63.8%). Proton and pion track candidates are selected via dE/dx measurement in the DC. For each proton and pion candidate a minimum track length of at least 30 and 50 cm is required, respectively. The track length must also be larger than 50% of the expected length value calculated by extrapolating the measured momentum at the DC entrance. Additionally, proton candidates must have a momentum higher than 170 MeV/c. These selections aim to improve the purity of the particle identification, minimise the pion contamination in the proton sample and minimise the contribution from low momentum tracks that are emitted parallel to the DC wires and reach the EMC barrel. The reconstructed $M_{p\pi^-}$ invariant mass shows a mean value of 1115.753 ± 0.002 MeV/c^2 for the mass, with a resolution of $\sigma = 0.5$ MeV/c^2, well in agreement with the PDG value [18]. The Λ candidates are selected using the following cut: $1112 < M_{p\pi^-} < 1118$ MeV/c^2.

A common vertex between the Λ candidate and an additional proton track is then searched for. The obtained resolution on the radial coordinate ($\rho_{\Lambda p}$) for the Λp vertex is 12 mm, and this topological variable is used to select the K$^-$ absorption processes inside the DC wall. The contamination of events of absorptions in the gas volume of the DC is below 1%. The Λp invariant mass resolution is evaluated with a phase space Monte Carlo simulation where the proton and Λ momenta are varied from 100 to 700 MeV/c and is found to be equal to 1.1 MeV/c^2. The contamination to the proton sample for the Λp final state due to heavier particles (deuterons or tritons) is estimated to be less than 2% by MC simulations of absorption events with Λd and Λt final state.

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 identification in the EMC. Photon candidates are selected by applying a cut on the difference between the EMC time measurement and the expected time of arrival of the photon within $-1.2 < \Delta t < 1.8$ ns. The resulting $\Lambda\gamma$ invariant mass distribution is shown in Fig. 1, where the Σ^0 signal is visible above a background distribution.

The following kinematic distributions are considered simultaneously in a global fit to extract the contributions of the different absorption processes: the Σ^0p invariant mass, the relative angle of the Σ^0 and proton in the laboratory system $\cos(\theta_{\Sigma^0 p})$, the Σ^0 and the proton momenta. The processes that are taken into account in the fit of the experimental data are: