EPJ Web of Conferences 37, 07002 (2012)
DOI: 10.1051/epjconf/20123707002

Kaon-nuclei interaction studies at low energies (the AMADEUS project)

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Abstract. The AMADEUS experiment aims to perform dedicated precision studies in the sector of low-energy kaon-nuclei interaction at the DAΦNE collider at LNF-INFN. In particular, the experiment plans to perform measurements of the debated deeply bound kaonic nuclear states, to deepen our knowledge about the controversial state $\Lambda(1405)$ and to measure the low energy cross section of K^- on light nuclei. AMADEUS will exploit the process of stopped kaons in cryogenic gaseous targets, measuring both charged and neutral particles produced in a 4π geometry, so performing a full study of the various interaction channels. Taking advantage of the fact that the KLOE drift chamber is mainly filled with ^{4}He (90% helium 10% isobutane) according to Monte Carlo simulations about 0.1% of kaons from DAΦNE should stop in the inner volume of the drift chamber; the analysis of the existing KLOE data (run from 2002 to 2005) is presently going on, searching for hadronic interactions of K^- in such an active target. The AMADEUS physics program and preliminary results from the analysis of KLOE data will be discussed.

1 Introduction

The AMADEUS (Antikaon Matter At DAΦNE Experiments with Unraveling Spectroscopy) experiment [1,2] will study the low energy interactions of kaons with nucleons and nuclei exploring the still open problems in the sector of strangeness nuclear physics. In particular our aim is to search for the most fundamental Deeply Bound Kaonic Nuclear States (DBKNS), namely the kaonic dibaryon states (K^-pp , K^-pn), produced by stopping K^- in a ^{3}He target and, as a next step, the kaonic tribaryon states (K^-ppn and K^-pnn) using a ^{4}He target. An intense debate followed the prediction of DBKNS formation in light nuclei, with large binding energies and narrow widths [3] and a great experimental effort is still ongoing [4–8].

Furthermore, the experiment will give the possibility to study with high statistics the $\Lambda(1405)$ resonance [9], whose nature is still not completely understood, and to explore its behaviour in nuclear

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environment. The structure of the $\Lambda(1405)$ has been found to be fundamental to understand various aspects of the strangeness nonperturbative QCD.

AMADEUS also plans to perform the measurement of low energy cross sections of charged kaons on H, d, and He (for kaons momentum lower than 100 MeV/c) and to study nuclear interactions of K^- in various targets.

2 Setup performance requirements

Kaonic nuclear states will be investigated both in the formation process, by means of missing mass spectroscopy, and in the decay processes. As DBKNS are expected to decay into states containing Λ and Σ hyperons, neutral (neutrons and photons) as well as charged particles are to be detected, with momenta in a wide range. All these detection requirements are perfectly satisfied by the KLOE detector and the DAΦNE collider, together with the implementation of a dedicated AMADEUS setup inside the KLOE Drift Chamber (DC). KLOE is made of a 4π cylindrical DC surrounded by a calorimeter, both immersed in the 0.52 T field of a superconducting solenoid. KLOE has an acceptance of 96%, is optimized for detection of charged particles in the relevant energy range, and has good detection efficiency for neutrons, as was checked by the KloNe group [10]. On the other side, DAΦNE is a unique source of low energy kaons. DAΦNE is a double ring e^+ e^- collider, designed to work in the center of mass energy of the ϕ meson. Charged kaons coming from ϕ decay are characterized by low momentum ($\sim$ 127 MeV/c), which enables to stop them in gaseous targets, and a back to back topology which turns to be ideal for triggering purpose.

3 The dedicated AMADEUS setup

The AMADEUS setup will be implemented inside the KLOE DC, between the beam pipe (6 cm diameter) and the DC entrance wall (50 cm diameter). Two main components of the experimental setup are presently under development: a high density cryogenic gaseous target and a trigger system.

An essential feature of the detector is the possibility to trigger on charged kaons coming from the interaction point. The main goal is a time resolution sufficient to clearly distinguish Kaons from background. This will be achieved by making use of scintillating fibers. Two layers of fibers surrounding the beam pipe, will trigger on the passage of the back-to-back kaons and will give the start signal to the acquisition system of the experiment. Using a double layer of fibers will give the possibility to perform a preliminary tracking as well, x and y position could be measured employing high granularity layers. The scintillating fibers will be read at both sides by silicon photomultipliers (SiPM). SiPM turn to be optimal for our purposes as they are rather insensitive to magnetic field and are characterized by reduced dimensions. A prototype of the SiPM + SciFi system was already tested on DAΦNE (fibers were placed under the lower scintillator of the SIDDHARTA Kaon Monitor) [11,12]. A second and more complex prototype, constituted of two layers of BCF-10 double cladded fibers, free to rotate and read at both sides by Hamamatsu S10362-11-050-U SiPMs was recently tested. An excellent time resolution for kaons was achieved ($\sigma \sim 300$ ps) [13].

For what concerns the target system a half toroidal cryogenic target is under study, enclosed in a vacuum chamber. Kaons coming from ϕ decay will pass a degrader and then stop in the high density gaseous target, filled with ^{3}He as a first step, ^{4}He in a second phase. According to MC simulation about 20% of the negative kaons from DAΦNE should be stopped in the gas filling the target. Scintillating fiber layers opposite to the target cell would enable to clearly identify the K^+, and to perform a reconstruction of the inner trajectory of the kaons. A similar target was recently successfully operated in DAΦNE, for the SIDDHARTA [14–16] experiment and our group will take advantage of the gained experience.

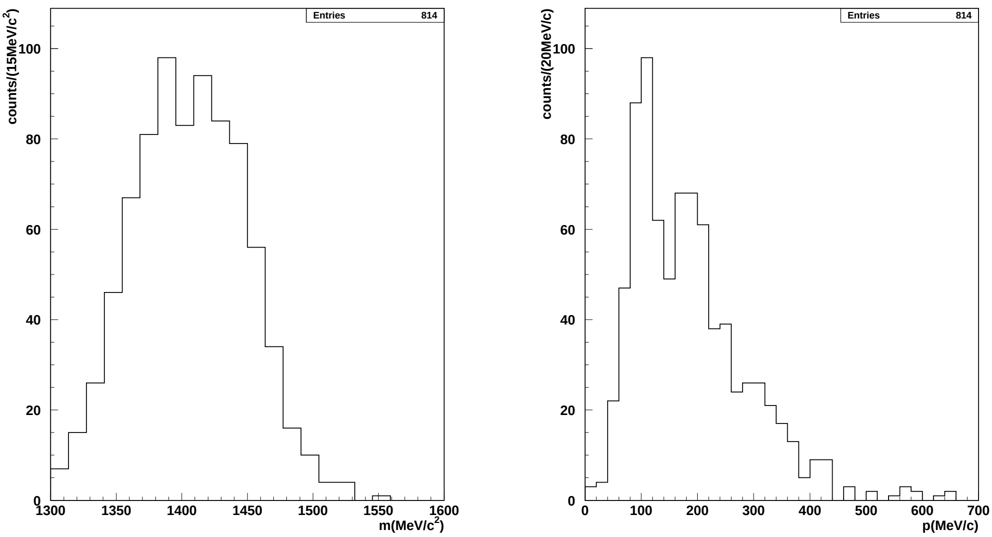

Fig. 1. Left: $m_{\Sigma^0\pi^0}$ distribution, right: $p_{\Sigma^0\pi^0}$ distribution (preliminary).

4 KLOE data analysis searching for K^--^{4}He interactions

Presently, we are performing dedicated Monte Carlo simulations to study the performance of the AMADEUS setup. In parallel, we are analyzing the existing KLOE data (runs from 2002 to 2005). The KLOE drift chamber is mainly filled with ^{4}He (90% helium 10% isobutane, in volume) and the analysis of KLOE Monte Carlo showed that about 0.1% of kaons from DAΦNE stop in the inner volume of the drift chamber. This represents a unique opportunity to check the reconstruction capability for Σ and Λ particles and for studying the hadronic interactions of K^- in such an active target. Up to now data for a total integrated luminosity of about 1 fb^{-1} were analyzed [17]. A challenging $\Lambda(1116)$ invariant mass spectrum was obtained through the charged decay vertex ($p\pi^-$ (BR $63.9 \pm 0.5\%$)), with a statistical error $\sigma \sim 3$ keV; the systematic being presently under evaluation. The investigation then focused on various items, in particular excellent results were obtained in the the Λp correlation study [18] (the Λd analysis in presently ongoing), together with the study of the $\Lambda(1405)$ through the neutral decay channel $\Sigma^0\pi^0$.

The nature of the $\Lambda(1405)$ is not still clear. In the context of chiral theories two poles are predicted in the neighborhood of the $\Lambda(1405)$ both contributing to the final experimental invariant mass distribution [19], while a single pole is preferred by other models [20]. The nature of the $\Lambda(1405)$ turns to be fundamental to understand the possibility of bound states of antikaons in nuclei. In this context a golden and still poorly explored decay channel is the the neutral one ($\Sigma^0\pi^0$) which is free from the main background source $\Sigma(1385)$ for isospin selection.

We are presently performing an exclusive study of K$^-$ nuclear interaction in the gas filling the KLOE DC, with $\Sigma^0\pi^0$ final state. As The Σ^0 electromagnetically decays in $\Lambda\gamma$, the $\Lambda \to p\pi^-$ vertex reconstruction is the first analysis step as described in 4. Once the Λ decay vertex is determined, three neutral clusters (clusters in the KLOE calorimeter not associated to tracks) are selected as photons by time of flight and then passed to an identification algorithm. A χ^2 minimization procedure (based on the combined Σ^0 and π^0 invariant masses) enables to distinguish the two photons from π^0 decay.

The selection and identification algorithms (together with standard KLOE background rejection cuts) guarantees an efficiency almost 100% to recognize photon clusters and an efficiency greater than 80% in distinguishing the two photons coming from π^0 decay (from the third one associated to the Σ^0 decay), as tested by true MC information.

The invariant mass $m_{\Sigma^0\pi^0}$ and momentum $p_{\Sigma^0\pi^0}$ resolutions ($\sigma_m \sim 30$ MeV/c^2 and $\sigma_p \sim 17$ MeV/c) are mainly dominated by the calorimeter resolution. The $m_{\Sigma^0\pi^0}$ distribution (figure 1) is broad and shows an excess of events above the kinematic limit for K$^-$ absorptions on helium nuclei at rest ($\sim$ 1412 MeV/c^2). The $p_{\Sigma^0\pi^0}$ distribution (figure 1) shows a double structure, with a lower momentum peak (LM) at around 100 MeV/c and a higher momentum peak (HM) around 200 MeV/c. The LM peak is correlated with higher mass values (around 1430 MeV/c^2) and greater $\theta_{\Sigma^0\pi^0}$ angles, the HM peak is correlated with lower masses and smaller $\theta_{\Sigma^0\pi^0}$ values, we refer to this contribution [21] slide 19 for the corresponding plots. $\theta_{\Sigma^0\pi^0}$ represents here the angle between $\mathbf{p}_{\Sigma^0}$ and $\mathbf{p}_{\pi^0}$ in the laboratory reference frame.

The two main background sources for such channel, namely internal conversion events ($\Sigma^0 N \rightarrow \Lambda N$) and $\Sigma(1385) \rightarrow \Lambda\pi^0$ are characterized by the same final state topology ($\Lambda\pi^0$). Their global contribution to the final selected sample was estimated, by means of dedicated MC simulations, to be less then 5%.

Multi-dimensional fits to the relevant kinematical variables, with different pole parameters for the $\Lambda(1405)$ together with a non resonant $\Sigma^0\pi^0$ contribution, are presently undertaking.

Acknowledgments

Part of this work was supported by HadronPhysics I3 FP6 European Community program, Contract No. RII3-CT-2004-506078; the European Community-Research Infrastructure Integrating Activity "Study of Strongly Interacting Matter" (HadronPhysics 2, Grant Agreement No. 227431), and HadronPhysics 3 (HP3), Contract No. 283286 under the Seventh Framework Programme of EU.

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