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

K. Piscicchia[a b * †]

[a]Laboratori Nazionali di Frascati dell'INFN, Via E. Fermi 40, 00044 (Frascati) Roma, Italy

[b]Dipartimento di Fisica, Universita' degli Studi 'Roma Tre', Via della Vasca Navale 84, 1-00146 Roma, Italy

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 so-called (very debated) deeply bound kaonic nuclei and, if existent, to measure their properties (binding energies and widths) by using the process of stopped kaons in cryogenic gaseous targets ($He3$ and $He4$). AMADEUS will measure all particles coming from negative kaons stopped in these targets, so performing a full study of various interaction channels. Other important measurements proposed by AMADEUS are the low-energy interaction studies of negative kaons in various targets. The kaon beam is ideal (low-energy kaons from the ϕ-decay at DAΦNE) and the setup, an implementation in the central region of the KLOE detector with dedicated additional items, is having very good performances (high acceptance and capacity to measure charged and neutral particles with excellent resolution). The results of AMADEUS will give a boost to the sector of non-perturbative QCD in the strangeness sector. The physics program, preliminary results from analysis of KLOE data and future plans will be presented.

1. The AMADEUS scientific case

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. AMADEUS will search for kaonic nuclear states, which could give important information for investigating the way in which spontaneous and explicit chiral symmetry breaking pattern of low energy QCD occurs in nuclear environment. Deeply bound kaonic nuclear states (DBKNS) were first predicted by Wycech [3], and in recent years an intense debate is going on following the publication by Akaishi and Yamazaki [4], predicting that such states could be formed by interactions of K^- in light nuclei, due to a strong K^-p potential. As a result DBKNS could have large binding energies and narrow widths. Recently, several experimental approaches were followed in the search for such states [5–9], however the possible experimental indications of the formation of dibaryonic (K^-pp) and tribaryonic (K^-ppn) states, have received alternative explanations in the framework of known processes. Moreover, recent calculations about K^-pp systems [10,11] suggest relatively moderate binding energies and larger widths. It is evident that new complete experimental results are needed; new dedicated experiments are planned at J-PARC, GSI, and at DAΦNE. The need for a complete experimental study of the scientific case, will be faced by AMADEUS performing a full acceptance, high precision measurement of DBKNS, both in formation and in the decay processes. In a first phase AMADEUS aims to study the most fundamental DBKNS, that are the kaonic dibaryon states (K^-pp , K^-pn) produced by stopping K^- in a ^{3}He target. As a next step, kaonic tribaryon states will be studied (K^-ppn , K^-pnn) using a ^{4}He target. Other important objectives are the measurement of low energy cross sections

*On behalf of the AMADEUS collaboration
†E-mail: kristian.piscicchia@lnf.infn.it

of charged kaons on H, d, and He (for kaons momentum lower than 100 MeV), the study of nuclear interactions of K^- in He and the possibility to deepen our knowledge about elusive resonance states such as $\Lambda(1405)$, and their behavior in nuclear medium.

2. Setup performance requirements

Let us consider the case of a ^{4}He target. Stopping K^- in ^{4}He could give rise to the formation of kaonic tribaryon states which should decay into channels containing Λ and Σ hyperons, which subsequently decay into nucleons, pions and photons. As an example the possible decays of the (K^-ppn) strange tribaryon are

$$\begin{aligned}(K^-ppn) &\rightarrow \Lambda + d \\ &\rightarrow \Lambda + p + n \\ &\rightarrow \Sigma^- + p + p \\ &\rightarrow \Sigma^0 + d \\ &\rightarrow \Sigma^0 + p + n\end{aligned} \tag{1}$$

with the Σ^0 decaying in a Λ and a photon. In the formation process, a neutron or a proton is as well resulting. The study of the formation process by means of missing mass spectroscopy, needs to measure the energy and the momentum of ejected neutrons and protons. In the decay process, neutral (neutrons and photons) and charged particles are produced, with momenta in a wide range (from tens of MeV to several hundred MeV). All these detection requirements are perfectly satisfied by the KLOE detector, which is made of a 4π cylindrical drift chamber (DC) and a calorimeter. KLOE has an acceptance of 96%, is optimized in the energy range of the involved charged particles, and has good performances in neutron detection as was checked by the KloNe group [12]. 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. After its recent upgrade [13] it has reached a luminosity as high as $5\text{x}10^{32} cm^{-2} s^{-1}$, which corresponds to the production of about 600 K^+K^- pairs per second.

3. The dedicated AMADEUS setup

The AMADEUS setup will be implemented inside the KLOE DC, in the free space between the beam pipe (6 cm diameter) and the DC entrance wall (50 cm diameter). Three main components of the experimental setup are actually under development: a high density gaseous target, a trigger system, and an inner tracking device to be positioned inside the KLOE DC, which will serve to a better reconstruction of the primary vertex and secondary particles tracking. A representation of the dedicated AMADEUS setup surrounding the beam pipe is given in Figure 1 with some of the elements previously introduced. In the following a brief description of the trigger and the target will be given.

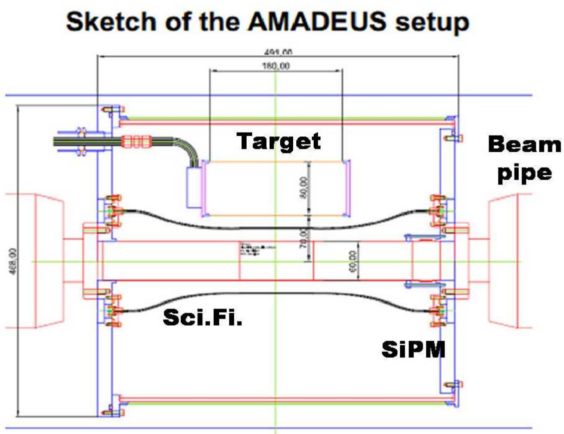

Figure 1. Lateral view of the dedicated AMADEUS setup. The beam pipe is surrounded by scintillating fibers, read by silicon photomultipliers. The target system is also represented.

3.1. The trigger system

An essential feature of the detector is the possibility to trigger kaons coming from the interaction point. This will be achieved by making use of scintillating fibers. Two layers of fibers surrounding the beam pipe, will trigger 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 as well the possibility to perform a preliminary tracking, x and y position could be measured employing high granularity layers.

The scintillating fibers will be glued at both sides to silicon photomultipliers (SiPM). SiPM turns 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 SIDDHARTA's Kaon Monitor) [14,15]. Further developments and optimizations are undergoing.

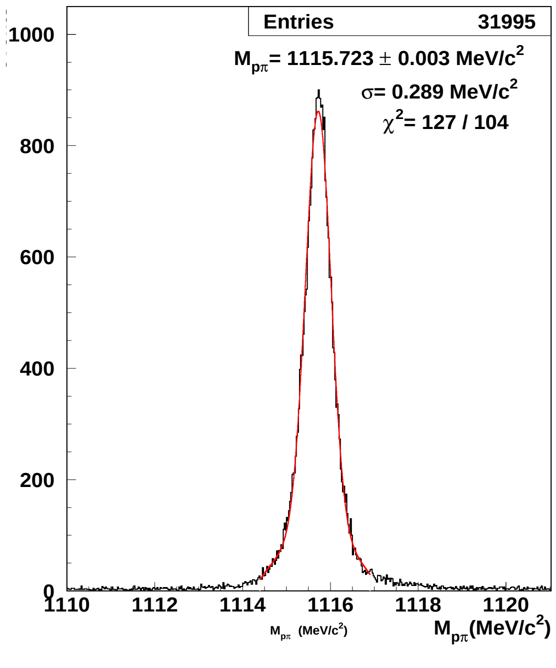

Figure 2. Λ invariant mass reconstruction.

3.2. The target system

Various configurations are presently under study for the target and the cryogenic system. A toroidal or half toroidal cryogenic target will be used, 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. If a half toroidal configuration will be preferred, then the possibility arises to put more outer layers of scintillating fibers opposite to the target cell. This would enable to clearly identify K^+, and eventually a rough reconstruction of kaons inner trajectory.

It has to be stressed that a similar target was recently installed in DAΦNE, for the SIDDHARTA [16] experiment and our group will take advantage of the gained experience.

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

As we discussed before, the kaonic nuclear states are expected to decay into states containing Λ and Σ hyperons, together with protons, neutrons and deuterons, so an important feature of the detector and the tracking procedure is the reconstruction capability for Σs and Λs. Of course the main source of background comes from classical interactions of K^- in ^{4}He, which is poorly known and is based on a paper from 1970 [17]. As a preliminary search for kaonic nuclear clusters inside the KLOE setup, a first output of the KLOE-AMADEUS collaboration is the study of hadronic interactions of K^- in the data collected by KLOE in previous runs.

The KLOE drift chamber is mainly filled with ^{4}He (90% helium 10% isobutane) and the analysis of KLOE Monte Carlo showed that about 0.1% of kaons from DAΦNE should stop in the inner volume of the drift chamber. This represents a unique opportunity for the study of hadronic interactions of K^- in such an active target.

Up to now, a total luminosity of 1.1 fb^{-1} was analyzed from a sample of 2005 KLOE data [18]. Dedicated ntuples were built containing charged kaons, identified by using two body decay and/or $\frac{dE}{dx}$ signature in the gas filling the DC volume.

The primary strategy consists in the identification of the $\Lambda(1116)$, trough it's decay into a p and a π^- (with a branching ratio of 64%. Next step consists of the backwards extrapolation of the Λ path to reconstruct the vertex formed by the Λ with protons or deuterons. This could give a direct signal of the formation of the exotic states, or the products of K^- absorption by the nucleons of the gas.

An excellent result was already achieved, as can be seen in Figure 2 , representing the proton pion invariant mass distribution for the selected $\Lambda(1116)$ event candidates. An excellent statistical error was obtained below 3 KeV, with the systematics, depending on the momentum calibration of the KLOE setup, being presently under evaluation.

5. Conclusions

The implementation of a dedicated AMADEUS setup in the KLOE detector, also thanks to the excellent features of the DAΦNE accelerator, will represent a unique scenario to perform a complete search for deeply bound kaonic nuclear states, and, in general, for the study of low energy K^- light nuclei interaction. All charged and neutral particles coming from K^--nuclei interaction will be detected in a 4π geometry, enabling a complete experimental measurement of eventual kaonic nuclear clusters, both in the decay and in the formation processes. The reconstruction capability for Λs and Σs, which are present in most of the expected decay channels of the bound states, was already tested by analyzing the data from previous KLOE runs. The KLOE data analysis is going on, also in view of KLOE2 data taking which will provide an increased statistics.

Acknowledgements

We Acknowledge the support of the European Community-Research Infrastructure Integrating Activity 'Study of Strongly Interacting Matter' (acronym Hadron-Physics2, Grant Agreement n. 227431) under the Seventh Framework Programme of EU.

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