PROCEEDINGS OF SCIENCE

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

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The AMADEUS experiment aims to perform dedicated studies in the sector of low-energy kaon-nuclei interaction, at the DAΦNE collider at LNF-INFN. In particular, the collaboration plans to perform measurements of the so-called (very debated) deeply bound kaonic nuclei and, if existent, of their properties (binding energies and widths). Other important measurements proposed by AMADEUS are the low-energy interaction studies of charged kaons in various targets. The physics program and the proposed setup (consisting of dedicated additional items inserted in the central region of the KLOE detector) are presented. Preliminary results from the analysis of the existing KLOE data and future plans will be discussed.

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1. THE AMADEUS SCIENTIFIC CASE

An important, yet unsolved problem, in hadron physics is how the hadron masses and interactions change in the nuclear medium. This topic could be investigated by means of "in-medium hadron-mass spectroscopy", producing bound states of a hadron from which to deduce the hadron-nucleus potential and the in-medium hadron mass. 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 originally 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. The formation of DBKNS requires the presence of strong attractive $\overline{K}N$ interaction in the $I = 0$ channel and its prediction is based on the low energy $\overline{K}N$ scattering data, the shift and with of kaonic hydrogen $1s$ level and the binding energy of the $\Lambda(1405)$, seen as a bound state of $\overline{K}+N$ in the $I = 0$ channel. As a result, it was suggested that DBKNS could have large binding energies and narrow widths.

Recently, several experimental approaches were followed in the search for such states [5, 6, 7, 8, 9], but 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 [10]. Moreover, recent calculations on the K^-pp systems [11, 12] suggest relatively moderate binding energies and larger widths. It is evident that new and complete experimental results are needed; 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 by performing a full acceptance, high precision measurement of the DBKNS, both in the formation and in the decay processes. In a first phase the experiment 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.

Another important subject is the $\Lambda(1405)$ resonance [13], whose nature is still not completely understood. The structure of $\Lambda(1405)$ has been found to be important in various aspects in the strangeness sector of nonperturbative QCD. AMADEUS will give the possibility to better understand such state and its behavior in nuclear environment, with high statistics.

Moreover, AMADEUS 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) and the study of nuclear interactions of K^- in various targets.

2. SETUP PERFORMANCE REQUIREMENTS

The formation of kaonic dibaryon states will be investigated by stopping K^- in a ^{3}He target. This could give rise to the ejection of a neutron, resulting from the formation of a K^-pp state, or to the ejection of a proton with the formation of a K^-pn state. Similarly, the formation of kaonic tribaryon states (K^-ppn , K^-pnn) could be obtained by stopping K^- in a ^{4}He target, with the ejection of a neutron and a proton, respectively. It was estimated that protons and neutrons have momenta in the range of $400 \div 500$ MeV/c. The exotic states are expected to predominantly decay into final states containing Λ and Σ hyperons, with maximum momenta of $500 \div 700$ MeV/c. The same holds for the other decay products of the K^--nuclear clusters, like protons, neutrons and deuterons. The decay of these high-momentum Λs and Σs produces protons and neutrons of $500 \div 800$ MeV/c, together with negative pions, neutral pions and photons. As an example, the possible decay channels of the $(K^- ppn)$ strange tribaryon are:

$$\begin{aligned}(K^- ppn) &\rightarrow \Lambda + d \\ &\rightarrow \Lambda + p + n \\ &\rightarrow \Sigma^- + p + p \\ &\rightarrow \Sigma^0 + d \\ &\rightarrow \Sigma^0 + p + n\end{aligned} \tag{2.1}$$

with the Σ^0 decaying in a Λ and a photon. AMADEUS aims to measure DBKNS both in formation and in the decay processes. 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. For what concerns the decay process, the reconstruction of the invariant mass requires the identification and measure of all the decay products. All these detection requirements are perfectly satisfied by the KLOE detector, which is made of a 4π cylindrical drift chamber (DC) and 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 [14]. 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 [15] it has reached a luminosity as high as $5\text{x}10^{32} cm^{-2} s^{-1}$. Charged kaons coming from ϕ decay are characterized by low momentum ($\sim$ 127) MeV, 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, 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 presently under development: a high density cryogenic 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 to the 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 of the target will be given.

3.1 The trigger system

An essential feature of the detector is the possibility to trigger on charged 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 on the passage of the back-to-back kaons and will

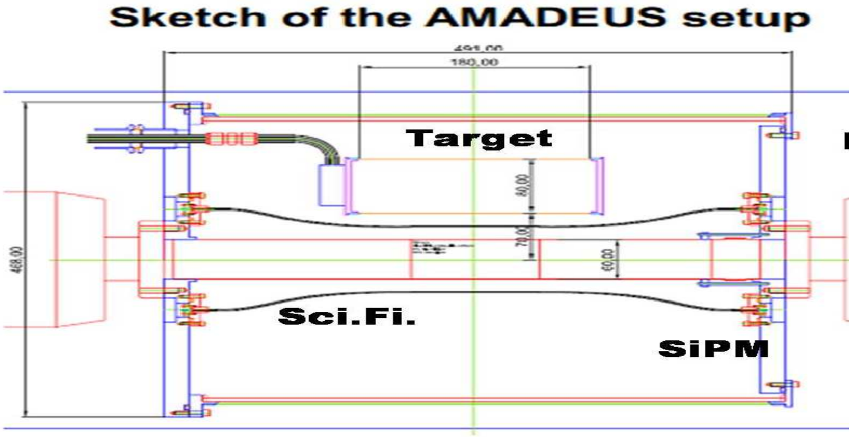

Figure 1: Lateral view of the dedicated AMADEUS setup. The beam pipe is surrounded by scintillating fibers, read by silicon photomultipliers. The target system is also represented.

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 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) [16, 17]. 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 is presently under test.

3.2 The target system

Various configurations are presently under study for the target and 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 to perform a reconstruction of the inner trajectory of kaons.

It has to be stressed that a similar target was recently installed in DAΦNE, for the SIDDHARTA [18] experiment and our group will take advantage of the gained experience.

4. ANALYSIS OF THE KLOE DATA SEARCHING FOR K^--^{4}He INTERACTIONS

Presently, we are performing dedicated Monte Carlo simulations to study the performance of the AMADEUS setup: signal and background studies for the channels presented in section 2. In parallel to these studies we are analyzing the existing KLOE data (runs from 2002 to 2005) to check the reconstruction capability for Σ and Λ states and the possible presence of eventual signals of deeply bound states, as explained below.

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 1.8 fb^{-1} was analyzed from a sample of 2005 KLOE data [19]. 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. The statistical error for the Λ invariant mass was obtained as 3 KeV, with the systematics, depending on the momentum calibration of the KLOE setup, being presently under evaluation.

The reconstruction capability of the KLOE detector for Σ^0 and Λ states is also under investigation, trough their neutral channel decays $\Lambda \to n\pi^0$ (Σ^0 always decays electromagnetically in $\Lambda\gamma$). The importance of such neutral channels stands in the possibility of characterizing the neutron clusters formed in the KLOE calorimeter. Neutron identification is of great importance for invariant and missing mass spectroscopy in the search for K^-pp and K^-ppn states.

Also, related to the neutral channels is the possibility to study the $\Lambda(1405)$ resonance formation, in the reaction K^{-4}He followed by the decay $\Lambda(1405) \to \Sigma^0\pi^0$. This represents a golden decay channel as it is forbidden to the nearby $\Sigma(1385)$ by isospin selection rules. Work on this item is presently going on.

5. CONCLUSIONS

The implementation of a dedicated AMADEUS setup inside 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 possible

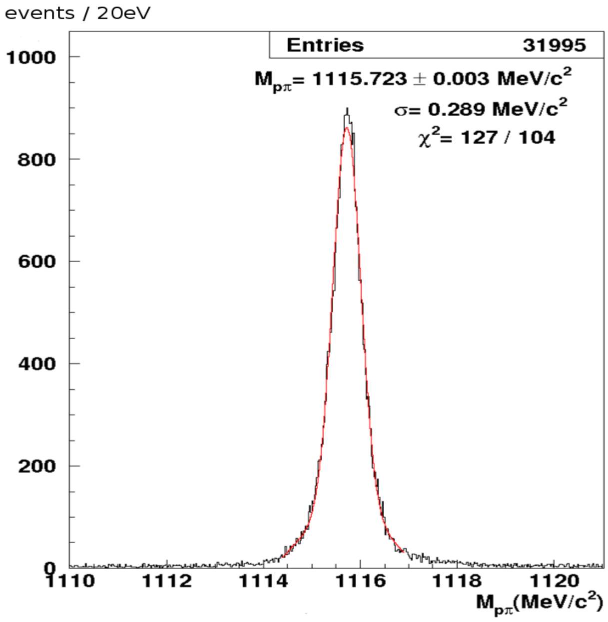

Figure 2: Invariant mass reconstruction for Λ.

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.

For AMADEUS presently R&D activities are ongoing together with Monte Carlo simulations, to arrive at the final setup definition.

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