The AMADEUS project

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On behalf of the AMADEUS Collaboration

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Abstract. The recently proposed AMADEUS project makes use of mono energetic, low energy K^- beams from the upgraded high luminosity DAΦNE (e^+e^-)-collider of the LNF, Frascati for the production of antikaon mediated deeply bound nuclear states using the ($K^-_{stopped}$, n/p) reaction. The existing KLOE detector with a target for stopping the K^- surrounded by trigger detectors will be used for an exclusive detection of all particles in the production and decay processes of the antikaonic nuclei formed. Using missing mass and invariant mass spectroscopy a conclusive observation of these exotic objects should be in reach and then their properties, such as binding energies, total and partial widths, size and density could be determined, thus opening a new spectroscopy of exotic strongly bound nuclear systems.

PACS. 13.75.Jz Kaon-baryon interaction

1 Introduction in Antikaon mediated bound nuclear systems

Recently a collaboration consisting of 111 scientists from 33 institutes of 13 countries proposed in a letter of intent the study of deeply bound antikaon mediated nuclear systems at the upgraded DAΦNE 2 (e^+e^-)-collider by making use of the existing KLOE detector within the AMADEUS (**A**nti**M**atter **A**t **DA**ΦNE: **E**xperiments with **U**nravelling **S**pectroscopy) collaboration[1].

Exotic nuclear systems with antikaons $\overline{K}$ as constituents (K^-,$\overline{K^0}$) have been predicted by Akaishi and Yamazaki on the basis of a phenomenological constructed $\overline{K}N$ interaction strength [1,2]. It is known since long time [3] that the K^-p interaction is dominated by the $\Lambda(1405)$ resonance, which is 27 MeV below the K^-p threshold and is 40 MeV wide. Using non-perturbative coupled channel techniques it has been shown that the $\Lambda(1405)$ resonance can be generated dynamically as an $I = 0$ $\overline{K}N$ quasi bound state and as a resonance in the $\Sigma\pi^-$ channel, into which it dominantly decays [3,4]. Consequently a dispersive behaviour of the K^-p interaction is predicted with strong attraction below the resonance and repulsion around the K^-p threshold. The latter is evidenced by the results of scattering experiments [5] and repulsive shifts measured by precision X-ray spectroscopy of the binding energy of the 1s-state of kaonic hydrogen [6,7].

[1] AMADEUS, LOI, `http://www.oeaw.ac.at/smi`.

2 First experimental searches for kaonic nuclear states

Iwasaki *et al.* [8] proposed searches for the $ppnK^-$ system using neutron knock out reactions induced by stopped K^- in a liquid ^{4}He target as initiated by Akaishi and Yamazaki [1,2]. Preliminary results (KEK E471) were reported [9] indicating the possible existence of an $S^+(3140)$ strange tribaryon state in the missing mass spectrum of the ^{4}He($K^-_{stopped}$,n) $ppnK^-$ reaction with a binding energy of $B = -169$ MeV and a width $\Gamma < 21.6$ MeV. In the same experiment proton missing mass spectra from the ^{4}He($K^-_{stopped}$,p)$pnnK^-$ reaction showed an $S^0(3115)$ strange tribaryon state with a still higher binding energy of $B = -194$ MeV and a width $\Gamma < 21.6$ MeV [10], respectively. In view of the low statistical relevance, especially of the S^+ state, the experiment has been repeated with an improved set up and higher statistics as KEK E549/570 experiment. The complicated analysis is still in progress, and Iwasaki [11] reported at this conference that the peak in the proton spectrum assigned to the $S^0(3115)$ was instrumental and has not been confirmed. The analysis of the neutron spectra reported by Yim [12] at this conference concluded that no peak structure was evident in the semi-exclusive spectra at full statistics, but more detailed study of the hyperon motion is ongoing.

Very recently the FINUDA collaboration at the DAΦNE (e^+e^-)-collider reported the observation of the strange dibaryon using invariant mass spectroscopy of Λp decay products following the absorption of stopped K^-

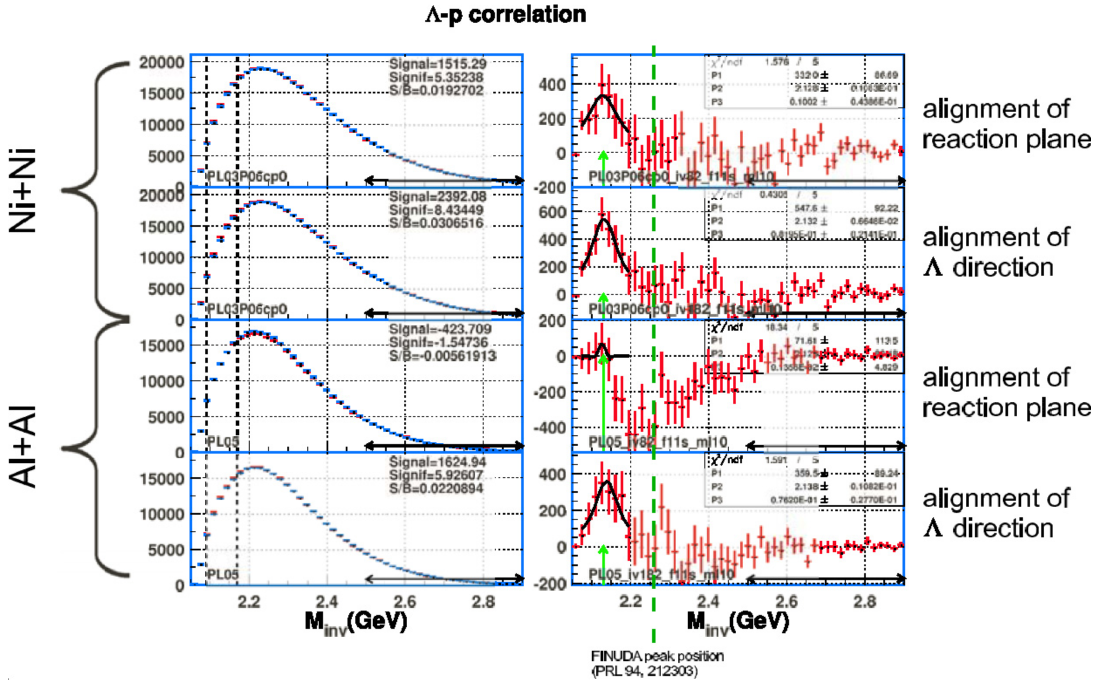

Fig. 1. Λp invariant mass spectra from 1.9A GeV Ni-Ni and 2.0A GeV Al-Al collisions. Left panel: Data and combinatorial background, determined in 2 ways as indicated. Right panel: Difference of data and combinatorial background.

in ^{6}Li, ^{7}Li, and ^{12}C targets [13]. The invariant mass spectrum indicates a binding energy of $B = -115$ MeV and a width of $\Gamma = 67$ MeV. FINUDA [14] reported at this conference the observation of a line in $d\Lambda$ missing mass spectra, corresponding to the decay of a $pnnK^-$ state and Bressani [15] reported a state with a mass of 2.212 GeV/c^2 from an analysis of antiproton annihilation in ^{4}He.

3 Heavy ion reactions for the production of kaonic nuclei

Recently heavy ion induced reactions and even simpler proton induced reactions were considered for the production of antikaonic light nuclei [16,17]. Experiments on enhanced K^- production in heavy ion collisions at energies below the NN threshold [18,19] gave a hint of a possible decrease of the K^- mass in the dense hot fireball created in the collision. In context with chiral $SU(3)$ dynamics a decrease of the K^- mass was also predicted, which is equivalent to strong binding in terms of our previous discussion. So, in heavy ion collisions K^- nuclear clusters may be abundantly produced in the fireball, but they escaped direct discovery until now. We proposed [20] to search for K^- nuclear clusters which survive the freeze out process by invariant mass spectroscopy of its decay products in a 4π detector, such as FOPI at the GSI heavy ion synchrotron SIS.

Recently preliminary results for $d\Lambda$ correlation have been reported [21] from 1.9A GeV Ni-Ni collisions indicating the possible formation of a $ppnK^-$ cluster with a mass of 3.16 GeV/c^2 decaying into a $d\Lambda$ pair. At this conference the FOPI collaboration [22] reported the analysis of $p\Lambda$ correlations in the many body final state which may originate from the 2-body ppK^- decay. Fig. 1 shows $p\Lambda$ invariant mass spectra from 1.9A GeV Ni-Ni and 2A GeV Al-Al collisions. After subtraction of the combinatorial background from the measured spectra (left panel) using two procedures as indicated, the difference spectra (right panel) shows clearly for both collision systems peaks at a $p\Lambda$ invariant mass of (2.13±0.02) GeV/c^2 and no indication of peaks from the ppK^- decay expected from the FINUDA result as indicated by the line in Fig. 1. The observed peak at 2.13 GeV/c^2 corresponds to the mass of the $\Sigma^0 p$ system at threshold; its origin is so far not clear.

In summary it is noticed that the experimental evidence for the existence of antikaon mediated deeply bound nuclear states is not convincing and partly contradictive. All experimental data rely so far on missing mass spectra or invariant mass spectra, no exclusive data exist.

4 AMADEUS strategy and requirement

The AMADEUS strategy is based on confirmation or rejection of the existence of antikaon mediated deeply bound nuclear states by an exclusive measurement of all reaction and decay products of a suitable process leading to a light kaonic nuclear clusters. For such a program a 4π-detector with sufficient efficiency and resolution is needed for an accurate missing mass measurement of the reaction products combined with an invariant mass determination of the decay products with similar precision.

As reaction we propose the use of the $(K^-_{stopped}, N)$ reaction, similar to the original KEK experiments, but making use of the low momentum, monochromatic K^- beams

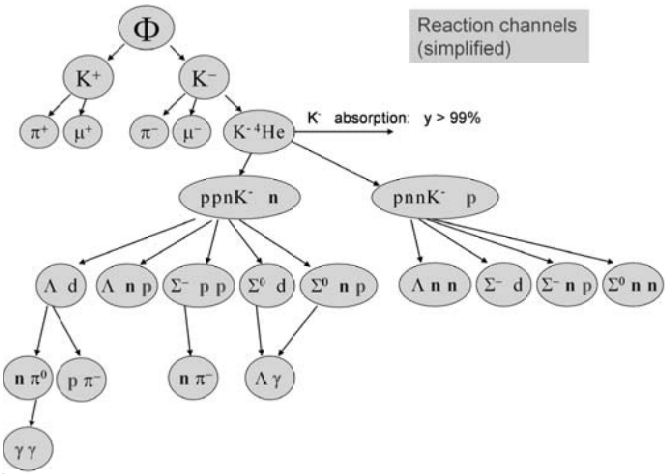

Fig. 2. Φ decay in K^+ and K^- , and 2 K^- reaction channels with knock out neutron (left) and knock out proton (right) including the decay channels of 2 tribaryons formed.

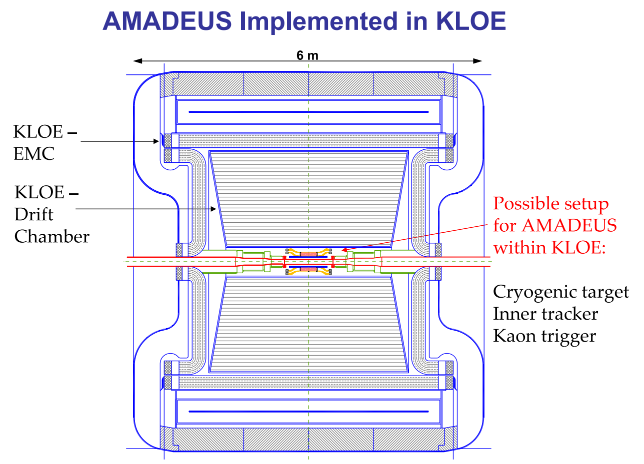

Fig. 3. Schematic drawing of the KLOE detector implemented with a cryogenic target, a kaon trigger and an inner tracker.

of 127 MeV/c from the decay of ϕ-mesons produced by the (e^+e^-) high luminosity collider DAΦNE nearly at rest and with only small pion contamination. The presently reached peak luminosity of 10^{32} cm^{-2}s^{-1} is planned to be upgraded to reach $L = 10^{33}$ cm^{-2}s^{-1}. Under such conditions 1500 s^{-1} kaon pairs could be produced or 3.1×10^9 per month assuming a 80% duty factor.

As the K^- are nearly monochromatic and of low energy, they can be efficiently stopped in a cryogenic gas target, such as ^{3,4}He, surrounding the interaction region. For the detection of the reaction and decay products we propose to use the high performance KLOE detector [23] implemented with a stopped K^- trigger system.

Fig. 2 shows a simplified version of the ϕ decay channel in a K^+K^- pair followed by kaonic helium formation and two reaction channels in the K^- absorption with the emission of a neutron and a proton and the formation of $ppnK^-$ and $pnnK^-$ systems, respectively. By measuring the momentum of the neutron and the proton in this 2-body final state, the missing mass of $ppnK^-$ and $pnnK^-$ can be deduced, respectively. Depending on the binding energy, the monochromatic neutrons from $ppnK^-$ formation have a momentum of ∼460 MeV/c. For the protons from $pnnK^-$ formation a momentum of the same order is expected. After formation the strange tribaryons can decay in various 2 or 3 body channels with Λ and Σ^0/Σ^- carrying the s quark, as indicated in Fig. 2. The neutrons produced in the 3-body decay channel Λpn of tribaryon have continuous momentum spectra ranging from a few tens of MeV/c up to 600 MeV/c with the protons showing similar distributions. From a measurement of the 4-momentum of all decay particles the invariant mass of the tribaryon may be determined.

5 KLOE detector

Fig. 3 shows a sketch of the KLOE detector with a cryogenic target, a kaon trigger detector, and one possible version of an inner tracker implemented. The KLOE detector consists of a large, He filled drift chamber for stereoscopic precision tracking of charged particles in a homogeneous magnetic field of 0.52 T. The drift chamber is completely surrounded by a fine sampling lead scintillation fibre electromagnetic calorimeter. The KLOE detector has outstanding figures of merit, such as 96% geometrical acceptance, a momentum resolution for charged particles < 0.4% in a momentum range from 100-500 MeV/c for large angle tracks, a spatial decay vertex resolution of 3 mm, a photon energy resolution of $5.7\%/\sqrt{E}$ (in GeV), a time resolution of the calorimeter of ($54/\sqrt{E}$ (in GeV) + 50) ps, a spatial resolution of the calorimeter of 1 cm/$\sqrt{E}$ (in GeV) (longitudinal), and 1cm (transversal),

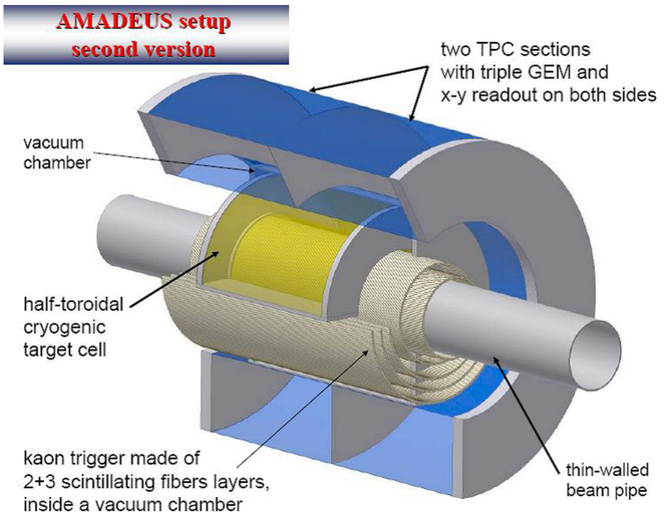

Fig. 4. A version of a half toroidal cryogenic target cell surrounding a thin walled beam tube and a kaon trigger module consisting of 2+3 scintillating fibre layers. The outer region of the target cell is surrounded with 2 TPC sections read out with 2 triple GEM's from both sides.

and for the reconstruction of π^0 from the 2-photon decay a 2-3% mass resolution.

These figures of merit makes the KLOE detector well suited for the AMADEUS program. The charged particles from the formation and decay process of the kaonic nuclei are within the energy range of KLOE, the particle identification and the momentum resolution are excellent. The detection and energy measurement of neutral pions is optimized in KLOE. The strange baryons from the decay processes can be reconstructed from their decay products. Most important is the potential for detection of neutrons from the formation and decay processes with sufficient detection efficiency and momentum resolution using time of flight techniques. The neutrons will be detected in the electromagnetic calorimeter. Its detection efficiency, as calculated by Monte Carlo simulations, rises from (20-30)% at low energies up to (50-60)% at higher energies depending on the detection energy threshold. Experiments are in progress to measure the detection efficiency of a KLOE prototype calorimeter using monoenergetic neutron beams from the TSL accelerator in Uppsala.

For the integration of the AMADEUS setup within KLOE a solution under study is to use a toroidal target placed around the beam pipe and surrounding the interaction region. The beam pipe will be of the same type as used for the DEAR/SIDDHARTA [7,24] experimental setups, a thin-walled aluminium pipe with carbon fibre reinforcement. A degrader which might be an "active" one, i.e. a scintillator (or scintillating fibre) detector is placed around the pipe just in front of the target. This detector is essential in delivering an optimal trigger signal by making use of the back-to-back topology of the kaon pair generated from the ϕ-decay. We consider as well the implementation of an inner tracker, to get more information about the formation position of the deeply bound states for better background suppression. Fig. 4 shows a sketch of an optional design of the target region with a thin wall pipe, a half toroidal gas cell as target and 5 layers of scintillating fibre for the kaon trigger and outside of the gas cell an outer tracker based on a TPC with GEM read out.

6 Scientific program

The scientific program of AMADEUS has to clearly settle the question about the existence of antikaon-mediated bound nuclear clusters. If they exist, a series of precision spectroscopy studies of light kaonic nuclei will be performed. First experiments will be a search for the basic dibaryon state ppK^- and pnK^- using the ^{3}He($K^-_{stopped}$,n/p) reaction, followed by a search for the tribaryon states $ppnK^-$ and $pnnK^-$ using the ^{4}He($K^-_{stopped}$,n/p)$ppnK^-/pnnK^-$ reactions, respectively.

Using Monte Carlo simulations with optimized degrader and target layout, we expect 40% of the produced K^- being stopped in a cryogenic He target with 15% liquid He density and about 4 cm thickness. With 3.1×10^9 K^- per month we expect to produce $\sim 1.25\times10^9$ kaonic ^{4}He atoms per month. Using as a crude estimate a cluster formation probability of 10^{-3} one expects 1.25×10^6clusters per month. An estimate of the tracking efficiency, K-pair identification and the detection efficiency of the decay products would give $\sim 10^5$ detected kaonic nuclear clusters per month, a quantity which would allow an interesting research program with the following objectives.

1. Precision measurements of the binding energies, and decay widths and determination of quantum numbers (spin, parity, isospin) of all states, including excited ones. The masses of kaonic clusters are obtained by missing mass analysis, measuring proton and neutron momentum spectra from the formation process. In KLOE the proton spectra can be obtained with 1-2 MeV precision. For the neutron spectra the achieved precision is of the order of 2-4 MeV.
2. As all the states of kaonic nuclei are quasi-stationary, important information on their structure is contained in their total and partial decay widths. Until now, the experimental values on the total decay width are under discussion and no information on partial decay channels is available. Total decay widths, accessible via the formation process, can be resolved in AMADEUS at the 1-3 MeV level for proton spectra, and at a few MeV for neutron spectra. The partial decay widths may be resolved at the level from 2 to 10 MeV depending on the decay channel.
3. Detailed structure information such as angular momentum, parity, size and density of kaonic nuclei can be extracted from a Dalitz analysis of three-body decays, as was pointed out recently by Kienle, Akaishi and Yamazaki [25].

7 Summary and conclusion

The AMADEUS project plans the use of monoenergetic K^- beams from the ϕ decay produced by a luminosity upgraded DAΦNE collider at LNF for the production of kaonic nuclei using ($K^-_{stopped}$, n/p) reactions on cryogenic ^{3,4}He targets in an initial program. The existing KLOE detector, implemented with a cryogenic gas target, a kaon trigger and an inner tracker will be used as a dedicated 4π-system for the detection, identification and precise momentum measurement of all charged and neutral particles emitted in the formation and decay processes of kaonic nuclei for a first definitive clarification of their debated existence, followed by a detailed spectroscopy of such exotic systems.

As a pre-experimental activity we have started a search for kaonic nuclei in the existing KLOE data. Preliminary Monte Carlo simulations have shown that with 2 fb^{-1} data, one might find more than 1500 events produced by stopped K^- in the ^{4}He gas of the KLOE drift chamber of the type ^{4}He($K^-_{stopped}$,p) ($pnnK^-$), and more than 500 events of the type ^{4}He($K^-_{stopped}$,n) ($ppnK^-$) revealed by peaks in the proton and neutron momentum spectra at around 500 MeV/c depending on the masses and the decay widths of the kaonic nuclei formed.

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