KAONNIS

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1 The KAONNIS scientific program

KAONNIS represents an integrated initiative in the field of the experimental low-energy kaon-nucleon/nuclei interaction studies. Under KAONNIS the following activities are performed:

- the study of kaonic atoms by the SIDDHARTA and SIDDHARTA-2 experiments
- the study of kaon-nuclei interaction at low energies in the framework of AMADEUS.

We present in what follows these scientific lines, together with the 2015 activities and the plans for 2016. The KAONNIS scientific program and its realization were partially financed within the FP7 HadronPhysics2 and HadronPhysics3 EU programs.

2 The SIDDHARTA and SIDDHARTA-2 experiments

The objective of the SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by Timing Application) experiment and of its successor, SIDDHARTA-2, is to perform high precision measurements of X-ray transitions in exotic (kaonic) atoms at DAΦNE.

The precise measurement of the shift and width of the 1s level, with respect to the purely electromagnetic calculated values, in kaonic hydrogen and kaonic deuterium, induced by the strong interaction, through the measurement of the X-ray transitions to this level, will allow the first precise experimental determination of the isospin dependent antikaon-nucleon scattering lengths, fundamental quantities for the understanding of the low-energy QCD in strangeness sector.

The accurate determination of the scattering lengths will place strong constraints on the low-energy K^-N dynamics, which, in turn, constraints the SU(3) description of chiral symmetry breaking in systems containing the strange quark. The implications go from particle and nuclear physics to astrophysics (the equation of state of neutron stars).

SIDDHARTA performed the most precise measurement of kaonic hydrogen and the first exploratory one of kaonic deuterium. Moreover, the kaonic helium 4 and 3 transitions to the 2p level were measured, for the first time in gas in He4 and for the first time ever in He3. Presently, a major upgrade of SIDDHARTA, namely SIDDHARTA-2, is under way, with the aim to measure kaonic deuterium and other types of kaonic atoms in the coming years.

2.1 The SIDDHARTA setup

SIDDHARTA represented a new phase in the study of kaonic atoms at DAΦNE. The previous DEAR experiment's precision was limited by a signal/background ratio of about 1/70 for the kaonic hydrogen measurement, due to machine background. To significantly improve this ratio, a breakthrough was necessary. An accurate study of the background sources at DAΦNE was done. The background includes two main sources:

- synchronous background: coming from the K^- interactions in the setup materials and ϕ-decay processes; it can be defined as *hadronic background*;
- *asynchronous background*: final products of electromagnetic showers in the machine pipe and in the setup materials, originating from particles lost from primary circulating beams either due to the interaction of particles in the same bunch (Touschek effect) or due to the interaction with the residual gas.

Accurate studies showed that the main background source in DAΦNE is of the second type, which points to the way to reduce it. A fast trigger correlated to a kaon entering into the target would cut the main part of the asynchronous background. X rays were detected by DEAR using CCDs (Charge-Coupled Devices), which are excellent X-ray detectors, with very good energy resolution (about 140 eV FWHM at 6 keV), but having the drawback of being non-triggerable devices (since the read-out time per device is at the level of 10 s). A new device, which preserves all good features of CCDs (energy resolution, stability and linearity), but additionally is triggerable - i.e. fast (at the level of 1μs), was implemented. The new detector was a large area Silicon Drift Detector (SDD), specially designed for SIDDHARTA. The development of the new 1 cm^2 SDD device, together with its readout electronics and very stable power supplies, was partially performed under the Joint Research Activity JRA10 of the I3 project"Study of strongly interacting matter (HadronPhysics)" within FP6 of the EU.

The trigger in SIDDHARTA was given by a system of scintillators which recognized a kaon entering the target making use of the back-to-back production mechanism of the charged kaons at DAΦNE from ϕ decay:

$$\phi \to K^+K^-. \tag{1}$$

The SIDDHARTA setup contained 144 SDD chips, 1 cm^2 each, placed around a cylindrical target, filled with high density cryogenic gaseous hydrogen (deuterium or helium). The target was made of kapton, 75μm thick, reinforced with aluminium grid.

The SIDDHARTA setup was installed on DAΦNE in late summer 2008, and the period till the end of 2008 was used to debug and optimize the setup performances (degrader optimization included). The kaonic atoms (hydrogen, deuterium, helium4 and 3) measurements were done in 2009 and data analysis followed in the coming years.

2.2 SIDDHARTA activities in 2015

SIDDHARTA was in data taking until 9 November 2009. In 2015 the group activity was dedicated to the yield of kaonic hydrogen analysis, and to the upgrade of the setup, SIDDHARTA-2, to perform in the future the kaonic deuterium and other precision kaonic atoms measurements.

2.3 *SIDDHARTA-2*

The proposal for the SIDDHARTA upgrade was put forward in 2010. The upgrade of SIDDHARTA to SIDDHARTA-2 is based on five essential modifications:

- *Trigger geometry and target density*: By placing the upper kaon-trigger detector in front of the target entrance window the probability that a triggered kaon really enters the gas and is stopped there is improved. Making the detector smaller than the entry area gives away some signal, but suppresses efficiently the kaonic lines from "wall-stops" (kaons entering the gas volume, but passing from the inside of the target to the cylindrical walls). The number "signal per trigger" goes up, which also reduces the accidental background coming along with every trigger. We plan as well to double the gas density which enhances the gas stops and further reduces the wall-stops.

- *K^+ discrimination to suppress kaon decay background*: A "kaon stopper" scintillator is placed directly below the lower kaon trigger scintillator. When a K^- is stopped there, only one (large) signal from pileup of stopping and kaon-absorption secondaries is seen, whereas when a K^+ is stopped, the kaon-decay particles are seen after the signal from the stopping (mean K^+ lifetime 12.8 ns). Using a flash-ADC we will be able to efficiently separate the 2 cases. In addition, we will use scintillators surrounding the target to measure K^- absorption secondaries pions). The time window for gas stops is about 4 ns wide. By this condition we also suppress stops in the entry window.

- *Active shielding*: The scintillators surrounding the target will also be used in prompt anti-coincidence if the spatial correlation of SDD and scintillator hits indicates that it originated from a pion ("charged particle veto"). An anticoincidence covering the SDD time window of about 600 ns (with the exception of the 4 ns of the gas stopping time) will reduce the accidental background. Although the scintillators have low efficiency for gammas, the abundance of secondaries from the electromagnetic showers allows a relevant reduction of accidental ("beam") background. The upper trigger scintillator has 2 functions, it is also used as an anticoincidence counter: after the kaon and eventual prompt kaon-absorption secondaries pass, it vetos beam background.

- *Use of new SDD detectors*, produced by FBK, having a much better active/total surface ratio (about 85%, with respect to 40% in SIDDHARTA SDDs) (see Figure 1).

- *Operating SDDs at a lower temperature*: tests indicate that an improvement of the timing resolution by a factor of 1.5 is feasible by more cooling. The signal enhancement by a factor 2 to 3 is due to moving the target cell closer to the IP, by changing its shape, by a better solid angle of the SDDs and by the higher gas density. In such conditions, with an integrated luminosity of 800 pb$^-1$ a precision of about 70 eV for the shift, and 160 eV for the width are attainable, resulting in a relative precision similar to that obtained for kaonic hydrogen.

A scheme of the SIDDHARTA-2 setup is shown in Figure 2.

In 2015 various tests on SDD prototypes, of the veto and the trigger systems were performed, in laboratory, at the INFN-LNF and at PSI Villigen, together with Monte Carlo simulations to optimize the setup. As an example, we reported in Table 1 the results obtained at PSI beam line, together with a ^{55}Fe calibration source on a new SDD element, in terms of energy resolution and stability.

More details can be found in the various presentations to the LNF International Scientific Committee on the LNF-INFN web-site.

2.4 Activities in 2016

The LNF group main activities in SIDDHARTA-2 for 2016 are the following ones:

- finalization of the construction and tests of the SIDDHARTA-2 setup components: target, veto counters, new trigger, new cryogenic systems;

- Monte Carlo simulations for the SIDDHARTA-2 setup and physics;

- definition of the strategy for SIDDHARTA-2 measurements (including interaction region definition and construction) at DAΦNE.

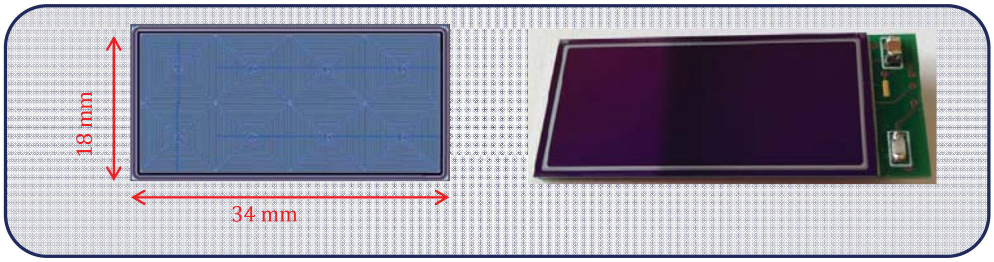

Figure 1: Layout and picture of the SDD array. Left side: layout of the front side. Right side: picture of the detector mounted in a proper carrier (back side view)

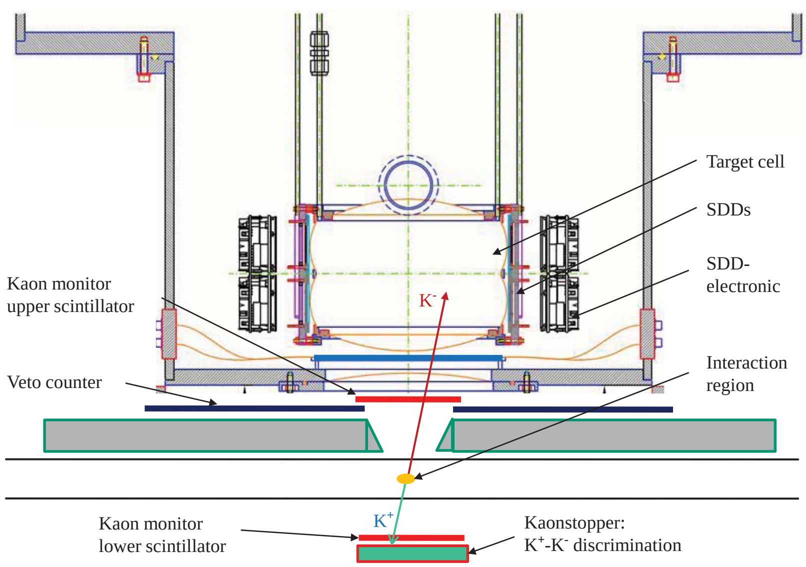

Figure 2: Schematic view of the SIDDHARTA-2 setup

Table 1: The results obtained at PSI-PiM1 beam line together with a ^{55}Fe calibration source on a new SDD element, in terms of energy resolution and stability.

Ovearll SDD hit rate (Hz)	X-ray rate (Hz)	FWHM@6 keV (eV)	Mn K_α position (ch) (error<0.1)
28	24	132.9 ± 0.2	376.9
65	48	131.9 ± 0.2	376.6
152	107	132.1 ± 0.2	376.4
290	200	138.7 ± 0.2	376.5
870	570	133.7 ± 0.3	376.5
1630	1050	138.7 ± 0.3	376.1
2370	1470	140.3 ± 0.3	376.5

3 The AMADEUS proposal, the 2015 activities and plan for 2016

The low-energy kaon-nuclei interaction studies represent the main aim of AMADEUS. In order to do these type of measurements in a most complete way, by detecting all charged and neutral particles coming from the K^- interactions in various targets with an almost 4π acceptance, a possible solution could be to implement the existent KLOE detector in the internal region of the Drift Chamber with a dedicated setup (see Figure 3). The dedicated setup contains the target which can be either solid or a gaseous cryogenic one, a trigger (TPC-GEM) and a tracker system (scintillating fibers read by SiPM detectors).

The negatively charged kaons can stop inside the target or interact at low energies, giving birth of a series of processes we plan to study. Among these, a key-role is played by the generation of $\Lambda(1405)$ which can decay into $\Sigma^0\pi^0$, $\Sigma^+\pi^-$ or $\Sigma^-\pi^+$. We plan to study all these three channels in the same data taking. Another important item is represented by the debated case of the "kaonic nuclear clusters", especially the K^-pp, and K^- -ppn cases. We can study these channels by measuring their decays to Λp and to Λd. In the same time, many other kaon-nuclei processes will be investigated, either for the first time, or in order to obtain more accurate results than those actually reported in literature. Cross sections, branching ratios, rare hyperon decay processes will be investigated, taking advantage of the unique kaon-beam quality delivered by DAΦNE and of the unique characteristics of the KLOE detector implemented with the AMADEUS dedicated setup.

As targets to be employed, we plan to use gaseous ones, like d, ^{3}He or ^{4}He and solid ones as C, Be or Li. In the summer of 2012 a first dedicated target, half cylinder done in pure carbon was realized and installed inside the Drift Chamber of KLOE as a first setup towards the realization of AMADEUS (see Figure 4). The target thickness was optimized to have a maximum of stopped kaons (about 24% of the generated ones) without degrading too much the energy of resulting charged particles inside the target material. In the period of data taking a total integrated luminosity of about 80 pb^{-1} was achieved. The analysis of these data will provide new insights in the low-energy interactions of charged kaons in the nuclear matter. For the future, other targets are planned to be used compatible with the beam assignment.

Activities done in 2015:

- analysis of 2002-2005 KLOE data searching for processes generated by negatively cherged kaons interacting at rest or in-flight in the setup materials (wall of the Drift Chamber and

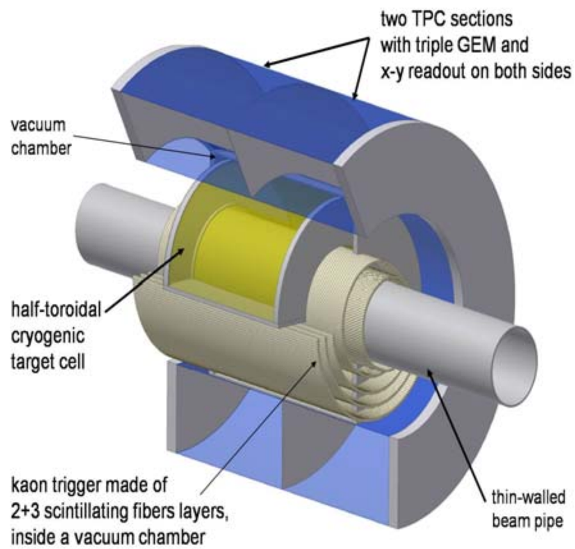

Figure 3: A possible solution for the AMADEUS dedicated setup. In this situation a cryogenic gaseous target is used.

Figure 4: The AMADEUS carbon target (half cylinder) installed inside the Dift Chamber of KLOE detector.

gas inside the Drift Chamber);

- Ph D thesis of I. Tucakovic at Tor Vergata University (C. Curceanu - Tutor) on "Studies of the Λ-triton corelations in the low-energy kaon-nuclei interactions at DAΦNE with the KLOE detector", finalized;
- analysis of the 2012 Carbon target data;
- R&D for the trigger system: a prototype based on scintillating fibers read by Silicon Photo-Multipliers;
- Monte Carlo dedicated simulations.

3.1 AMADEUS activities in 2016

The main activities of AMADEUS in 2016 will be:

- continuation of the R&D for the trigger system: tests of the prototype and readout electronics at BTF-LNF and PSI.
- R&D for the inner tracker: tests of a prototype for TPC-GEM and for Si-detectors.
- Monte Carlo simulations.
- KLOE 2002-2005 data analyses searching for processes generated by kaons interacting in the materials of the KLOE setup.
- continuation of the analyses of data taken with the dedicated carbon target
- definition of the experiment strategy

The AMADEUS activities were supported in the framework of the EU FP7 HadronPhysics3 by WP24 (GEM), WP28 (SiPM) and WP9 (Network on kaon-nuclei interaction studies at low energies) programs.

3.2 Workshops organization

In 2015 the following workshops, where the KAONNIS physics was discussed, were organized:

- Quest for visibile and invisibile strange stuff in the Universe, ISU 2015, 27 November 2015, LNF-INFN.
- Frontiers in the hadron and nuclear physics with strangeness and charm, ECT*, Trento, Italy, 19-23 October 2015.

Acknowledgements
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4 Publications in 2015

1. J-PARC E15 Collaboration, Structure near K$^-$pp threshold in the in-flight ^{3}He(K$^-$,Λp)n reaction, e-Print: arXiv:1601.06876 [nucl-ex].

2. T. Tatsuno *et al*, Absolute Energy Calibration of X-ray TESs with 0.04 eV Uncertainty at 6.4 keV in a Hadron-Beam Environment, DOI: 10.1007/s10909-016-1491-2.

3. H. Shi *et al*, Precision X-ray spectroscopy of kaonic atoms as a probe of low-energy kaon-nucleus interaction, e-Print: arXiv:1601.02236 [nucl-ex].

4. Frascati-DAΦNE-AMADEUS Collaboration (A. Scordo *et al*), Shedding New Light on Kaon-Nucleon/Nuclei Interaction and Its Astrophysical Implications with the AMADEUS Experiment at DAΦNE, e-Print: arXiv:1512.06555 [nucl-ex].

5. O. Vazquez Doce *et al*, K$^-$ absorption on two nucleons and ppK$^-$ bound state search in the Σ^0 p final state, e-Print: arXiv:1511.04496 [nucl-ex].

6. T. Yamaga *et al*, Spectroscopic Study of Hyperon Resonances below ($\bar{K}$N) threshold via the (K^-n) reaction on Deuteron.

7. L. Gruber, S.E. Brunner, C. Curceanu, J. Marton, A. Romero Vidal, A. Scordo, K. Suzuki, O. Vazquez Doce, Recovery Time Measurements of Silicon Photomultipliers Using a Pulsed Laser, e-Print: arXiv:1510.06906 [physics.ins-det].

8. J. Marton *et al*, Strong interaction studies with kaonic atoms, e-Print: arXiv:1508.05285 [nucl-ex].

9. Marco Poli Lener, Giovanni Corradi, Catalina Curceanu, Diego Tagnani, Antonio Romero Vidal, Johann Zmeskal, Performances of an Active Target GEM-Based TPC for the AMADEUS Experiment, Mod.Instrum. 4 (2015) 32-41, DOI: 10.4236/mi.2015.43004.

10. K. Piscicchia *et al*, Investigation of the low energy kaons hadronic interactions in light nuclei by AMADEUS, Hyperfine Interact. 234 (2015) 1-3, 9-15, DOI: 10.1007/s10751-015-1185-1.

11. I. Tucakovic *et al*, Low-energy kaon-nucleon/nuclei interaction studies at DANE by AMADEUS, EPJ Web Conf. 95 (2015) 04072, DOI: 10.1051/epjconf/20159504072.

12. C. Curceanu *et al*, Unprecedented studies of the low-energy negatively charged kaons interactions in nuclear matter by AMADEUS, Acta Phys.Polon. B46 (2015) 1, 203-215, DOI: 10.5506/APhysPolB.46.203.

13. J. Zmeskal *et al*, Measurement of the strong interaction induced shift and width of the 1s state of kaonic deuterium at J-PARC, Acta Phys.Polon. B46 (2015) 1, 101-112, DOI: 10.5506/APhysPolB.46.101.