KAONNIS

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1 KAONNIS: the scientific program

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

- kaonic atoms measurements by the SIDDHARTA-2 experiment
- studies of kaon-nuclei interactions at low-energies in the framework of the AMADEUS Collaboration
- participation at experiments at J-PARC (Japan) dedicated to strangeness studies
- future kaonic atoms measurements program at the DAΦNE collider

We present in what follows the KAONNIS 2024 activities and plans for 2025.

The KAONNIS activities were partially financed within the STRONG-2020 European project (grant agreement No. 824093).

2 The SIDDHARTA-2 experiment

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

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 deliver the first precise experimental determination of the isospin-dependent antikaon-nucleon scattering lengths, fundamental quantities for the understanding of the strong interaction 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 extend from particle and nuclear physics to astrophysics (the equation of state of neutron stars).

The SIDDHARTA collaboration performed the most precise measurement of kaonic hydrogen and the first exploratory study of kaonic deuterium. Moreover, the kaonic helium 4 and 3 transitions to the 2p level were measured, for the first time in gas in He^4 and for the first time ever in He^3.

The SIDDHARTA-2 experiment successfully completed its kaonic deuterium run in June 2024, collecting more than 800 pb^{-1} of data, which are under analysis. It has also performed a series of other measurements, including the most precise determination of the KHe-4 L_α, transition and yields in gas, the first observation of the KHe-4 M-series transitions, a precision measurement of the high-n transitions in kaonic carbon, oxygen, nitrogen, and aluminium and a measurement of kaonic neon transitions.

2.1 The SIDDHARTA experiment

In the first decade of this century, 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 the high machine background. To significantly improve this ratio, an experimental 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 beam 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 procedure to reduce it. A fast trigger correlated to the kaons entering into the target cuts 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 1 μs), was implemented. The new detector was a large area Silicon Drift Detector (SDD), specially designed for SIDDHARTA. 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:

$$\Phi \rightarrow K^+ K^- \tag{1}$$

The SIDDHARTA setup contained 144 SDD chips, 1cm^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 an 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 measurements were done in 2009 and data analysis followed in the coming years, which produced the most precise measurement of kaonic hydrogen [1] and measurements of kaonic helium 3 [2] and kaonic helium 4 [3], [4]. Kaonic deuterium could not be measured by SIDDHARTA, since the signal/background was too small.

2.2 The SIDDHARTA-2 setup

The upgrade from SIDDHARTA to SIDDHARTA-2 is based on the following 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 optimized. 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.

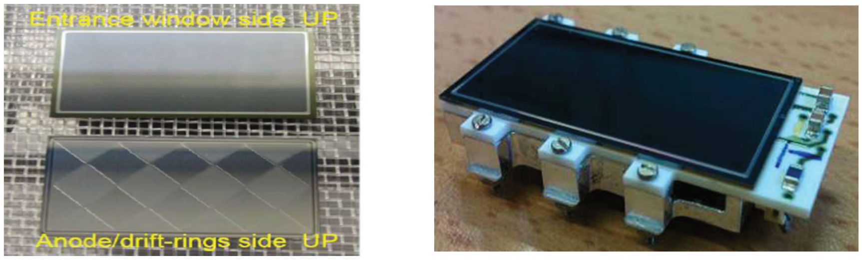

Figure 1: *The new 2 x 4 SIDDHARTA-2 SDDs array together with the readout electronics.*

- *Active shielding*: The scintillators surrounding the target are 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) reduces 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.
- *New SDD detectors*, produced by FBK, having a much better active/total surface ratio (about 85%, with respect to 40% in SIDDHARTA SDDs) (see Fig. 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 similar to that obtained for kaonic hydrogen should be reachable.

Figure 2 shows an image of the SIDDHARTA-2 apparatus, where the main components are highlighted.

To perform both conditioning of the machine and tuning of the various components of the SIDDHARTA-2 setup, a reduced version, named SIDDHARTINO, with only 1/6 of the X-ray silicon drift detectors (SDD), was installed in 2019 in the interaction point of the DAΦNE accelerator. Due to the pandemic situation, the SIDDHARTINO run started in January 2021 and lasted until July 2021. During this period, two runs with a target cell filled with ^{4}He gas at about 1.5% and 0.8% of liquid helium density were performed to optimize various setup components, as well as to provide feedback to the machine during its commissioning phase. The choice of ^{4}He was dictated by the high yield of the kaonic helium-4 (3d→2p) transition allowing for fast tuning. The experimental outcomes of this run already represented the first important physics results of the SIDDHARTA-2 experiment, delivering the most precise measurement of the 2p level shift and width in the gaseous target [5].

In the second half of 2021, the full SIDDHARTA-2 setup was installed on the DAΦNE interaction region in order to perform the difficult kaonic deuterium measurement. The optimization phase of the collider and of the full setup performance was performed, in dedicated periods, from

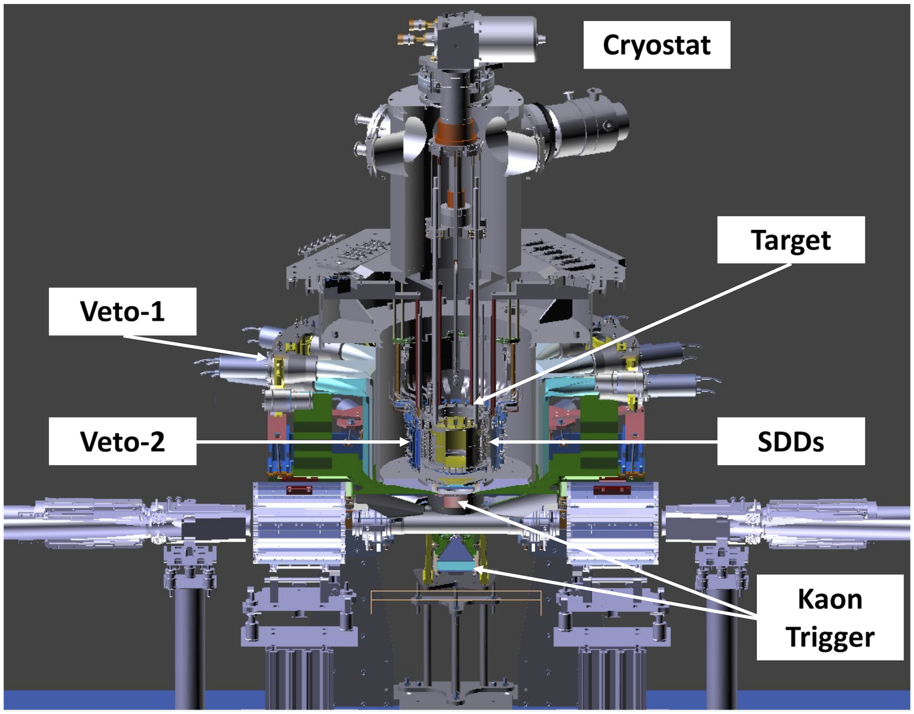

Figure 2: *Schematic view of the SIDDHARTA-2 setup.*

2021 to 2023. To optimize the performance of the detectors and of the veto systems, various measurements with helium-4 and neon gas targets were realized in this period. The kaonic deuterium data taking campaign began in May 2023 and was successfully completed in June 2024, collecting more than 800 pb^{-1} of kaonic deuterium data.

2.3 More details on 2024 SIDDHARTA-2 activities

2.3.1 The First kaonic neon measurement

After additional improvements and optimizations of the SIDDHARTA-2 setup, in the periods April - May 2023 and September - October 2023, the first measurement ever of kaonic neon transitions was performed. The target cell was filled with neon gas and cooled down to 28 K to maintain a density of 0.3% of the liquid neon density, corresponding to 3.6 g/l. The data were collected for a total integrated luminosity of 125 pb^{-1}.

An efficient selection of events is essential to disentangle the X-rays emitted by the kaonic neon de-excitation process from background-related events. The main source of background is represented by the electromagnetic showers induced by lost electrons and positrons, due to the Touschek effect and beam-gas interactions. These events, which are asynchronous with the back-to-back K^+K^- production, are rejected by the kaon trigger, which reduces the background by a factor of approximately 10^4. However, minimum ionizing particles (MIPs) generated from beam-beam and beam-gas interactions can produce accidental trigger signals when passing simultaneously through the scintillators of the kaon trigger. To differentiate between K^+K^- pairs and MIP-induced triggers, the time of flight technique is then employed. Since the kaons' momentum is lower than that of MIPs, by measuring the time difference between the DAΦNE radio-frequency, which serves as a time reference, and the trigger signal, K^+K^- pair events are disentangled from MIPs.

Figure 3-left shows the correlation of the mean time distribution measured by the two scintillators of the kaon trigger during the kaonic neon run, demonstrating the effectiveness of the selection cut in distinguishing K^+K^- pairs from MIPs.

The SDD time resolution plays a key role in enhancing the background reduction. The time difference between the kaon trigger signals and the hits on the SDDs is shown in Figure 3-right. The peak corresponds to events in coincidence with the kaon trigger, while the flat distribution is due to uncorrelated events. By selecting the events falling within a 1.0 μs time window, determined by the SDDs' temporal resolution, the background is reduced by an additional factor about two.

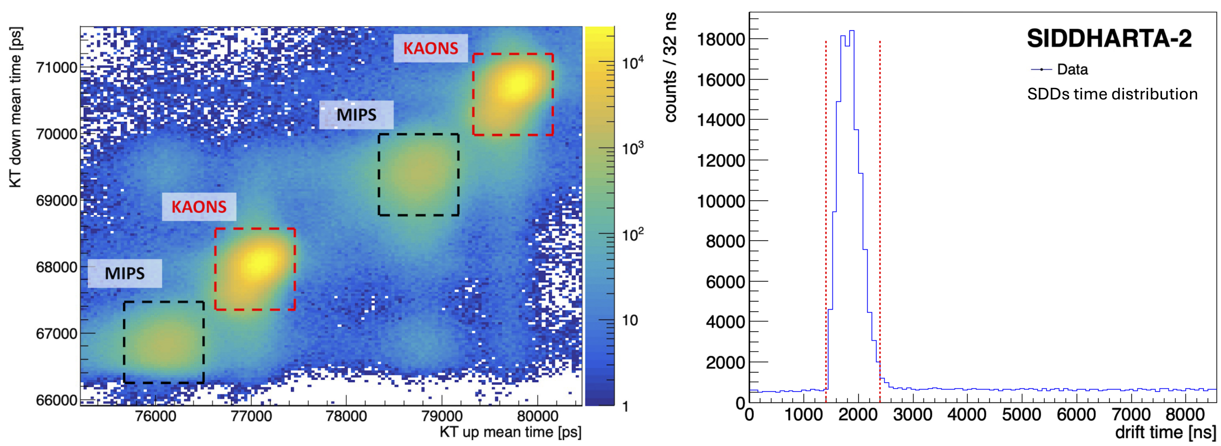

Figure 3: Left: Plot of the time difference between the kaon trigger top (KT up) and bottom (KT down) scintillators and the DAΦNE radio-frequency. The coincidence events related to kaons (high intensity) are clearly distinguishable from MIPs (low intensity). Right: Distribution of the time difference between the kaon trigger signals and X-ray hits on the SDDs. The dashed lines represent the 1.0 μs acceptance window.

Figure 4 shows the X-ray spectrum of the kaonic neon data obtained from the implementation of the event selection. Clear signals from kaonic atoms are observed, with highlighted peaks corresponding to X-ray emissions originating from kaonic atoms formed within the neon gas volume. Other lines are due to kaons stopped in the kapton ($C_{22}H_{10}O_5N_2$) entrance window and the aluminium frame of the target cell

Six kaonic neon transitions were measured and their energy values are reported in [15], together with corresponding absolute yields. Three of them, specifically the $8 \rightarrow 7$, $7 \rightarrow 6$, and $6 \rightarrow 5$ transitions, were determined with a statistical uncertainty below 1 eV. The main source of uncertainty arises from the calibration procedure, which ensures high precision up to ∼12 keV. Additionally, for the K-Ne (9→8) transition, the systematic uncertainty also considers the potential contamination from the titanium K_α transition. In future experiments, we plan to improve the calibration system by introducing elements with fluorescence emissions above 12 keV to preserve high calibration precision across the entire energy range.

These measurements provide new data for the kaonic atoms database and set a precedent for future high-precision kaonic atomic experiments, demonstrating the feasibility of sub-eV precision measurements using low-Z gaseous targets. This offers an advantage in terms of reduced electron screening effects and electron recapture, making high-n transitions in kaonic neon ideal for providing experimental input to investigate the bound-state QED.

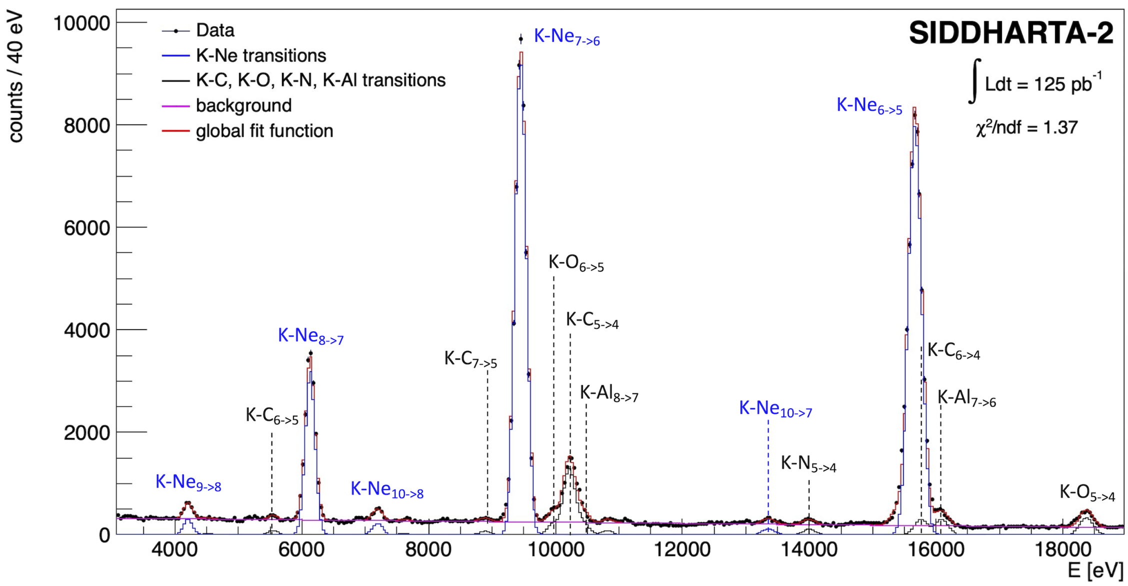

Figure 4: Kaonic Neon energy spectrum and relative fit after the events selection. The energy transitions are identified by the initial (n_i) and final (n_f) principal quantum numbers of the atomic levels. The several contributions of the fit function (red line) are highlighted: the kaonic neon (K-Ne) transitions in blue, the kaonic carbon (K-C), nitrogen (K-N), oxygen (K-O) and aluminium (K-Al) in black and the background in pink (reported from [15]).

The SIDDHARTA-2 collaboration has achieved a significant milestone in measuring the energies of high-n transitions in kaonic neon with high precision, as well as determining their yields, providing input data to develop the theoretical models accounting for the cascade processes in kaonic atoms. These results demonstrate that precision measurements of high-n transitions in kaonic atoms using low-Z gaseous targets are feasible.

2.3.2 The kaonic helium L-series X-ray yield at 2.25 g/l density

SIDDHARTA-2 setup was installed on DAΦNE and optimized by performing kaonic helium transitions measurements to the 2p level. There are two main interests in kaonic helium X-ray measurements: one is the shift and width induced by strong interaction between the kaon and the nucleus, and the other is the intensities of the X-rays transitions for each kaon stopped in the target, also known as the absolute yields.

The experimental results for the absolute yields are fundamental to test and develop the cascade model which consists of several processes that describe the de-excitation of a kaonic atom starting from the capture of a kaon to its final absorption by the nucleus. The X-ray emission is one of the main processes during the transitions to lower levels, but not all kaons reach the fundamental level. Other processes, such as the Stark effect, can induce the kaon nuclear absorption from high-energy levels, drastically reducing the X-ray yields. Since the Stark effect becomes more prevalent with density, experimental values of X-ray yield at new densities are the key to comprehend the kaonic atom cascade processes.

In Spring 2023, The SIDDHARTA-2 Collaboration performed a new kaonic helium-4 measurement at the density of 2.25 ± 0.11 g/l. The corresponding kaonic helium-4 energy spectrum for 12 pb^{-1} is shown in Figure 5. The kaonic helium L-series transitions are clearly visible at 6.4 keV (L_α), 8.7 keV (L_β), and 9.7 keV (L_γ). Other kaonic atom lines, such as the kaonic carbon (KC) high-energy transitions, are present due to the interaction of kaons with the Kapton entrance windows of the target cell.

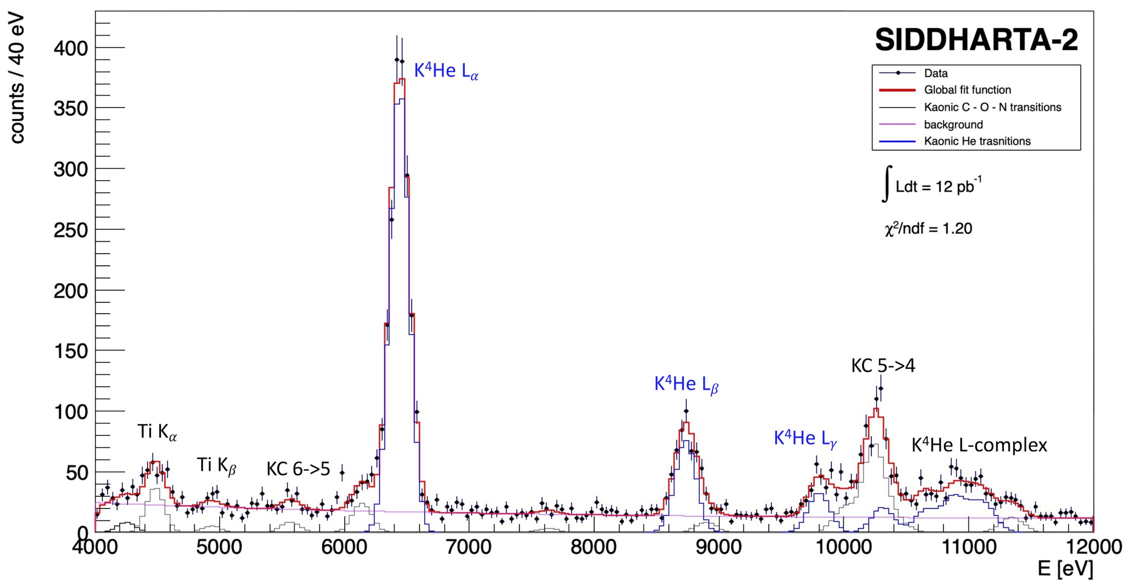

Figure 5: Kaonic helium-4 energy spectrum. The kaonic helium L-series transitions are visible together with the kaonic carbon high-n transitions (KC 6→5 and KC 5→4). The red solid line shows the fit function of the spectrum. The blue line shows the L-series kaonic helium-4 transitions(reported from [13]).

The absolute yields for the kaonic helium-4 L_α transition and the relative yield for the L_β and L_γ transitions are reported in [13].

This result adds a new data point for the study of the kaonic helium cascade process, and combined with the measurements of SIDDHARTA and SIDDHARTINO will allow to investigate the de-excitation processes of kaonic atoms along the density scale.

We compile a collection of the KHe-4 L_α yield in gas target, measured by the SIDDHARTA, SIDDHARTINO and SIDDHARTA-2 experiments in Table 1. The results are shown in Figure 6. These measurements are of fundamental importance for the understanding of the de-excitation mechanism in kaonic atoms, in terms of test and development of cascade models. As visible in Figure 6, the point at 2.25 g/l suggests a reduction of the yield, which is an expected indication of the Stark effect, which increases the kaon nuclear absorption from higher energy levels.

2.3.3 Kaonic deuterium measurement

The kaonic deuterium data taking campaign began in May 2023, aiming to collect data for a total integrated luminosity of about 800 pb^{-1}. This target is set to achieve the measurement of the 1s level shift and width with a precision similar to the kaonic hydrogen measurement, allowing to

Gas density (g/l)	KHe-4 L_α yield	reference
0.82 ± 0.082	0.126 ± 0.023	SIDDHARTINO [11]
1.37 ± 0.07	0.119 ± 0.002	SIDDHARTA-2 [12]
1.65	$0.231^{+0.060}_{-0.042}$	SIDDHARTA [7]
1.90 ± 0.095	0.148 ± 0.027	SIDDHARTINO [11]
2.15	$0.172^{+0.026}_{-0.095}$	SIDDHARTA [7]
2.25 ± 0.11	0.076 ± 0.003	SIDDHARTA-2 [13]

Table 1: Collection of the KHe-4 L_α yield in a gas target, measured by the SIDDHARTA, SIDDHARTINO and SIDDHARTA-2 experiments (reported from [14]).

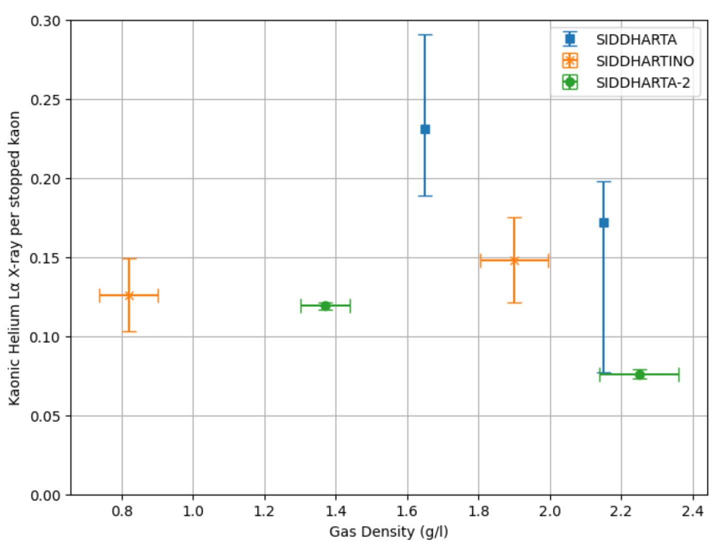

Figure 6: KHe-4 L_α yields as a function of the gas density. The increasing precision of the measurements is visible as the experiments were upgraded from SIDDHARTA [7] (blue markers) to SIDDHARTINO [11] (orange) and SIDDHARTA-2 [13] (green) (reported from [14]).

discriminate between the various theoretical models. To collect such a large quantity of data, the data taking has been divided into three distinct runs. The first period of the campaign measurement dedicated to the kaonic deuterium 2p$\rightarrow$ 1s transition, which was done from May to July 2023 (Run1) (total integrated luminosity of 196 pb^{-1}). Run2 of the kaonic deuterium measurement was performed in the period October - December 2023 (total integrated luminosity of 344 pb^{-1}), followed by Run3, which started in February 2024 and lasted until June 2024 (total integrated luminosity of 435 pb^{-1}). The total integrated luminosity delivered for kaonic deuterium measurement was 975 pb^{-1}, out of which 815 pb^{-1} are good for physics. These runs were punctuated by periods dedicated to the maintenance and optimization of both the experimental apparatus and the DAΦNE collider. The deuterium gas target was kept at a temperature of 26 K and a pressure of 1.30 bar, corresponding to a density of 2.28 g/l (1.4%) liquid deuterium density (LDD).

Data analysis is ongoing.

2.4 High Purity Germanium detector for testing the feasibility study of the measurement of kaonic lead X-rays at DAΦNE for the precise determination of the charged kaon mass

A test measurement of the X-rays from kaonic lead with an HPGe detector at the DAΦNE collider was done, in order to study the feasibility of X-ray measurements from targets suitable for the determination of the charged kaon mass. This measurement was performed in parallel with SIDDHARTA-2 measurements.

High Purity Germanium detector equipped with a transistor reset preamplifier and readout with a CAEN DT5781 fast pulse digitizer was employed in the measurement of X-rays from kaonic lead.

In the SIDDHARTA-2 experiment, the target and SDD detectors of the SIDDHARTA-2 setup are placed above the Interaction Point (IP). Two plastic scintillators (80 $\times$ 40 $\times$ 2 mm^3), SC1 and SC2, which serve as a luminosity monitor in the SIDDHARTA-2 measurements, are placed on opposite sides of the IP, with the long side parallel to the beams. One Pb target of the same size as the scintillation detector SC1 and with a thickness of 1.5 mm was placed immediately behind. It was 78 mm from the IP and it completely stopped the entering kaons. The HPGe detector is a p-type detector produced by Baltic Scientific Instruments. The active part is a cylinder with a base diameter of 59.8 mm and a height of 59.3 mm. The front side of the cylinder could be positioned at a minimal distance of 155 mm from the lead target, a constraint posed by the geometry of the SIDDHARTA-2 setup. The measurement was performed at this position, which, by using GEANT4 simulations, was shown to be optimal in the given configuration. The active part of the HPGe detector was shielded by 5 cm thick lead bricks, Figure 7, right. The front brick (not shown in the figure) was 2.5 cm thick with a circular hole of 4 cm in diameter in the center, for the X-rays to reach the active part of the detector from the lead target.

The measurement was performed in parallel with the SIDDHARTA-2 experiment in June 2023. The total integrated luminosity measured with the SIDDHARTA-2 luminosity monitor was 39.4 pb^{-1}. The calibration of the energy scale of the digitizer was done by using a 1 μCi ^{133}Ba source. This was also used to determine and monitor the energy resolution of the detector during the whole period of the measurement.

Fig. 8 shows the final energy spectrum seen by the HPGe detector after applying all the cuts. Clear peaks are visible at 208.92 $\pm$ 0.17 keV, 292.47 $\pm$ 0.17 keV and 427.07 $\pm$ 0.24 keV which come from the (10 $\rightarrow$ 9), (9 $\rightarrow$ 8) and (8 $\rightarrow$ 7) transitions in the kaonic lead, respectively.

The peak at 154.2 $\pm$ 1.2 keV, from the (11 $\rightarrow$ 10) transition, is less pronounced. Besides the peak at 511 keV from positron annihilation, there are peaks which originate from the transitions in ordinary lead with which the sensitive part of the HPGe detector was shielded. Expected peaks are at 72.80 keV and 74.96 keV, which are not resolved due to the resolution of the detector, and the peak at 84.94 keV. There are also visible peaks at 356.0 keV and 81.0 keV which are due

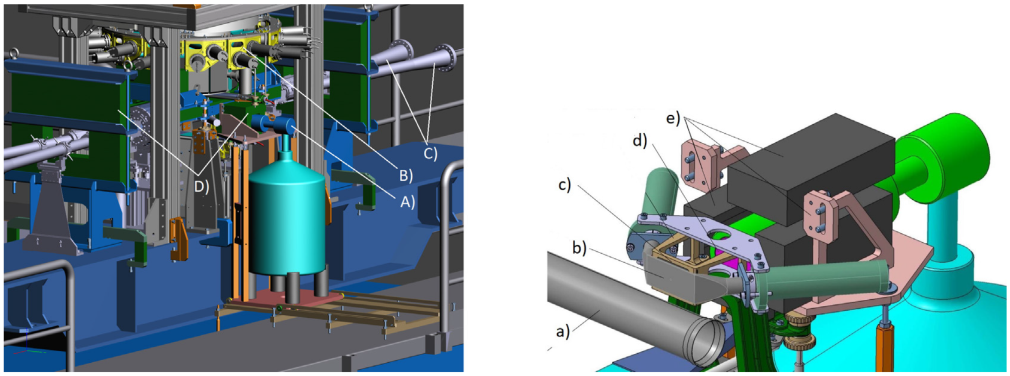

Figure 7: The location of the HPGe detector in the SIDDHARTA-2 setup, left: A) the HPGe detector, B) the SIDDHARTA-2 setup, C) beam pipes, D) shielding. Details of the HPGe setup, right: a) beam pipe, b) scintillation detector SC1, c) lead target, d) active part of the HPGe detector, e) lead shielding with holder (reported from [16]).

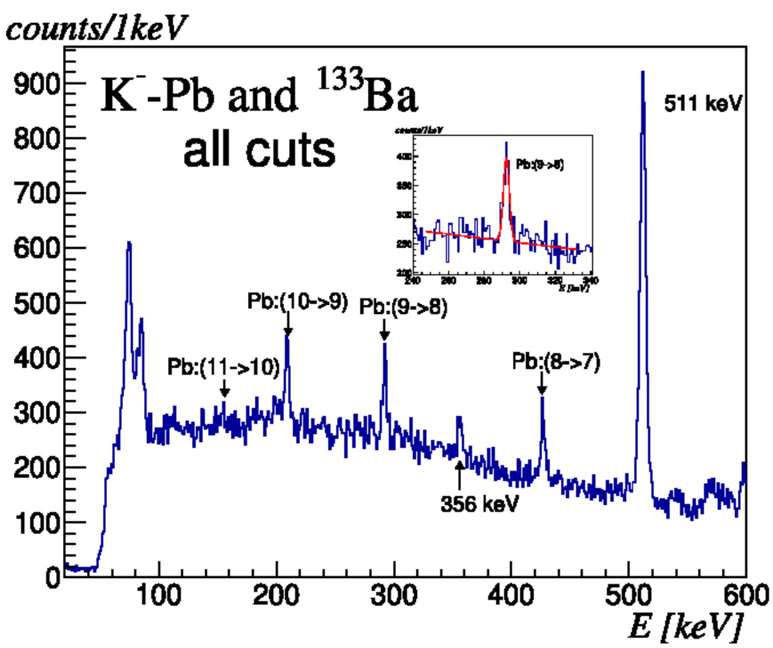

Figure 8: The spectrum seen by the HPGe detector after applying all cuts. The inset shows the peak at 292.47 ± 0.17 keV with a fit done by a Gaussian and a linear function for the background, the energy resolution is 3.97 ± 0.49 keV (FWHM) (reported from [16]).

to the ^{133}Ba source, which was in front of the sensitive part of the HPGe detector during the measurement. The inset of Fig. 8 shows the peak at 292.47 $\pm$ 0.17 keV from ($9 \rightarrow 8$) transitions in kaonic lead. The energy resolution is 3.97 $\pm$ 0.49 keV. Compared with the resolution of 4.39 $\pm$ 0.02 keV at 302.9 keV of ^{133}Ba in the measurement with the beams off, it can be concluded that there is no worsening of the resolution in measurements in the full beam conditions at DAΦNE.

Assuming the standard resolution of the HPGe detector, we estimated the required number of events in the ($9 \rightarrow 8$) transition peak to reach the 10 keV accuracy on the charged kaon mass. In a simple approach, we used the Rydberg formula for kaonic lead atoms, with the kaon-nucleus reduced mass, to obtain the relation between the precision of the transition and the accuracy of the charged kaon mass. To reach the 10 keV accuracy, the required precision of the ($9 \rightarrow 8$) transition needs to be approximately 6 eV. Approximately 8500 events in the ($9 \rightarrow 8$) transition peak are needed to reach the 10 keV accuracy on the charged kaon mass, assuming a detector with a resolution of 1.3 keV at 292 keV. The total number of events in the ($9 \rightarrow 8$) peak in our measurement is 770 $\pm$ 65. This implies that a total integrated luminosity of 435 pb^{-1} is needed to achieve the required accuracy by using only the ($9 \rightarrow 8$) transition in kaonic lead. This measurement serves as a test bed for future dedicated kaonic X-rays measurements for the more precise determination of the charged kaon mass.

2.5 Characterization for CZT Detection System in a collider environment

SIDDHARTA2 collaboration has developed a new detection system based on the appealing CZT compound semiconductor in order to measure the strong interaction in kaonic atoms systems in the intermediate-mass range (Al, F, C, S). The transitions of interest for such systems lay in the 30-300 keV range, where CZT devices are the radiation detectors best fulfilling the high efficiency and high-resolution requirements demanded to measure the emitted X-rays with precisions of a few tens of eV, thus pinning down those of the older experiments.

Moreover, with their excellent performances at room temperatures, CZT detectors allow for realizing small and compact detection systems, easy and fast to be installed and integrated with the existing SIDDHARTA-2 apparatus. The arrangement of this detection system was particularly challenging because this is the first application in a collider and this experiment can open the way to new use in this environment.

The CZT detection system consists of eight single 13 mm $\times$ 15 mm $\times$ 5 mm quasi-hemispherical CZT detectors enclosed in a thin aluminum box with an 0.27 μm thick aluminum window. To stabilize the temperature of the electronic components (not of the crystals), a FRYKA DLK 402 recirculating chiller working at a temperature of 15 ° C, was put on the lower side of the aluminum box. The front part of the aluminum box was enclosed with a lead shielding to lower down the intense radiative background caused by the particle losses at the last focusing quadrupole near the interaction point at DAΦNE that cause a huge background for kaonic atoms researches, being the detector as close as possible to the interaction point.

The detector was placed at 25 cm far from the IP of the DAΦNE collider, and between them, 10.2 cm from the IP, a plastic scintillator read by two PMTs was placed, working as a luminosity monitor for the whole experiment. A scheme reporting the experimental setup can be seen in Figure 9.

During the data taking of the SIDDHARTA-2 experiment , the CZT detector collected data for several months. At first the detector experienced a long phase of optimization of the setup, the HV, and the detector's position. The calibrations with source (^{152}Eu) was done.

The first linearity and stability characterization for CZT detection system in a collider was done, by performing a run with a source and the collider beam on, with the source placed in front of the detection system. The results of the tests are:

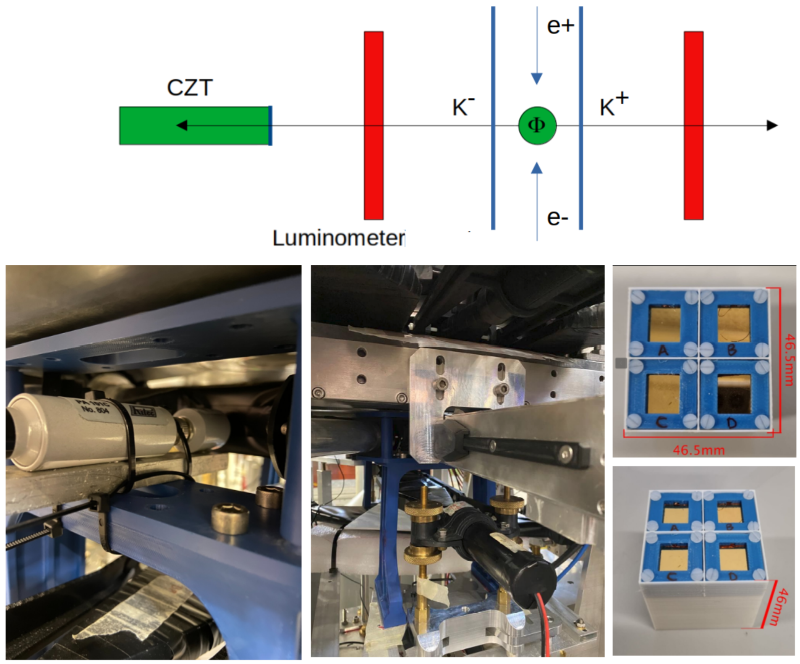

Figure 9: Top: Schematic of the main components for the two CZTe tests (not in scale) Bottom: picture of the installed RITEC CZT/500 detector (left), of the custom one (center) and of the unit cell installed in its aluminum box (right) (reported from [17]).

- The study on the short-term stability of the detectors showed that the outcome signals of the complex apparatus do not depend on environmental conditions, confirming the perfect stability of these kinds of detectors also after being exposed at high rates.
- The study of the long-term stability showed that the system is extremely stable also after switching off the apparatus and the machine and after changing some detectors, confirming the robustness of the electronics and the hardware and software data acquisition.
- The single long calibration every two of three weeks, even a month, is sufficient to control accurately the systematics and to obtain precise results on the kaonic atoms observables.
- The high rate due to the environment does not affect at all the detector properties.

2.6 Plan for the SIDDHARTA-2 activities in 2025

The LNF group main activities in SIDDHARTA-2 for 2025 will be the following ones:

- refined data analysis using also Machine Learning techniques to extract the shift and width of kaonic deuterium transitions to fundamental level
- analyses of post-calibration kaonic atoms data (with various solid targets)
- data analysis of the test run with CdZnTe detectors, which are ideal for detecting transitions toward both the upper and lower levels of intermediate-mass kaonic atoms, like kaonic carbon and aluminium

- consolidation of the proposal for kaonic atoms measurements beyond SIDDHARTA-2, i.e. EXKALIBUR program
- test of the new Silicon Drift Detectors 1mm thick, developed in collaboration with Fondazione Bruno Kessler.

3 Events organization in 2024

In 2024 the following event related to the physics of SIDDHARTA-2, was organized:

- KAMPAI - Kaonic, Antiprotonic, Muonic, Pionic and “onia” exotic Atoms: Interchanging knowledge and recent results, 30/09-04/10/2024, ECT*, Trento.

  https://indico.ectstar.eu/event/215/

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4 List of Conference Talks by LNF Authors in 2024

1. F. Artibani, “A Strangeness Adventure: Kaonic Atom Measurements with SIDDHARTA-2 at the DAΦNE Collider”, DISCRETE2024, 02-06 December 2024, Ljubljana, Slovenia.
2. F. Artibani, “The SIDDHARTA-2 experiment: Kaonic Atoms measurements at DAΦNE”, 8th Young Researchers’ Workshop “Physics Challenges in LHC era”, 13-17 May 2024, Laboratori Nazionali di Frascati, Italy.
3. F. Artibani, “New CdZnTe Detectors for Exotic Atom Research”, Exploring the Quantum Boundaries: an Odyssey into the gravity related collapse models, 12-14 June 2024, Laboratori Nazionali di Frascati, Italy.
4. F. Artibani, “New CdZnTe detectors for exotic atoms research”, “A Modern Odyssey: Quantum Gravity meets Quantum Collapse at Atomic and Nuclear physics energy scales in the Cosmic Silence”, 03-07 June 2024, ECT* Trento, Italy.
5. F. Artibani, “Intermediate mass kaonic atoms with CdZnTe detectors at the DAΦNE collider”, Congresso Società Italiana di Fisica 2024, 09-13 September 2024, Bologna, Italy.
6. D. Bosnar, “Feasibility study of kaonic lead X-ray measurement with an HPGe detector at DAΦNE”, workshop KAMPAI – Kaonic, Antiprotonic, Muonic, Pionic and ”onia“ exotic Atoms, 29 September - 04 October 2024, Trento (ECT*), Italy.
7. D. Bosnar, “Feasibility measurement of kaonic lead X-rays with an HPGe detector at DAΦNE for the precise determination of the charged kaon mass“, SPICE: Strange hadrons as a Precision tool for strongly InteraCting systEms, 13-17 May 2024, Trento (ECT*), Italy.
8. C. Curceanu, “From exotic atoms at accelerators to testing quantum foundations underground”, Colloquium, Melbourne University, 10th December 2024.
9. C. Curceanu, “We are stardust:from J-PET to kaonic atoms and back The strong connection between Krakow and Frascati”, Workshop First Total Body J-PET meeting, 5-6 October 2024, Krakow, Poland.

10. C. Curceanu, “A strangeness Odyssey: kaon-nuclei interaction studies at DAΦNE”, 20 Years of Stefan Meyer Institute, 11 November 2024, Vienna, Austria.
11. C. Curceanu, “Low-energy kaon-nuclei interaction studies at the DAΦNE collider: a strangeness Odyssey”, XVI Quark Confinement and the Hadron Spectrum Conference, 19-24 August 2024, Cairns, Australia.
12. C. Curceanu, “Low-energy kaon-nuclei interaction studies at the DAΦNE collider: a strangeness Odyssey”, Advances in the investigation of weak and strong interactions, 1-4 July 2024, Bucharest, Romania.
13. C. Curceanu, “Low-energy kaon-nuclei interaction studies at the DAΦNE collider: a strangeness Odyssey”, Exotic multi-quark states and baryon spectroscopy workshop, 25-27 June 2024, Bonn, Germany.
14. C. Curceanu, “Kaonic atoms at the DAΦNE Collider in Italy: a strangeness Odyssey”, Fourth International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility (HEF-ex 2024), 19-21 February 2024, J-PARC, Japan.
15. C. Curceanu, “Kaonic atoms at the DAΦNE Collider in Italy: a strangeness Odyssey”, Excited QCD, 14-19 January 2024, Benasque Science Center, Spain.
16. F. Clozza, “A new measurement of the Kaonic Helium L-lines with SIDDHARTA-2 at DAΦNE”, 8th Young Researchers’ Workshop “Physics Challenges in LHC era”, 13-17 May 2024, Laboratori Nazionali di Frascati, Italy.
17. L. De Paolis, “The KAMEO proposal: investigating the strong kaon-nucleus interaction through the E2 nuclear resosnance effect in kaonic atoms”, Advances in the investigation of weak and strong interactions, 1st - 4th July 2024, Bucharest, Romania.
18. L De Paolis, “Kaonic atoms at the DAΦNE Collider in Italy: a strangeness Odyssey”, Sesto Incontro Nazionale di Fisica Nucleare, 26th-28th February 2024, Trento, Italy.
19. S. Manti, “Kaonic Atom Properties and Cascade Models: Exploring Strong Interactions through First-Principles Calculations”, Advances in the investigation of weak and strong interactions, 01–04 July 2024, Bucharest, Romania.
20. S. Manti, “Kaonic Atom Properties and Cascade Models: Exploring Strong Interactions through First-Principles Calculations and Monte Carlo simulations”, KAMPAI - Kaonic, Antiprotonic, Muonic, Pionic and “onia” exotic Atoms: Interchanging knowledge and recent results, September 30 to October 4, 2024, ECT*, Trento, Italy.
21. K. Toho, “Development of the K^+ identification counter for DAΦNE - SIDDHARTA-2 experiment”, Research center for Electron Photon Science (Tohoku University) ELPH symposium, March 2024, Sendai, Japan.
22. K. Toho, “Measurement of Kaonic Neon X-rays in the SIDDHARTA-2 experiment”, JPS Spring Meeting, online, March 2024.
23. K. Toho, “Kaonic Neon X-ray measurement by SIDDHARTA-2”, XXI Frascati Spring School “BRUNO TOUSCHEC”, INFN-LNF, May 2024, Frascati, Italy.
24. K. Toho, “Overview of the SIDDHARTA-2 experiment at the DAΦNE collider”, GPPU school, Tohoku University, September 2024, Sendai, Japan.

25. F. Napolitano, “Kaonic Atoms with the SIDDHARTA-2 experiment”, 5th Jagiellonian Symposium on Advances in Particles physics and Medicine,29 June - 07 July 2024, Cracovia, Poland.
26. F. Sgaramella, “Kaonic atoms measurements with SIDDHARTA-2 at the DAΦNE collider”, SPICE: Strange hadrons as a Precision tool for strongly InteraCting systEms, 13-17 Maggio 2024, Trento (ECT*), Italy.
27. F. Sgaramella, “Kaonic Atoms Measurements with SIDDHARTA-2 at the DAΦNE collider”, Present and Future Perspective in Hadron Physics, 17-19 Giugno 2024, Frascati, Italy.
28. F. Sgaramella, “The SIDDHARTA-2 Experiment at the DAΦN collider”, EXA/LEAP, 25-30 Agosto 2024, Vienna, Austria.
29. F. Sgaramella, “Low energy kaon-nuclei interaction studies at the DAΦN collider: A strangeness Odyssey”, 110th Congresso della società italiana di fisica (SIF), 9-13 Settembre 2024, Bologna, Italy.
30. A. Scordo, “Present and future kaonic atoms measurements with new generation radiation detectors”, Fourth International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility (HEF-ex 2024), 20 February 2024, J-PARC (Tokai), Japan.
31. A. Scordo, “Cutting edge technology X and gamma-ray detectors for kaonic atoms’ measurement”, SPICE: Strange hadrons as a Precision tool for strongly InteraCting systEms, 13-17 Maggio 2024, Trento (ECT*), Italy.
32. A. Scordo, “Present and Future Perspective for Hadron Physics at LNF’s infrastructures”, Present and Future Perspective in Hadron Physics, 17-19 Giugno 2024, Frascati, Italy.
33. A. Scordo, “Advancements in Kaonic Atom Measurements: Insights from the SIDDHARTA-2 Experiment at the INFN-LNF DAΦNE Collider”, “QNP2024” 8–12 July 2024, Barcelona, Spain.
34. F. Sirghi, “High precision X-ray spectroscopy at the DAΦNE collider: with SIDDHARTA-2 experiment”, Advances in the investigation of weak and strong interactions, 01–04 July 2024, Bucharest, Romania.
35. F. Sirghi, “High precision X-ray spectroscopy at the DAΦNE collider: from SIDDHARTA-2 to EXCALIBUR, overview and perspective”, SPICE: Strange hadrons as a Precision tool for strongly InteraCting systEms, 13-17 May 2024, Trento (ECT*), Italy.
36. F. Sirghi, “Experimental challenges in study kaon-nucleon interaction at low energy at DAΦNE collider”, KAMPAI - Kaonic, Antiprotonic, Muonic, Pionic and “onia” exotic Atoms: Interchanging knowledge and recent results, 30 September – 4 October 2024, ECT*, Trento, Italia.
37. D. Sirghi, “Kaonic atoms measurements: a strange adventure at DAΦNE accelerator”, KAMPAI - Kaonic, Antiprotonic, Muonic, Pionic and “onia” exotic Atoms: Interchanging knowledge and recent results, 30 September – 4 October 2024, ECT*, Trento, Italia.

    “helium puzzle”

5 Publications in 2024

1. F. Sgaramella, D. Sirghi, K. Toho, F. Clozza, L. Abbene *et al*, High precision X-ray spectroscopy of kaonic neon, e-Print: 2412.16101 [nucl-ex].

2. F. Napolitano, L. Abbene, F. Artibani, M. Bazzi, G. Borghi *et al*, Kaonic Atoms with the SIDDHARTA-2 Experiment at DAΦNE, Acta Phys.Polon.A 146 (2024) 5, 669-673.

3. Francesco Artibani, Francesco Clozza, Massimiliano Bazzi, Cesidio Capoccia, Alberto Clozza *et al*, Intermediate Mass Kaonic Atoms at DAΦNE, e-Print: 2410.17921 [nucl-ex].

4. Leonardo Abbene, Francesco Artibani, Manuele Bettelli, Antonino Buttacavoli, Fabio Principato *et al*, First Stability Characterization for a CZT Detection System in an e^+ e^- Collider Environment, Sensors 24 (2024) 23, 7562, e-Print: 2410.11294 [physics.ins-det].

5. F. Sgaramella, L. Abbene, C. Amsler, F. Artibani, M. Bazzi *et al*, The SIDDHARTA-2 experiment for high precision kaonic atoms X-ray spectroscopy at DAΦNE, Nuovo Cim.C 47 (2024) 5, 285.

6. P. Achenbach, K. Aoki, S. Aoki, C. Curceanu, S. Diehl *et al*, Mini-Proceedings of the "Fourth International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility (HEF-ex 2024)", e-Print: 2409.00366 [nucl-ex].

7. D. Bosnar, L. Abbene, C. Amsler, F. Artibani, M. Bazzi *et al*, A feasibility study of the measurement of kaonic lead X-rays at DAΦNE for the precise determination of the charged kaon mass, Nucl.Instrum.Meth.A 1069 (2024) 169966. e-Print: 2405.12942 [physics.ins-det].

8. J-PARC E15 Collaboration, T. Yamaga *et al*, Measurement of the mesonic decay branch of the KNN quasibound state, Phys.Rev.C 110 (2024) 1, 014002. e-Print: 2404.01773 [nucl-ex].

9. Francesco Sgaramella, Francesco Clozza, Leonardo Abbene, Francesco Artibani, Massimiliano Bazzi *et al*, Characterization of the SIDDHARTA-2 Setup via the Kaonic Helium Measurement, Condens.Mat. 9 (2024) 1, 16.

10. J-PARC E31 Collaboration, Hiroyuki Noumi *et al*, Measurement of KN scattering below the KN mass threshold, EPJ Web Conf. 291 (2024) 05011.

11. F. Sirghi, L. Abbene, M. Bazzi, D. Bosnar, M. Bragadireanu *et al*, Kaonic atoms with SIDDHARTA-2 at the DAΦNE collider, EPJ Web Conf. 291 (2024) 01008.

12. L. De Paolis, L. Abbene, M. Bazzi, M. Bettelli, G. Borghi *et al*, The measurement of the E2 nuclear resonance effects in kaonic atoms at DAΦNE: The KAMEO proposal, EPJ Web Conf. 291 (2024) 05003.

13. F. Sgaramella, M. Bazzi, A. Clozza, C. Curceanu, L. De Paolis *et al*, Kaonic Helium-4 *L*-series Yield Measurement at 2.25 g/l Density by SIDDHARTA-2 at DAΦNE, Acta Phys.Polon.Supp. 17 (2024) 1, 1-A8.

14. F. Sirghi, M. Iliescu, L. Abbene, C. Amsler, M. Bazzi *et al*, SIDDHARTA-2 apparatus for kaonic atoms research on the DAΦNE collider, JINST 19 (2024) 11, P11006. e-Print: 2311.16144 [physics.ins-det].

15. F. Sgaramella, D. Sirghi, L. Abbene, F. Artibani, M. Bazzi *et al*, First measurement of kaonic helium-4 M-series transitions, J.Phys.G 51 (2024) 5, 055103. e-Print: 2310.20584 [nucl-ex].

16. A. Scordo, L. Abbene, F. Artibani, M. Bazzi, M. Bettelli *et al*, CdZnTe detectors tested at the DAΦNE collider for future kaonic atoms measurements, Nucl.Instrum.Meth.A 1060 (2024) 169060.

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5. D. Sirghi *et al*, J. Phys. G 49 (2022) 0551026.
6. F Sgaramella *et al*, Physica Scripta 97(11) (2022) 114002
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8. D. Sirghi *et al*, Nucl. Phys. A 1029 (2023) 122567
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11. D. Sirghi *et al*, Nucl. Phys. A 1029 (2023) 122567.
12. F. Sgaramella *et al*, J. Phys. G 51(5) (2024) 055103.
13. F. Sgaramella *et al*, Acta Physica Polonica B Proceedings Supplement 17(1) (2024) 1.
14. F. Napolitano *et al*, Acta Phys.Polon.A 146 (2024) 5 669.
15. F. Sgaramella *et al* https://arxiv.org/abs/2412.16101
16. D. Bosnar *et al*, Nucl.Instrum. Meth. A 1069 (2024) 169966.
17. A. Scordo *et al*, Nucl.Instrum .Meth. A 1060 (2024) 169060