THE ODYSSEY OF KAONIC ATOMS STUDIES AT THE DAΦNE COLLIDER: FROM DEAR TO SIDDHARTA-2*

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In this paper, an overview of kaonic atoms studies from the late 90s to nowadays at the DAΦNE collider at INFN-LNF is presented. Experiments on kaonic atoms are an important tool to test and optimize phenomenological models on the low-energy strong interaction. Since its construction, the DAΦNE collider has represented an ideal machine to perform kaonic atoms measurements, thanks to the unique beam of kaons coming from the ϕs produced in the collider decays. The DEAR and SIDDHARTA experiments achieved the precise evaluation of the shift and width of the $2p \to 1s$ transition in kaonic hydrogen due to the strong interaction, and thus provided a measurement strictly linked to isospin-dependent antikaon–nucleon scattering lengths. To fully disentangle the iso-scalar and iso-vector scattering lengths, the measurement of kaonic deuterium is necessary as well. The SIDDHARTA-2 experiment is now taking data at the DAΦNE collider with the aim to fulfill the need of this measurement, and therefore provide important information to the various phenomenological models on low-energy strong interactions with strangeness. The SIDDHARTA-2 Collaboration is also exploring the possibility to perform future kaonic atoms experiments, developing X-ray detector systems beyond the current state-of-art. These measurements are crucial for a deeper understanding of the kaon interactions with nuclei and for solving the kaon mass "puzzle".

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1. Introduction

According to the Standard Model (SM), the visible matter in the Universe is made of elementary fermions: leptons and quarks. The three interactions described by the SM, the electromagnetic, weak, and strong ones, are mediated by bosons: the photon, the Z boson, the charged W bosons, and the gluons. Stable atoms are systems in which electrons are bound to the nucleus. Protons and neutrons, *i.e.* hadrons made by quarks and gluons, are constituents of the nucleus.

Quantum ChromoDynamics (QCD) is the theory that describes the strong interaction, namely how quarks and gluons interact with each other. Differently from photons in Quantum ElectroDynamics (QED), in this theory, the mediators (gluons) are self-interacting. This peculiarity is reflected in a completely different running of the coupling constant as a function of the energy scale: at high momentum transfer (Q^2), namely smaller probed distances, the coupling of the strong interaction (α_{s}) is decreasing, and the quarks and gluons behave almost as free particles (*Asymptotic Freedom*), enabling the treatment of QCD by using the perturbation theory. At low Q^2 (below energies of ~ 200 MeV), or larger probed distances, on the other hand, α_{s} diverges making QCD non-treatable perturbatively. In this low-energy regime, a phenomenon known as *Confinement* takes place: quarks and gluons are confined inside the hadrons. For this reason, phenomenological models are an appropriate method to understand how hadrons interact at low Q^2.

In this framework, the exotic atoms [1] represent a unique experimental tool to test and provide inputs to phenomenological models on low-energy strong interactions. Exotic atoms are systems in which a negatively-charged particle (either a lepton or a hadron) binds to an atomic nucleus through their electromagnetic interaction, replacing an electron; the exotic particle is captured in a highly excited state. In hadronic atoms, de-excitation processes provide important information on the strong interactions between the nucleus and the hadron at very low energies.

In this context, the experimental studies of kaonic atoms play a key role since they can directly probe the non-perturbative regime of the QCD in the strangeness sector, thus providing important input to the phenomenological kaon–nucleon (K–N) and kaon–multinucleon (K–multi$N$) interaction models. A better understanding of the low-energy interaction between strange and normal matter is relevant since the s-quark mass is between those of the light and heavy quarks and its behaviour in the non-perturbative regime is still not fully understood. Comprehending these features will also have a significant impact on studies devoted to neutron stars. Indeed, the constraints on the K–N and K–multi$N$ interactions as a function of the nuclear density are related to studies about the possible existence of pulsars with strange matter in their interior. This problem is known as *The Hyperon Puzzle* [2].

Theories describing K–N interactions at threshold are often based on the Chiral Perturbation Theory (χPT), a complex study due to the presence of the strong coupling to the π–Σ channel and the existence of the Λ (1405) resonance just below threshold [3]. As an example, results of experiments on various theoretical models are presented in [4].

2. The physics of kaonic atoms

An exotic atom forms when a negatively-charged particle other than an electron binds to a nucleus, replacing an electron. The capture happens when the overlap of the wave-function of the exotic particle with the outermost electron orbit of an atom of the target is maximal, namely when their Bohr radii[1] are almost equal. The starting principal quantum number n of the exotic atom is [5]

$$n \approx \sqrt{\frac{\mu}{m_e}}\, n_e \,, \tag{1}$$

[1] The Bohr radius is $r_{\mathrm{B}} = \frac{\hbar c}{\mu c^2 \alpha Z}$.

where n_e is the principal quantum number for the electron, m_e is the electron mass, and μ is the reduced mass[2] of the system. As a reference, for the kaonic hydrogen ($n_e = 1$), this value is $n \approx 25$.

Once the exotic atom is formed, a cascade process takes place. The exotic atom experiences a series of de-excitations, and for lower-lying states, radiative transitions in the X-ray energy domain become dominant [6]. The capture and de-excitation processes happen in a timescale of the order of $10^{-12} \div 10^{-9}$ s. Therefore, for hadrons with a mean lifetime greater than this timescale (*e.g.* kaons, pions, antiprotons, *etc.*), the effects of the strong interaction in the system can be studied. The presence of an additional contribution in hadronic atoms results in a shift (ε) of the lowest energy levels with respect to those calculated solely with QED, and in a broadening (Γ) of the levels themselves, caused by the limited lifetime of the level due to the interaction of the hadron with the nucleus.

From the measurement of the shift and of the broadening induced by the strong interaction on the $1s$ level of kaonic hydrogen and kaonic deuterium the isospin-dependent antikaon–nucleon scattering lengths, important phenomenological parameters can be obtained [3, 4, 7–9]. In particular, the $\bar{K}p$ scattering length ($a_{\bar{K}p}$) is connected to the two experimental observables by the Deser–Trueman formula [10]. In an improved version by Meißner *et al.* [7, 8] which takes into account isospin-breaking corrections, this equation is written as

$$\varepsilon_{1s}^{H} + \frac{i}{2}\Gamma_{1s}^{H} = 2\alpha^3\mu^2 a_{\bar{K}p}\left[1 - 2\alpha\mu(ln\alpha - 1)a_{\bar{K}p} + \ldots\right] , \tag{2}$$

where α is the fine structure constant and μ is the reduced mass of the exotic atom. In a similar way, the $\bar{K}d$ scattering length $a_{\bar{K}d}$ is related to the kaonic deuterium width ε_{1s}^{D} and shift Γ_{1s}^{D}

$$\varepsilon_{1s}^{D} + \frac{i}{2}\Gamma_{1s}^{D} = 2\alpha^3\mu^2 a_{\bar{K}d}\left[1 - 2\alpha\mu(ln\alpha - 1)a_{\bar{K}d} + \ldots\right] . \tag{3}$$

The $\bar{K}p$ scattering length is connected to the $\bar{K}N$ isospin-dependent scattering lengths a_I, with $I = (0, 1)$, via the relation

$$a_{\bar{K}p} = \frac{1}{2}\left(a_0 + a_1\right) . \tag{4}$$

The individual iso-scalar (a_0) and iso-vector (a_1) scattering lengths can be obtained by also measuring the kaonic deuterium, which provides information on a different combination of a_0 and a_1

$$a_{\bar{K}n} = a_1 , \tag{5}$$

$$a_{\bar{K}d} = \frac{4\left[m_N + m_K\right]}{2m_N + m_K} Q + C , \tag{6}$$

[2] The reduced mass is $\mu = m_1 m_2/(m_1 + m_2)$.

where

$$Q = \frac{1}{2}\left[a_{\bar{K}p} + a_{\bar{K}n}\right] = \frac{1}{4}\left[a_0 + 3a_1\right] . \tag{7}$$

The first term in equation (6) represents the lowest-order impulse approximation, which is the K^- scattering from each (free) nucleon of deuterium. The second term C takes into account all higher-order contributions, namely all other physics associated with the K^-d three-body problem. In the case of deuterium, the three-body interactions can be studied by solving Faddeev-type equations[3], while for heavier nuclei, the multi-body interactions that depend on the nuclear density, are more complicated.

In order to obtain more and more precise models, it is extremely important to measure the kaonic hydrogen and deuterium with good precision. It is also important to measure shifts and widths due to the strong interaction in kaonic atoms along the whole periodic table. These measurements will contribute to having a clear picture of the kaon–nucleus interactions also as a function of the nuclear density.

3. Kaonic atoms at DAΦNE

Kaons need to be produced and stopped inside a target in order to form kaonic atoms. The DAΦNE collider (Double Annular Φ Factory for Nice Experiment) at the INFN-LNF, a unique accelerator, presents itself as the best candidate where to perform such experiments by providing a low-energy and almost monochromatic kaon beam from the decay of the produced ϕ resonance.

3.1. The DAΦNE collider

DAΦNE is a world-class electron–positron collider at the Laboratori Nazionali di Frascati of INFN (INFN-LNF). The collider was designed in the early 90s to work at the center-of-mass energy of the ϕ resonance (1.02 GeV), providing, via its decay, charged K^+–K^- pairs with a branching ratio of 48.9%. The produced charged kaons have a momentum of ≈ 127 MeV/c, and a momentum spread of $\Delta p/p < 0.1\%$. In the present configuration, the crossing angle between the two beams in the interaction point is ~ 50 mrad. This relatively high crossing angle causes the produced ϕ to be boosted towards the center of the collider [11].

As shown in figure 1, the DAΦNE accelerator complex consists of a double-ring lepton collider and an injection system. In its original configuration [12], the collider consisted of two independent rings, each one ~ 97 m long,

[3] The Faddeev equations are a set of three differential equations equivalent to the 3-body Schrödinger equation that exploit the simplifications associated with configurations consisting of a 2-body cluster that is well-separated from the third atom.

sharing two 10 m long Interaction Points (IP). A full injection system and an accumulator or damping ring, provide fast and high-efficiency e^-/e^+ injections.

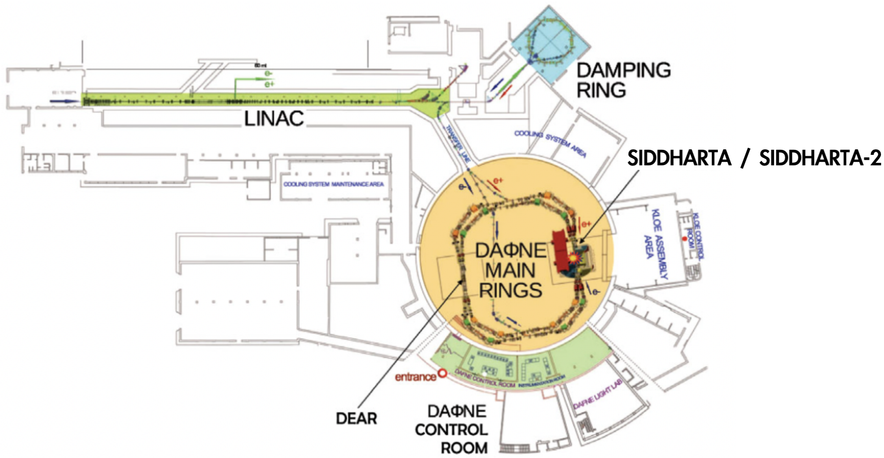


Fig. 1. A schematic view of the DAΦNE accelerator complex. Figure taken from Ref. [13].

At the end of the 2005 run, the maximum daily integrated luminosity was ~ 9.6 pb^{-1} [14]. In 2008, the collider underwent a major upgrade to improve the luminosity with an innovative collision scheme — the crab-waist [15]. While providing data to the SIDDHARTA experiment [11, 16], this resulted in an increase in the peak[4] and of the integrated luminosities with respect to the previous collider's configuration performance.

3.2. The DEAR experiment

Old measurements on kaonic hydrogen were in high contrast with theoretical predictions [13]: three measurements of kaonic-hydrogen X-rays were carried out at CERN and at the Rutherford Laboratory [17–19], from the late 1970s to early 1980s. These experiments measured a positive sign of the shift, namely a positive real part of the K^-p scattering length, which implied an attractive-type strong interaction. This was in contradiction with the results obtained by fixed target experiments that measured low-energy interactions between kaons and nuclei, and which found a negative real part of the scattering length, corresponding to a repulsive-type strong interaction. This discrepancy between kaonic atoms measurements and low-energy scattering data went under the name of *Kaonic Hydrogen Puzzle*.

[4] An increase of a factor three.

This inconsistency was finally solved in the 90s by the KpX experiment [20] at the KEK proton synchrotron in Japan. This experiment measured a negative sign for the shift of the 1s level in kaonic hydrogen, thus confuting the old experiments' claims. The resulting shift and width of the kaonic hydrogen 1s level turned out to be [20]

$$\epsilon_{1s} = -323 \pm 63(\mathrm{stat.}) \pm 11(\mathrm{syst.})\ \mathrm{eV}\,, \tag{8}$$

and

$$\Gamma_{1s} = 407 \pm 208(\mathrm{stat.}) \pm 100(\mathrm{syst.})\ \mathrm{eV}\,. \tag{9}$$

Figure 2 shows the KpX results compared to the old measurements and the theoretical predictions.

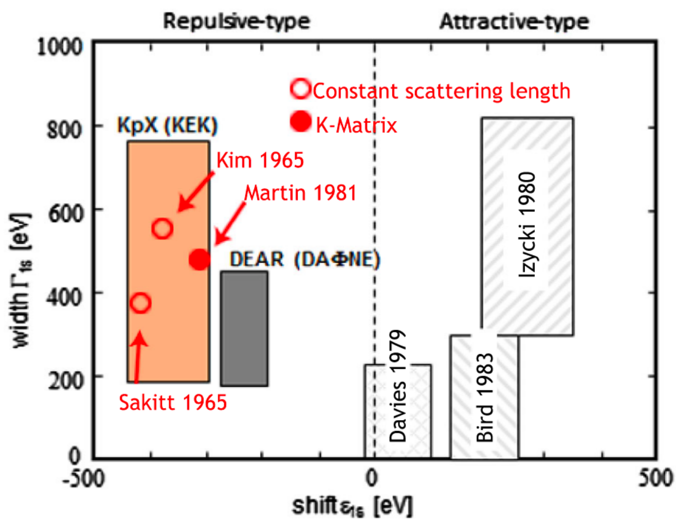


Fig. 2. The shift and width obtained by the KpX experiment are compared with the results of three previous measurements and with some of the analyses of the low-energy K^-N scattering data. The DEAR result is also reported. Figure taken from [13].

The first experiment on kaonic atoms that exploited the advantages of the low-energetic and almost mono-chromatic beam of charged kaons from the ϕ mesons decay delivered by DAΦNE was DEAR (DAΦNE Exotic Atoms Research). The primary goal of DEAR [21] was to perform a measurement of the shift and width of the fundamental level of kaonic hydrogen due to the strong interaction to confirm the results of the KpX experiment with an improved precision.

Kaons travelling through the DEAR beam pipe made out of aluminium with carbon fiber reinforcement were degraded in energy to a few MeV, and stopped in a gaseous hydrogen target placed about 10 cm above the beam pipe [22]. Charge Coupled Devices (CCDs) were used as X-ray detectors. A schematic view of the experiment is reported in figure 3.

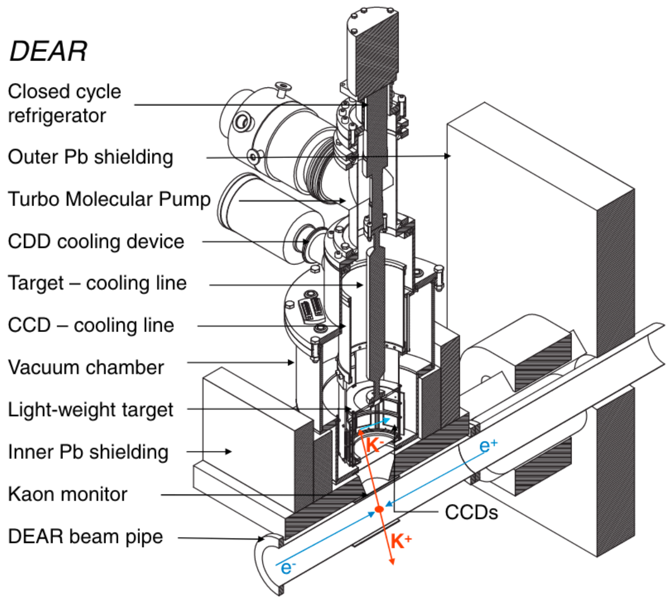


Fig. 3. A schematic view of the DEAR experimental setup. Figure taken from [13].

Analysis of the kaonic hydrogen lines had to meet many crucial challenges. To overcome all the problems and achieve the most precise measurements (of that time) for the shift and width of the kaonic hydrogen due to the strong interaction, two different analyses, described in [22], were performed. The resulting weighted average of the ground-state shift was [22]

$$\epsilon_{1s} = -193 \pm 37(\mathrm{stat.}) \pm 6(\mathrm{syst.})\ \mathrm{eV}\,, \tag{10}$$

while for the width, they obtained

$$\varGamma_{1s} = 249 \pm 111(\mathrm{stat.}) \pm 30(\mathrm{syst.})\ \mathrm{eV}\,. \tag{11}$$

A comparison between the results of DEAR, KpX, the three older measurements, and the theoretical predictions coming from other low-energy scattering measurements, is reported in figure 2.

The results of the DEAR experiment confirmed KpX which solved the kaonic hydrogen puzzle and, at the same time, demonstrated the need for new, more precise measurements as explained in the next section.

3.3. The SIDDHARTA experiment

Theoretical studies have been performed with possible higher-order contributions using several models to fit DEAR's data. However, most of them had difficulties in explaining all the experimental results in a consistent way. Therefore, new precision measurements were essential for the understanding of the low-energy strong interactions theoretical framework. With this aim, the SIDDHARTA (SIlicon Drift Detector for Hadronic Atom Research by Timing Application) experiment was realized. SIDDHARTA [23] was able to improve the precision of the measurement due to two main factors. Firstly, the luminosity was increased by a factor of 3 compared to DEAR thanks to the machine improvements in 2005, described in Section 3.1. Secondly, novel techniques were used to exploit the microsecond timing and excellent energy resolution of large area Silicon Drift Detectors (SDDs) [24–26]. While DEAR's CCDs cannot be used for timing applications, the SIDDHARTA SDDs are suitable detectors to perform timing analysis due to their small value of the capacitance of the anode. The SIDDHARTA setup [23] consisted of various components: the kaon detector (a system of two scintillators to detect the back-to-back K^+K^- coming from ϕ decays, which also provided a luminosity measurement), an X-ray detection system that used the SDDs, and a cryogenic target system filled with hydrogen. A schematic view of the SIDDHARTA experiment is reported in figure 4.

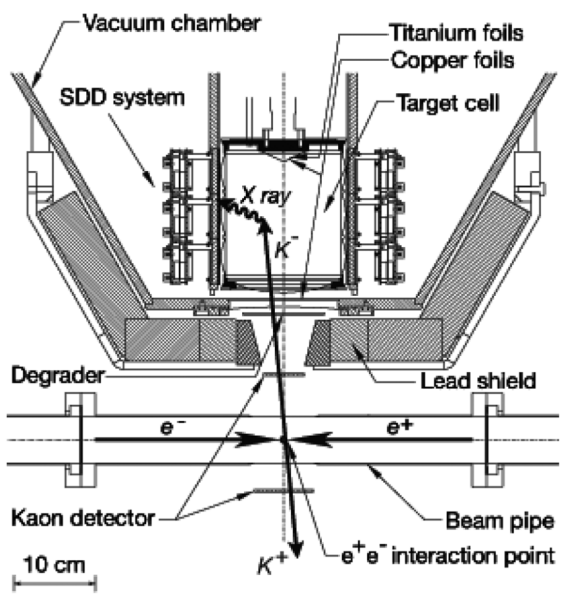


Fig. 4. A schematic side-view of the SIDDHARTA setup installed at the e^+e^- interaction point of DAΦNE. Figure taken from [27].

The timing improvements due to the use of the SDDs as X-ray detectors brought a higher control of the background, resulting in cleaner spectra, and thus in a better precision of the measurement. As a result, the $1s$-level shift and width for the kaonic hydrogen were determined to be [23]

$$\epsilon_{1s} = -283 \pm 36(\text{stat.}) \pm 6(\text{syst.})\ \text{eV}\,, \tag{12}$$

and

$$\Gamma_{1s} = 541 \pm 89(\text{stat.}) \pm 22(\text{syst.})\ \text{eV}\,. \tag{13}$$

In figure 5, the comparison between the results of the KpX, DEAR, and SIDDHARTA experiments is reported.

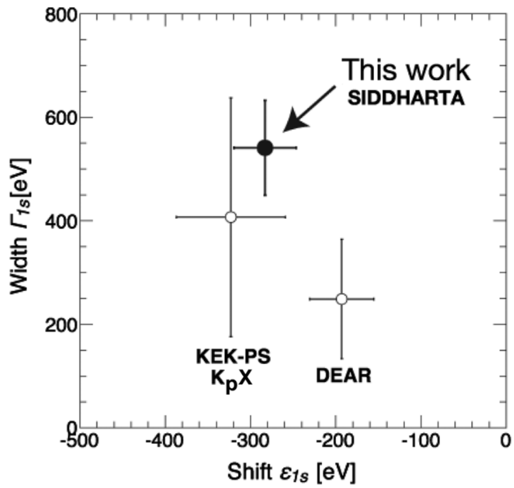


Fig. 5. Comparison of the experimental results for the strong interaction $1s$ energy level shift and width of kaonic hydrogen: KEK-PS KpX [20], DEAR [22], and SIDDHARTA [23]. The error bars correspond to quadratically added statistical and systematic errors. Figure taken from [23].

The SIDDHARTA experiment also measured the K^{-3}He and K^{-4}He lines coming from the $3d \to 2p$ transitions [27], giving an important contribution to the models of the K–multi$N$ interactions.

In addition, the first exploratory measurement of kaonic deuterium, providing important limits for the models on K^-N and K^-NN interactions, was performed. Although a clear signal was not evidenced, it was an important measurement for a first estimation on the yield limit of the $2p \to 1s$ (K_α) transition that resulted to be more than ten times lower than the kaonic hydrogen one [28].

The results achieved by this experiment were crucial to develop theoretical models on the low-energy interactions between nucleons and kaons. The continuous improvements of the theories on low-energy K^-N and K^-–multi$N$ interactions to fit the SIDDHARTA data pushed the theoretical community to ask for new experiments to measure the kaonic deuterium K-lines, *i.e.* SIDDHARTA-2.

3.4. Kaonic He measurement with SIDDHARTINO

During the commissioning phase of the DAΦNE collider in 2021, a reduced version of the SIDDHARTA-2 apparatus, called SIDDHARTINO, was installed above the interaction region of the DAΦNE collider. The aim of the SIDDHARTINO pilot run was to optimize the setup and the run conditions, namely to test the collider luminosity, the trigger system, and the new SDDs (see the next section) in view of the crucial deuterium run with the complete setup. The optimization was performed through the measurement of the kaonic helium-4 transitions on the $2p$ level, which lie in the kaonic deuterium region of interest. Moreover, the high yield of these transitions ensured high statistics during the data taking.

The main components of the SIDDHARTINO setup are similar to those of SIDDHARTA with differences in dimensions and positioning of the single elements. This new configuration is the result of an optimization performed by exploiting a detailed Geant4 Monte Carlo simulation, with the aim of maximizing the X-ray signal emitted from the de-excitation of the kaonic atoms in the target cell. A sketch of the SIDDHARTINO experimental apparatus is shown in figure 6 (a). A complete description of the setup and the calibration and data analysis techniques can be found in [29].

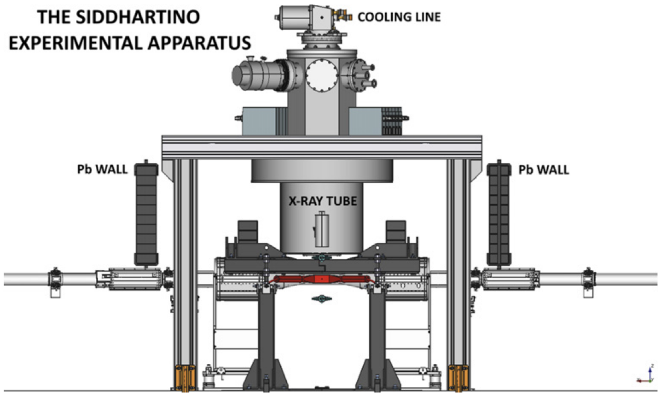
The final spectrum obtained by the SIDDHARTINO pilot run for a total integrated luminosity of 26 pb^{-1} is reported in figure 6 (b). The K^4He $3d \to 2p$ transition (L_α) was clearly visible together with the $4d \to 2p$ (L_β) and $5d \to 2p$ (L_γ) ones. Other transitions coming from kaonic atoms different from helium were observed. These lines are generated by kaons stopped in the target window and in other components of the experimental apparatus, and represent a possible background also for the deuterium run [29].

From the results of the fit on the spectrum, reported with a red line in figure 6 (b), the strong interaction-induced shift and width of the $2p$ level in the kaonic helium were measured to be [29]

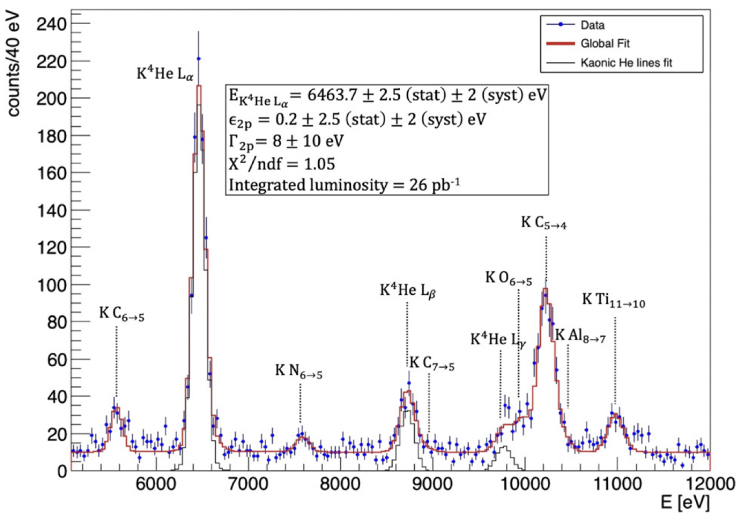
$$\epsilon_{2p} = 0.2 \pm 2.5(\text{stat.}) \pm 2.0(\text{syst.})\ \text{eV} \tag{14}$$

and

$$\Gamma_{2p} = 8 \pm 10(\text{stat.})\ \text{eV}\,. \tag{15}$$



(a)



(b)

Fig. 6. (a) A schematic view of the SIDDHARTINO experimental setup installed on the IP of the DAΦNE collider. Figure taken from [29].(b) Fit (red line) of the K^4He energy spectrum. The L_α peak is seen together with the L_β and L_γ ones (black lines). The other labelled peaks are a background due to kaonic atoms formations out of the target cell. Figure taken from [29].

The result obtained by this preliminary run represents the most precise measurement of the K^4He L_α transition in gas and, in addition to the main goal of optimizing and studying the new SIDDHARTA-2 setup, it provided a solid confirmation of the measurements performed by the SIDDHARTA experiment.

3.5. The SIDDHARTA-2 experiment

The measurement of the kaonic deuterium K_α transition is particularly challenging: as evidenced by the exploratory measurement of the SIDDHARTA experiment, the yield of the transition is at least by a factor of ten lower than the kaonic hydrogen one. To perform this difficult measurement, a new experimental setup was conceived by the SIDDHARTA-2 Collaboration, with the aim to increase the signal-to-background ratio.

The full experimental setup of SIDDHARTA-2 was installed in the DAΦNE collider after the SIDDHARTINO pilot run in 2022. The setup is shown in figure 7. Its components are: the kaon trigger, the Mylar degrader, the luminosity monitor, and a cylindrical vacuum chamber that contains the cryogenic target. The key upgrades with respect to SIDDHARTA are the new SDDs and the new complex veto systems, used to reject the background synchronous and asynchronous with the production of the charged kaons pairs.

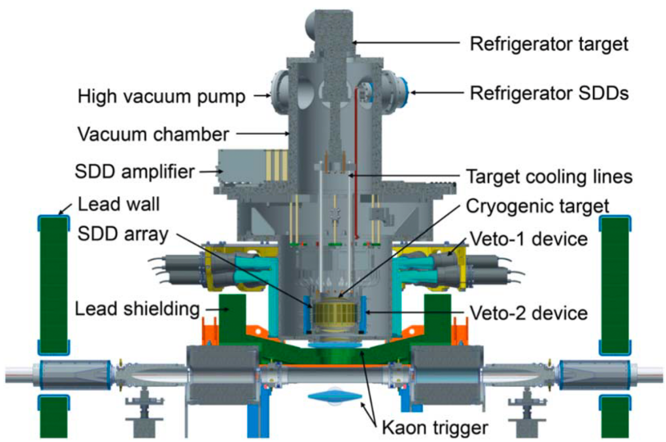


Fig. 7. An overview of the experimental setup. The whole system is installed at the e^+e^- IP in DAΦNE. Figure taken from [13].

Above and below the IP, the Kaon trigger, a pair of plastic scintillators read by two Photo-Multipliers Tubes (PMTs) each, are placed. The kaons are selected exploiting the time-of-flight measurement to distinguish them from MIPs passing through the scintillators. The vacuum chamber, evacuated to a pressure below 6^{-10} mbar, is placed above the interaction point and contains the Kapton cell reinforced with aluminium structures in which the target gas is enclosed. The charged kaons produced by the ϕ decays in the IP travel into the vacuum chamber until they stop inside the target cell, interact with the gaseous deuterium, and form kaonic atoms, emitting X-rays. Around the target cell, new silicon drift detectors [24–26, 30] are used to detect the X-rays coming from the cascade processes of the kaonic atoms. The Veto-1 system is composed of twelve units of plastic scintillators read out by pairs of PMTs [31]. The detectors are placed around the target cell, outside the vacuum chamber. The Veto-2 system is made of smaller scintillator tiles read by Silicon Photo-Multipliers (SiPMs) placed inside the vacuum chamber, surrounding the target cell [32, 33].

The asynchronous background related to particle losses from the DAΦNE beams is suppressed by the trigger system. Its logic consists of the coincidence between a signal on the SDDs and a signal on the kaon trigger. Upstream and downstream the beam pipe a lead shielding is placed, preventing particles, mostly MIPs, coming from the beams losses at the focusing quadrupoles near the IP to arrive at the detector. To provide a direct luminosity measurement to DAΦNE, an additional pair of plastic scintillators read by two PMTs each is placed on the longitudinal plane of the interaction point. The SIDDHARTA-2 Luminosity Monitor (Luminometer) [34] uses the kaon rates on the plastic scintillator to measure the luminosity and evaluate the background.

The geometry of the experimental setup was optimized using a detailed Geant4 simulation that guarantees the highest possible signal. More details on the setup can be found in [35].

3.6. The kaonic deuterium measurement

The first SIDDHARTA-2 run with a gaseous deuterium target started in 2023. Figure 8 shows, as an example, the most relevant phenomenological models describing the K–N scattering amplitudes after the inclusion of the results obtained by SIDDHARTA. For the case of K–p, they are in good agreement at threshold, but for the K–n the situation is dramatic: the models strongly disagree.

The SIDDHARTA-2 experiment aims to achieve a precision in the order of tens of eV on the measurement of the kaonic deuterium $1s$ level shift w.r.t. to the QED value, and on the width, a similar precision to the kaonic hydrogen measurement of SIDDHARTA. This precision will help in extracting the isospin-dependent K–N scattering lengths, providing important input for theoreticians to clarify the picture regarding the low-energy strong interactions with strangeness.

The SIDDHARTA-2 Collaboration aims to collect ≈ 800 pb^{-1} of integrated luminosity to achieve this important goal. The Monte Carlo simulation developed for SIDDHARTA-2 was exploited to simulate the expected spectrum of the experiment. The simulation was run assuming a total integrated luminosity of 800 pb^{-1}, the values of the kaonic deuterium $1s$ level shift and width to be -800 eV and 750 eV, respectively, and the yields ra-

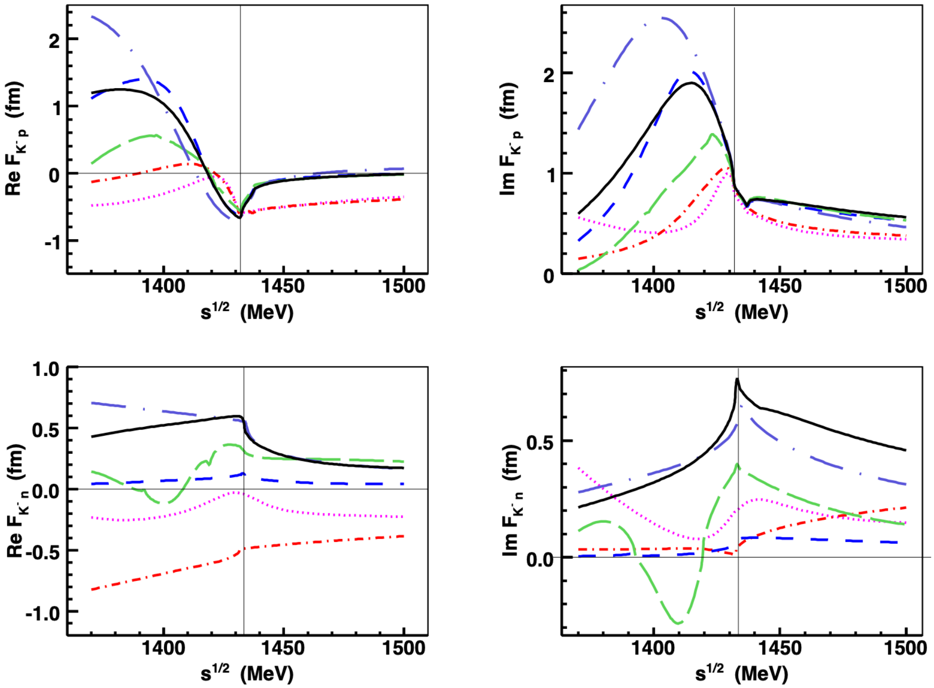


Fig. 8. The K–p (top panels) and K–n (bottom panels) elastic scattering amplitudes generated by the many phenomenological approaches considered. The various lines refer to the models: B2 (dotted, purple), B4 (dot-dashed, red), MI (dashed, blue), MII (long-dashed, green), PNLO (dot-long-dashed, violet), and KMNLO (continuous, black). Figure taken from [4].

tios $K_\alpha : K_\beta : K_{\mathrm{total}}$ to be the same as for kaonic hydrogen, with the K_α yield of 10^{-3} events per stopped kaons in the gas target. By analysing the data coming from the MC simulation based on these assumptions, the shift and width induced by the strong interactions on the $1s$ level of the kaonic deuterium can be determined with a precision of about 30 eV and 80 eV, respectively [36]. The simulated spectrum is reported in figure 9.

The kaonic deuterium measurement started in late spring 2023 and is ongoing.

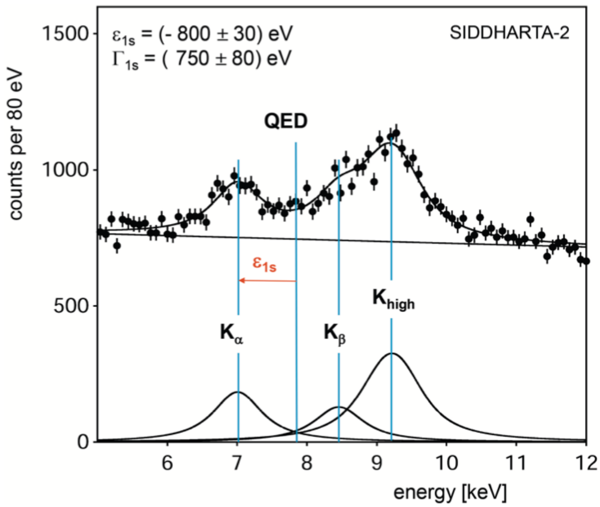


Fig. 9. The simulated SIDDHARTA-2 kaonic deuterium spectrum, assuming a shift $\epsilon_{1s} = -800$ eV and width $\Gamma_{1s} = 750$ eV of the $1s$ state, as well as a K_α yield of 10^{-3}. The spectrum was simulated for an integrated luminosity of 800 pb^{-1}. Figure taken from [36].

3.7. Measurements with CZT and HPGe detectors

In parallel with the K–d measurement, the SIDDHARTA-2 Collaboration prepared two other detector systems, placed in such a way as to exploit at best the kaon beam provided by DAΦNE to measure other kaonic atoms.

The SIDDHARTA-2 kaonic deuterium experimental setup using SDDs develop above the beam pipe, with part of the kaon detector below the beam pipe. The boost and anti-boost sides of the beam pipe are available to host additional setups. On the boost side (left-hand side referring to figure 10), an HPGe (High Purity Germanium) detector was installed, while on the anti-boost side (right-hand side referring to figure 10), a novel cadmium–zinc–telluride detector system has been positioned. Figure 10 shows the three detectors position beside the beam pipe.

3.7.1. High Purity Germanium detector

The SIDDHARTA-2 Collaboration plans to measure heavy-mass kaonic atoms transitions with high precision, using a High Purity Germanium (HPGe) detector. The detector, designed by the Baltic Scientific Instruments, is able to work in high-rate environments and is ideal to perform measurements at the DAΦNE collider.

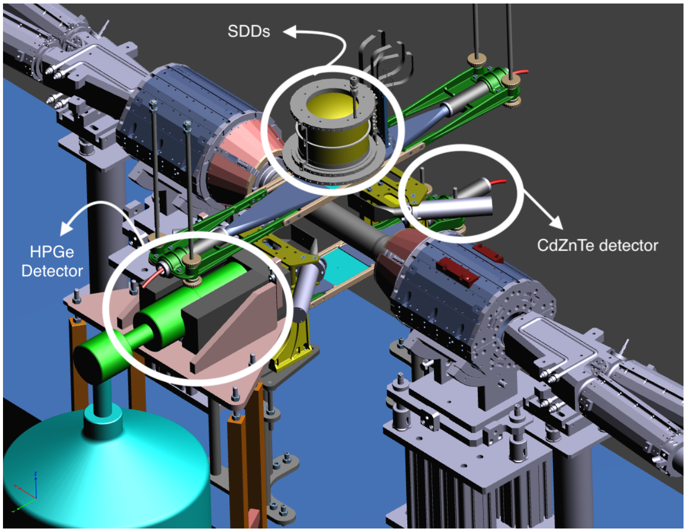


Fig. 10. The set-up of the three experiments of the SIDDHARTA-2 Collaboration exploiting the DAΦNE beam.

The HPGe detector can measure X-rays and γ-rays up to 1 MeV and perform kaonic atoms measurements for heavier targets. The prototype detector has a cylindrical active volume of 59.3 mm height and 29.9 mm base ray. It features a nominal resolution of 0.7% at 122 keV, 0.2% at 477.6 keV, and 0.14% at 1.33 MeV, and the resolution measured in DAΦNE using an in-beam ^{133}Ba source is of 0.4% at 302.9 keV. The collaboration is now taking data with the detector using a lead target which can contribute to the kaon mass measurement, examined in depth in the next chapter.

3.7.2. Cadmium–zinc–telluride detector

The SIDDHARTA-2 Collaboration together with the IMEM-CNR of Parma built a system of customized cadmium–zinc–telluride detectors highly efficient in an energy range between 20 keV and 300 keV. The cadmium–zinc–telluride (CdZnTe), also called CZT, an alloy of cadmium–telluride (CdTe) and zinc–telluride (ZnTe), is a promising compound semiconductor in the field of spectroscopy thanks to its unique properties. Over the last two decades, CdZnTe semiconductors attracted increasing interest as X-ray and γ-ray detectors, and are used in several sectors, from medical imaging [37] to astrophysics [38]. Differently from the most used high-performance X-ray detectors based on silicon and germanium that can only work at low temperature, the CZT detectors show high detection efficiency and suitable performances also at room temperature. Therefore, CZT is ideal to develop compact and reliable detection systems [39]. These features make this detector appealing to perform kaonic atoms measurement with targets in the intermediate-mass range, and fulfill in this way the need for new data highlighted by the theoretical community.

The collaboration managed to successfully test this kind of detector on a collider for the first time, and to explore high-rate measurements [40, 41]. The system in its last configuration is composed of eight $13 \times 15 \times 5$ mm^3 hemispherical CZT detectors provided by the Redlen Technologies, coupled to analogue charge-sensitive preamplifiers (CSPs) and to a digital pulse processing (DPP) readout electronics, with a measured energy resolution of 6% at 60 keV and 2.2% at 511 keV [40]. The detector is now taking data with a solid target made of carbon and aluminum, optimized using a Monte Carlo simulation, with the aim to measure values of shift and width induced on lower levels by the strong interactions between kaons and nucleus for these two atoms, with implications on the description of the nuclear density distribution [42]. Also, for the $4 \to 3$ kaonic aluminum line, which is subject to strong interactions, the old kaonic atoms dataset [43] reports incompatible measurements that result in uncertainties in the phenomenological models.

This study paves the road for new kaonic atoms experiments and new applications of CZT-based detectors in particle physics [40, 41].

4. Future plans

4.1. The EXKALIBUR project

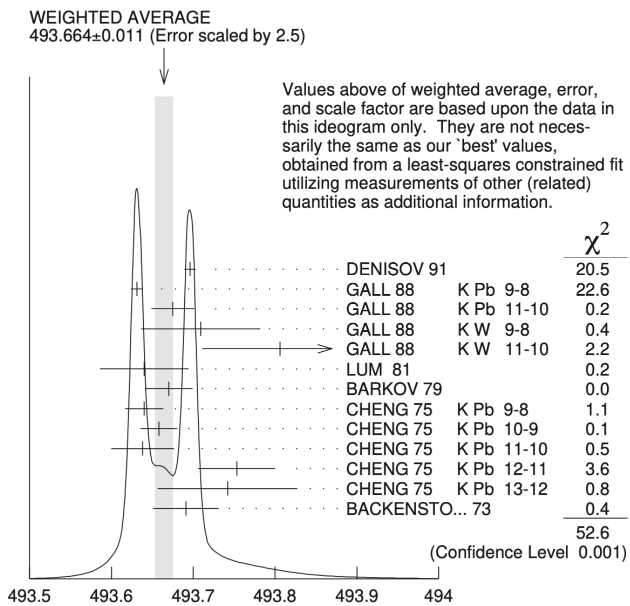
After the kaonic deuterium measurement, the collaboration proposed to exploit the ideal kaon beam produced by DAΦNE to measure selected kaonic atoms along the periodic table, for a better understanding of the low-energy strong interactions with strangeness, based on the improved precision that would be achievable by using modern X-ray detectors. With this aim, the EXKALIBUR project (EXtensive Kaonic Atoms research: from LIthium and Beryllium to URanium) was proposed.

EXKALIBUR represents a unique opportunity to provide theoreticians with a new, complete dataset on kaonic atoms that could result in an improvement in the knowledge of the strong interaction. New measurements would also provide important data for the kaon-mass measurements, new inputs for the determination of the cascade models, and important precision tests of the QED. More details on the proposal can be found in [44].

4.2. The kaon mass measurement

An open problem that EXKALIBUR is aiming to face is the determination of the kaon mass.

The two most precise measurements for the kaon mass come from kaonic atoms. In 1988, an experiment performed in Brookhaven [45], measured the charged-kaon mass starting from the high-precision measurements of the $11 \to 10$ and $9 \to 8$ transition lines of K–Pb and K–W, using three germanium detectors in a single cryostat, and exploiting these purely electromagnetic transitions to obtain a value of $m_{K^\pm} = 493.636 \pm 0.011$ MeV. Three years later, another experiment at the proton synchrotron of the Institute of High Energy Physics in Protvino, Russia [46], taking advantage of the $4 \to 3$ transition of K–C, measured the kaon mass using a crystal spectrometer, and obtained a value of $m_{K^\pm} = 493.696 \pm 0.007$ MeV, 60 keV away from the previous measurement. Up to now, the Particle Data Group (PDG) [47], reports on a weighted mean of all the measurements performed due to the disagreement between the most precise two and obtains a value of $m_{K^\pm} = 493.677 \pm 0.013$ MeV with an error scaled by 2.5. A schematic plot of the situation is reported in figure 11.



$m_{K^\pm}$ (MeV)

Fig. 11. A plot representing the value obtained from many measurements for the kaon mass and their weighted mean. Figure taken from [47].

The SIDDHARTA-2 Collaboration is exploring the possibility to precisely determine the kaon mass using purely electromagnetic kaonic atoms lines measurement with various atoms and detectors [44]. Note that an inaccurate measurement of the kaon mass also limits the precision of the kaonic atom measurements since all the transitions are dependent on the reduced mass μ. Furthermore, the precision of the kaon mass affects the systematics of other important measurements in particle physics, such as the D^0 meson mass [48].

5. Conclusions

The study of kaonic atoms is essential for the understanding of low-energy strong interactions with strangeness. Starting from the late 90s, a series of experiments utilized the ideal low-energy, quasi-monochromatic beam of kaons produced by the DAΦNE collider at the INFN-LNF. Together with the KpX experiment, the DEAR and SIDDHARTA experiments solved a puzzle that arose from the low quality of the old dataset of measurements performed between the 70s and 80s by measuring the kaonic hydrogen K_α transitions with extraordinary precision. They thus provided important information on the strong interaction between kaons and protons. The next step is to measure with SIDDHARTA-2 the kaonic deuterium transitions, providing the theoretical models input on the K–N and K–NN interactions.

The SIDDHARTA-2 Collaboration is also paving the way for dedicated kaonic atoms measurements with light, intermediate, and heavy mass. Together with the SDDs, the detectors used for the Kd measurement, the plan is to test novel cadmium–zinc–telluride detector systems for intermediate mass, and High Purity Germanium detectors for heavy-mass kaonic atoms to be used by the EXKALIBUR project.

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