

Kaonic atoms measurements at the DAΦNE Collider

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The DAΦNE electron-positron collider of the Laboratori Nazionali di Frascati of INFN is a world-wide unique low-energy kaon source, which is being used to produce and to study kaonic atoms by the SIDDHARTA collaboration. The X-ray measurements of kaonic atoms play an important role for understanding the low-energy QCD in the strangeness sector. Significant achievements have been obtained by the SIDDHARTA experiment, among which: the most precise kaonic hydrogen measurement of the $1s$ level shift and width induced by the presence of the strong interaction; an upper limit of the X-ray yield for kaonic deuterium K -series; the accurate measurement of the $2p$ level shift and width of kaonic helium-4 and kaonic helium-3; yields of various light kaonic atoms transitions. Using the experience gained with SIDDHARTA experiment, the first kaonic deuterium measurement is in preparation in the framework of the SIDDHARTA-2 experiment, with the goal to determine the antikaon-nucleon isospin dependent scattering lengths, which is possible only by combining the K^-p and the upcoming K^-d results. An overview of the experimental results of SIDDHARTA and an outlook to SIDDHARTA-2 experiments are given in this paper.

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1. Introduction

A kaonic atom is formed when a negative kaon enters a target and is slowed down to a kinetic energy of a few tens of eV by ionisations and excitations of the molecules of the target. The entering kaon is stopped inside the target and is captured by a target atom into an outer atomic orbit, in the $n \simeq 25$ excited state for kaonic hydrogen (as an example) by replacing an electron. Slowing down and capture occur on a time scale from picoseconds to nanoseconds. Then, the kaonic atom experiences a series of deexcitation processes which, at lower lying states, are dominated by X-ray emission. Finally, the kaon reaches the ground state where the strong interaction adds up to the electromagnetic one.

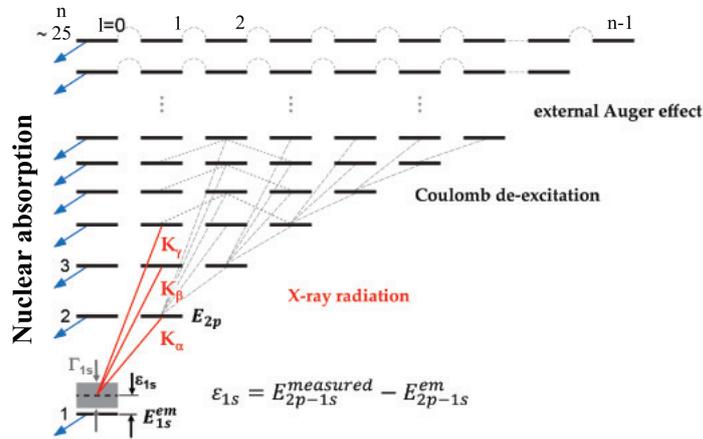


Figure 1: Cascade processes for kaonic hydrogen, starting when the kaon is captured in a highly excited state, down to the $1s$ ground state, which is shifted due to strong interaction and broadened due to nuclear absorption of the kaon by the proton. The shift and width of the $2p$ state due to strong interaction are negligible [1].

Since the atomic binding energies of light kaonic atoms are in the keV range, the kaonic atoms offer the unique opportunity to perform experiments equivalent to scattering at vanishing relative energy. This allows the study of the antikaon-nucleon/nucleus interaction “at threshold”, without the need of extrapolation to zero relative energy. Of particular interest in kaonic atoms experiments are the studies of systems formed with hydrogen isotopes, which give access to the basic low-energy physics parameters like the antikaon-nucleon scattering lengths. Kaonic deuterium enables access to the antikaon-neutron system. Other light elements provide information on how to construct the antikaon-nucleus interaction from the elementary reactions. It is noteworthy that light exotic atoms are formed almost “electron-free”, which opens the possibility for high-precision measurements, due to the absence of electron screening effect.

For the study of the strong interaction the observables of interest are the shift (ϵ) and the width (Γ) of the atomic level, caused by the strong interaction, relative to the electromagnetic value. The electromagnetic values of the energy levels can be calculated at a precision of eV by solving the Klein-Gordon equation. Even a small deviation from the electromagnetic value allows to get information of the strong interaction between the kaon and the nucleus.

In the case of kaonic hydrogen the relation between ε_{1s} and Γ_{1s} and the K^-p complex scattering length a_{K^-p} is given by the so-called Deser-Trueman formula [2, 3], where the of the isospin-breaking corrections are included [4, 5]:

$$\varepsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K^-p} [1 - 2\alpha\mu(\ln\alpha - 1)a_{K^-p} + \dots] \quad (1.1)$$

A similar formula holds for the K^-d scattering length a_{K^-d} :

$$\varepsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K^-d} [1 - 2\alpha\mu(\ln\alpha - 1)a_{K^-d} + \dots] \quad (1.2)$$

The K^-p s -wave scattering length a_{K^-p} is related to the $\bar{K}N$ isospin dependent ($I=0,1$) scattering lengths a_0 and a_1 through the average:

$$a_{K^-p} = \frac{1}{2}[a_0 + a_1] \quad (1.3)$$

In order to obtain the individual isoscalar a_0 and isovector a_1 scattering lengths one has to measure also the kaonic deuterium, which provides information on a different combination of a_0 and a_1 :

$$a_{K^-n} = a_1 \quad (1.4)$$

$$a_{K^-d} = \frac{4[m_N + m_K]}{[2m_N + m_K]}Q + C \quad (1.5)$$

where

$$Q = \frac{1}{2}[a_{K^-p} + a_{K^-n}] = \frac{1}{4}[a_0 + 3a_1]. \quad (1.6)$$

The first term in (1.5) represents the lowest-order impulse approximation (K^- scattering from each (free) nucleon of deuterium). The second term, C , includes all higher-order contributions, namely all other physics associated with the K^-d three-body interaction.

The three-body system, $\bar{K}NN$, can be studied by solving Faddeev-type equations, taking into account the dynamics of the system, namely specifying the two-body interactions.

2. The SIDDHARTA experiment at DAΦNE

DAΦNE (Double Annular Φ Factory for Nice Experiments) is a world-class electron-positron collider [6, 7] at the National Laboratories of Frascati (LNF) in Italy. DAΦNE is a unique low-energy kaon source via the decay of ϕ -mesons produced almost at rest, which decay with a probability of 48.9% in K^+K^- , with a momentum of 127 MeV/c, and a momentum spread $\Delta p/p < 0.1\%$. This “kaon beam” is intensively used for studies of the low-energy kaon - nucleon/nuclei interactions, a field still largely unexplored.

The SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by Timing Application) experiment ended its data taking campaign in November 2009, after having performed kaonic atoms transitions measurements on the upgraded DAΦNE collider.

In the SIDDHARTA experiment the monochromatic low-energy charged kaons are degraded and stopped in a cryogenic gaseous target where kaonic atoms are efficiently produced.

Fig. 2 shows a schematic view of the SIDDHARTA setup, which consisted of three main components: the kaon detector, a X-ray detection system and a cryogenic target system.

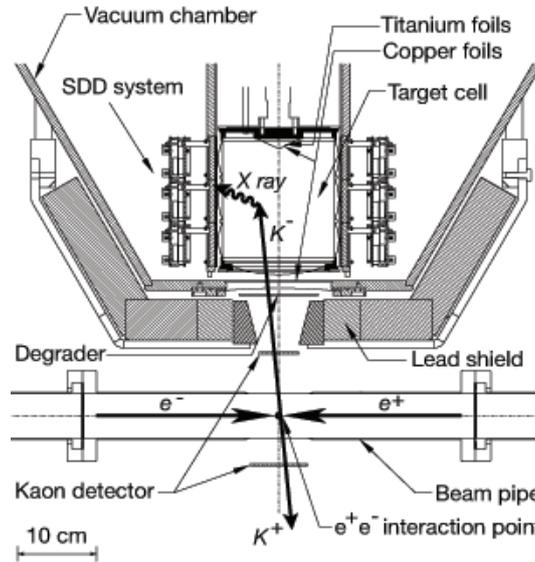


Figure 2: Schematic view of the SIDDHARTA setup [8].

The cryogenic gas-target system is a critical element of the experiment, because the yields of kaonic-atom X-rays decrease sensitively towards higher density due to collisions and Stark mixing with other atoms. For this reason it is essential to employ a low density gaseous target. The cylindrical target cell, 13.7 cm in diameter and 15.5 cm in height, was located inside the vacuum chamber and it was filled with Hydrogen at 22 K and $p = 2.5$ bar.

The kaonic atoms X-rays were detected using the Silicon Drift Detectors (SDDs). For the first time, large area SDDs, characterized by good values of energy resolution (160 eV FWHM at 6 keV) and time resolutions (800 ns), which turned out essential for the background suppression, were developed as 3×1 cm² cells on one silicon wafer, for SIDDHARTA at DAΦNE. A detailed description of the experimental setup is given in Ref.[9].

During the SIDDHARTA data taking campaign the following measurements were performed:

- kaonic hydrogen X-ray transitions to the $1s$ level, which represents the most precise measurement ever [9].
- kaonic helium4 transitions to the $2p$ level, the first measurement using a gaseous target [10], [11].
- kaonic helium3 transitions to the $2p$ level, the first measurement ever [11], [8].
- kaonic deuterium X-ray transitions to the $1s$ level - as an exploratory measurement [12].

The kaonic hydrogen spectrum together with the deuterium data used for background evaluation is shown in Fig. 3, where a global simultaneous fit of the hydrogen and deuterium spectra

was performed. Fig. 3(a) shows the residuals of the measured kaonic hydrogen X-ray spectrum after subtraction of the fitted background. K -series X-rays of kaonic hydrogen were clearly observed, while those for kaonic deuterium were not visible [9]. This appears to be consistent with the theoretical expectation of lower X-ray yield and greater transition width for deuterium.

Fig. 3 (b) and (c) show the fit result with the fluorescence lines from the setup materials and a continuous background.

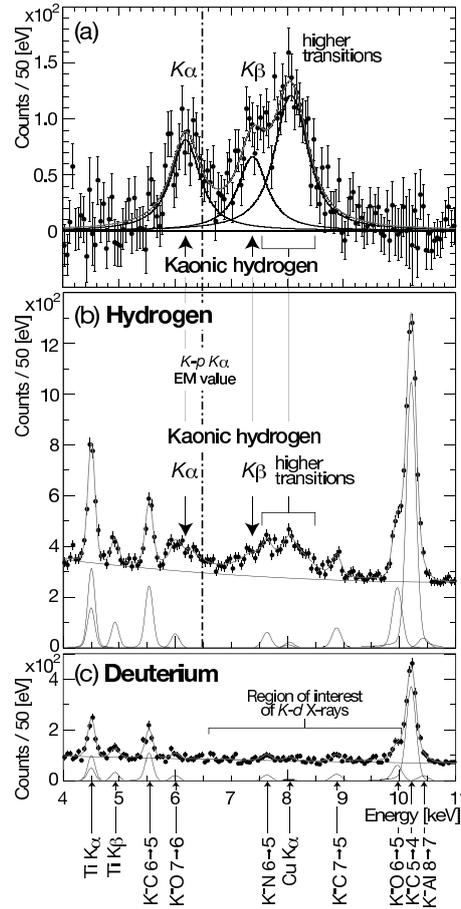


Figure 3: The global simultaneous fit of the X-ray energy spectra of hydrogen and deuterium data. (a) Residuals of the measured kaonic-hydrogen X-ray spectrum after subtraction of the fitted background, clearly displaying the kaonic-hydrogen K -series transitions. (b)(c) Measured energy spectra with the fit lines. [9].

The vertical dot-dashed line in Fig. 3 indicates the X-ray energy of kaonic-hydrogen K_{α} , calculated using the electromagnetic interaction only. Comparing the measured kaonic hydrogen K_{α} peak with the electromagnetic value, a *repulsive-type* shift (negative ϵ_{1s}) of the $1s$ -energy level turned out.

Many other lines were detected in both spectra, as indicated with arrows in the figure. These kaonic atom lines result from high- n X-ray transitions of kaons stopped in the target cell wall made of Kapton ($C_{22}H_{10}O_5N_2$) and its support frames made of aluminum. There are also characteristic X-rays from the titanium and copper foils installed for calibration.

As a result, the $1s$ -level shift ε_{1s} and width Γ_{1s} of kaonic hydrogen were determined to be [9]:

$$\varepsilon_{1s} = -283 \pm 36(stat) \pm 6(syst) \text{ eV} \quad (2.1)$$

$$\Gamma_{1s} = 541 \pm 89(stat) \pm 22(syst) \text{ eV}. \quad (2.2)$$

This is the most precise measurement performed so far of the K -series X-rays of kaonic hydrogen atoms.

The precise determination of the shift and width provides new constraints on theories, having reached a quality which demands refined calculations of the low-energy $\bar{K}N$ interaction.

For a deeper understanding of the $\bar{K}N$ interaction, it is essential to measure the kaonic-deuterium K -series X-rays to disentangle the isoscalar and isovector scattering lengths. The SIDDHARTA experiment, after performing the most precise measurement on kaonic hydrogen, made the first exploratory study of kaonic deuterium, from which the $K_d K_\alpha$ yield was extracted:

$$Y(K_\alpha) = 0.0019 \pm 0.0012 \quad (2.3)$$

Such values are compatible with what is expected, namely a yield of a factor about 10 smaller than the kaonic hydrogen yield, estimated to be between 1% to 2% for K_α . The larger absorption in the $2p$ state (larger Γ_{2p}) in the case of kaonic deuterium atoms, as compared to kaonic hydrogen, causes the lower K_α yield. The K_d spectrum is shown in Fig. 4a.

From the data analysis, the upper limits for the yields turned out (CL 90%): $Y(K_{tot}) < 0.0143$, $Y(K_\alpha) < 0.0039$ [12].

Apart of the kaonic hydrogen and kaonic deuterium measurement, the SIDDHARTA experiment measured at the DAΦNE electron-positron collider, both the $K^-^4\text{He}$ and the $K^-^3\text{He } 3d \rightarrow 2p$ transitions using gaseous targets [10, 8, 11]. The use of gaseous targets avoided the weakening of the yields due to the Stark effect and, also, the necessity to take into account the systematic uncertainty of the Compton scattering of X-rays inside the liquid helium target, which was big source of systematic errors in the previous kaonic helium-4 experiments.

Fig. 4 shows the X-ray energy spectra of different target data, (a) deuterium (2.50 g/l), (b) helium-3 (0.96 g/l), (c) helium-4 (1.65 g/l), and (d) helium-4 (2.15 g/l). Several kaonic atoms X-ray peaks are indicated for the deuterium target data. The X-rays of kaonic carbon (K^-C), kaonic nitrogen (K^-N), and kaonic oxygen (K^-O) were identified as produced from the Kapton polyimide used for the target cell and the target entrance window. The kaonic aluminum (K^-Al) was also seen. It comes from the target cell frame and the structures of the SDDs. For the data sets of helium-3 and helium-4 targets, clear L_α ($3d \rightarrow 2p$) peaks are seen. Other Balmer series X-rays can be also seen as smaller peaks. In the figure, the sum of the higher state transitions ($n > 5$) is indicated as L_{high} .

Two data sets of helium-4 targets were merged. The systematic uncertainty was calculated as the quadratic sum of the individual contributions.

The obtained values for ε_{2p} and Γ_{2p} are [10, 8, 11] :

$$K^-^3\text{He} : \varepsilon_{2p} = -2 \pm 2(stat) \pm 4(syst) \text{ eV}, \quad (2.4)$$

$$K^-^4\text{He} : \varepsilon_{2p} = +5 \pm 3(stat) \pm 4(syst) \text{ eV}. \quad (2.5)$$

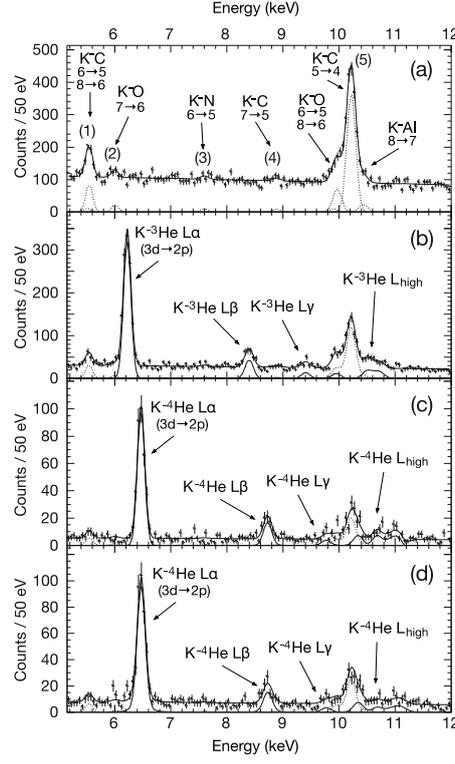


Figure 4: X-ray energy spectra of different SIDDHARTA targets data in the synchronous time window, (a) deuterium (2.50 g/l), (b) helium-3 (0.96 g/l), (c) helium-4 (1.65 g/l), and (d) helium-4 (2.15 g/l). The positions of the kaonic helium X-ray lines in (b), (c), (d) are indicated by arrows.

$$K^- \text{ } ^3\text{He} : \Gamma_{2p} = 6 \pm 6(\text{stat}) \pm 7(\text{syst}) \text{ eV}, \quad (2.6)$$

$$K^- \text{ } ^4\text{He} : \Gamma_{2p} = 14 \pm 8(\text{stat}) \pm 5(\text{syst}) \text{ eV}. \quad (2.7)$$

The $K^- \text{ } ^3\text{He}$ measurements were performed for the first time. The $K^- \text{ } ^4\text{He}$ SIDDHARTA results for ε_{2p} with gaseous target are consistent, within the errors, with the results of the KEK-PS E570 [13] with liquid target.

3. Kaonic deuterium: the SIDDHARTA-2 experiment

The kaonic deuterium X-ray measurement represents the most important experimental information missing in the low-energy antikaon-nucleon interactions field.

The experimental challenge of the kaonic deuterium measurement is the very small kaonic deuterium X-ray yield (one order of magnitude less than for hydrogen), the even larger width and the difficulty to perform X-ray spectroscopy in the high radiation environments of the machines delivering kaons.

SIDDHARTA-2 is a new experiment, which will be installed on DAΦNE in Spring 2019, taking advantage of the experience gained in the preceding SIDDHARTA experiment on kaonic hydrogen and kaonic helium.

The goal of the new apparatus is to increase drastically the signal-to-background ratio, by gaining in solid angle, taking advantage of new SDDs with improved timing, and implementing additional veto systems in order to perform the kaonic deuterium X-ray measurement. The Fig.5 shows the SIDDHARTA-2 apparatus.

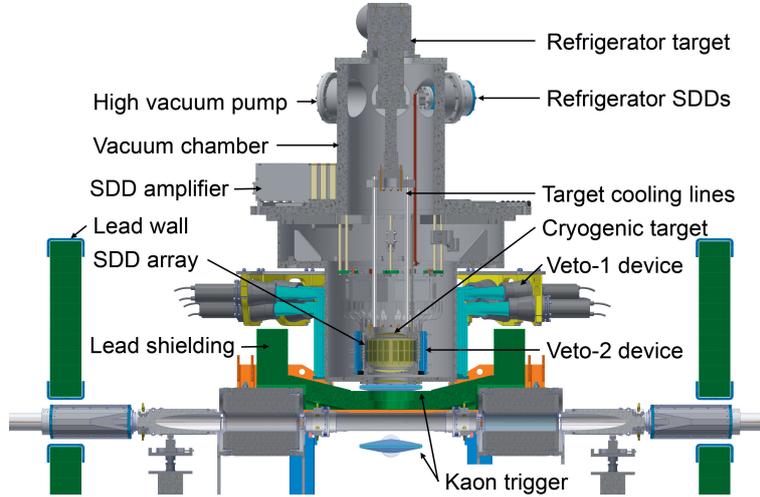


Figure 5: The SIDDHARTA-2 setup with the cryogenic target cell surrounded by the SDDs and the Veto-2 system within the vacuum chamber, while the Veto-1 device is surrounding the vacuum chamber on the outside.

A detailed Monte Carlo simulation was performed within the GEANT4 framework to optimise the critical parameters of the setup, like target size, gas density, detector configuration and shielding geometry. The Monte Carlo simulation took into account all the improvements with the following assumptions: the values of shift and width of the $1s$ ground state of kaonic deuterium are -800 eV and 750 eV, respectively; yields ratios $K_\alpha : K_\beta : K_{total}$ are those of kaonic hydrogen, with an assumed K_α yield of 10^{-3} . Fig. 6 shows the expected spectrum for an integrated luminosity of 800 pb^{-1} delivered by DAΦNE in similar machine background condition as in SIDDHARTA runs. The extracted shift and width can be determined with precisions of about 30 eV and 80 eV, respectively, similar to the SIDDHARTA results for kaonic hydrogen.

4. Conclusions

The DAΦNE collider delivers an excellent quality low-energy charged kaons beam. Such a beam was intensively used by the SIDDHARTA collaboration to perform unique quality measurements of kaonic atoms. Presently, an enlarged collaboration, SIDDHARTA-2, is upgrading the setup in order to perform the kaonic deuterium measurement. SIDDHARTA and SIDDHARTA-2 experiments on DAΦNE collider provide unique quality results for the understanding of the low-energy QCD in the strangeness sector, with implications going from particle and nuclear physics to astrophysics.

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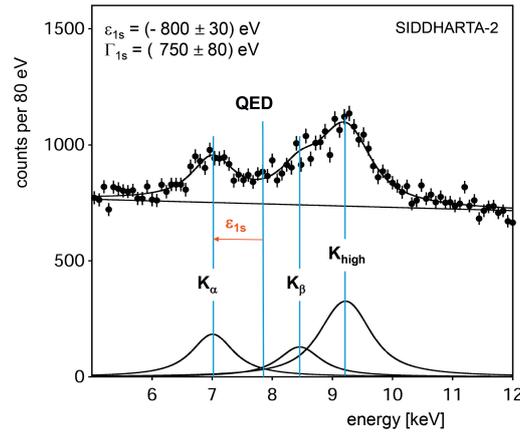


Figure 6: Simulated SIDDHARTA-2 kaonic deuterium spectrum, assuming a shift $\epsilon_{1s} = -800$ eV and width $\Gamma_{1s} = 750$ eV of the $1s$ state, as well as a K_α yield of 10^{-3} . The spectrum was simulated for an integrated luminosity of 800 pb^{-1} .

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