Kaonic atoms measurements at the DAΦNE collider: the SIDDHARTA-2 experiment

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Abstract. The X-ray spectroscopy measurements of light kaonic atoms' de-excitation towards the fundamental level provide unique information on the low-energy Quantum ChromoDynamics (QCD) in the strangeness sector, being a direct probe of the kaon/nucleon interaction at threshold, unobtainable through the scattering experiments. In this framework, the SIDDHARTA-2 collaboration is going to perform the first kaonic deuterium 2p → 1s transition measurement at the DAΦNE collider of Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Frascati. Combining this measurement with the kaonic hydrogen one performed by SIDDHARTA in 2009 it will be possible to obtain, in a model-independent way, the isospin-dependent antikaon-nucleon scattering lengths. The paper introduces the SIDDHARTA-2 setup, an upgraded version with respect to the one used for the kaonic hydrogen measurement, dedicated to the ambitious kaonic deuterium measurement, together with the preliminary results obtained during the kaonic helium run, preparatory for the SIDDHARTA-2 data taking campaign.

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1 Light kaonic atoms X-ray spectroscopy

Kaonic atoms are systems in which a negatively charged kaon (K^-) is bound to the nucleus by electromagnetic interaction. When K^- enters a target, it is slowed down by losing its kinetic energy through the interaction with the medium and is captured by an atom replacing an electron. The system is in a highly excited state given by the about thousand times higher mass of the negative meson with respect to the replaced electron. The subsequent kaonic atom cascades down to a low n-state where the strong interaction between the kaon and the nucleus adds up to the electromagnetic one. The X-ray emissions generated by the de-excitation processes provide direct information on the KN strong interaction at threshold. Therefore, kaonic atoms X-ray spectroscopy is a perfect tool to directly investigate the strong interaction in the low-energy limit, the so-called non-perturbative regime, without the need of extrapolation to zero energy as for the scattering experiments.

In this context, the X-ray spectroscopy measurements of the strong interaction induced shift and width for the 1s level of light kaonic atoms, in particular for hydrogen and deuterium, is a key tool to experimentally probe the low-energy KN interaction at vanishing energies, providing information on the relationship between spontaneous and explicit chiral symmetry breaking in low-energy Quantum ChromoDynamics (QCD). In detail, combining the most precise measurement for the kaonic hydrogen obtained by SIDDHARTA in 2009 [1] with the analogous kaonic deuterium one, it is possible to extract the K^-p and K^-d scattering lengths using the Deser–Truemann-type formulae with isospin-breaking corrections [2, 3]. The SIDDHARTA-2 collaboration has built an upgraded experimental apparatus with respect to the SIDDHARTA one, making use of new veto and Silicon Drift Detectors (SDDs) systems, with the aim to perform the unprecedented kaonic deuterium precision X-ray spectroscopy measurement. The setup is presently installed at the DAΦNE collider of Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Frascati (INFN-LNF), ready to measure the kaonic deuterium 1s level shift (ϵ) and width (Γ), important for a deeper understanding of the non-perturbative QCD in the strangeness sector, with implications from particle and nuclear physics to astrophysics [4]-[7].

2 The SIDDHARTA-2 experiment at the DAΦNE collider

The DAΦNE electron–positron collider at INFN-LNF [8, 9] generates K^--K^+ beams through the decay of the Φ-meson, with a branching ratio of about 50%. The INFN-LNF DAΦNE Φ-factory is unique in the world, since it provides an excellent quality low-energy and monochromatic K^- beam (16 MeV of kinetic energy, 0.1% energy spread) suitable to perform high precision kaonic atoms spectroscopy measurements. This beam has been used during the successful SIDDHARTA run in 2009 [10, 11]. SIDDHARTA-2, a major upgrade of SIDDHARTA setup, is presently installed at the DAΦNE collider, ready to perform the kaonic deuterium measurement with a precision comparable to the kaonic hydrogen measurement.

Figure 1 shows a schematic view of the SIDDHARTA-2 experimental apparatus (top) and the cross section layout of the target (bottom).

The major upgrades of the SIDDHARTA-2 setup are briefly, the following ones:

Luminometer: plastic scintillators read by Photo-Multipliers (PMs) placed on the lateral sides of the IR (Interaction Region), used to evaluate the beams' quality in terms of luminosity and background [12].

Target cell: the monochromatic, low-energy charged kaons are degraded and then stopped in a cryogenic gaseous target, producing kaonic atoms. The target is a critical item, since both its geometrical structure and the density gas density (temperature and pressure) must be optimized to maximize the kaonic atom X-ray signal. The cylindrically shaped target cell, with 75 μm thick Mylar wall reinforced by high purity aluminium bars, operates at around 30 K and a working pressure for the deuterium gas of 0.4 MPa (around 3% of Liquid Hydrogen Density, LHD).

SDDs and Front End Electronic (FEE): 48 large area fast SDDs detector array (2 x 4 matrix) are arranged in a head-to-head configuration all around the target cell, covering a total active surface of 245.76 cm^2. The 450 μm thick Silicon wafer is glued on a ceramic carrier which provides the polarization to the units, each one connected to the proper preamplifier (CUBE), then the signals are processed by a dedicated FEE (SFERA, [13, 14]). The SDDs system's spectroscopic response in terms of linearity, stability, energy and timing resolutions, has been proved to be suitable for high precision kaonic atoms X-ray spectroscopy [15]-[17].

Veto-1 system: scintillators read by PMs which externally surround the SIDDHARTA-2 vacuum chamber [18]. The functioning is based on the kaon moderation time in the gas, which is longer than the corresponding one in solid elements of the setup. Additionally, it allows the rejection of the background, both synchronous and asynchronous to the beams.

Veto-2 system: scintillators read by Silicon Photo-Multipliers (SiPMs) placed behind the SDDs [19], are used to reject the hadronic background coming from border hits of Minimum Ionizing Particles (MIPs), depositing energy in the X-ray range.

Kaon trigger: scintillators used as a trigger on K^--K^+ pairs from DAΦNE, to suppress the asynchronous (i.e. electromagnetic) background applying a timing window selection in coincidence with the SDDs' X-ray signals.

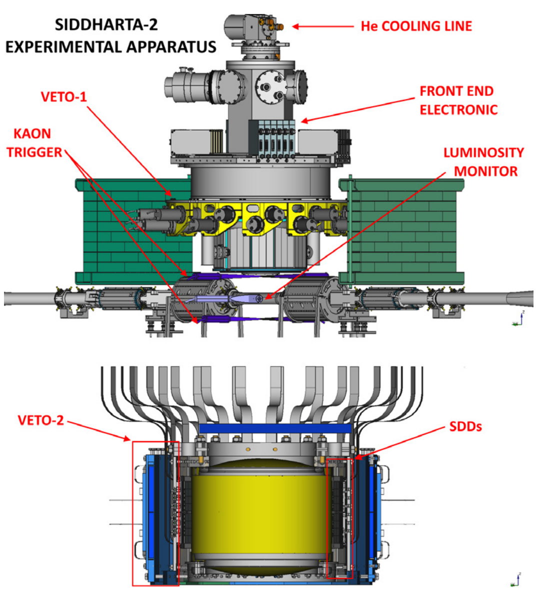

Figure 1. Top: Schematic view of the SIDDHARTA-2 experimental apparatus installed at the Interaction Region of the DAΦNE collider. Bottom: Cross section layout of the SIDDHARTA-2 target cell, red box highlights the SDDs arrays and the scintillators of the veto-2 behind them.

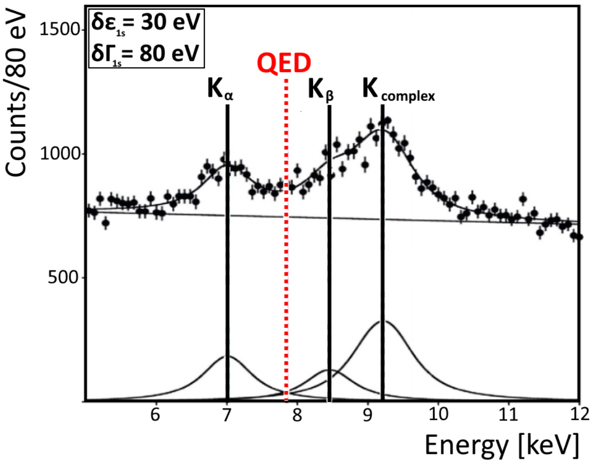

Figure 2. Simulated K-d Monte Carlo spectrum corresponding to an integrated luminosity of 800 pb^{-1}, assuming ϵ1s = -800 eV, and Γ1s = 750 eV and a yield of 0.1%. The red-dotted line at 7834 eV corresponds to the pure QED value. The precision (δ) on the shift and the width of the Kα peak resulting from the fit are reported on the top left inset

All the mentioned items have been included in the SIDDHARTA-2 GEANT4 simulation for 800 pb^{-1} acquired integrated luminosity, taking as input parameters: a yield of 0.1% of the 2p to 1s transition and a shift and width of -800 eV and 750 eV, respectively, from theoretical calculations [20, 21]. The fit on the Monte Carlo simulated signal shown in Figure 2 indicates that the K$^-$d 1s level, modified by the strong interaction, can be determined with a precision of 30 eV for the shift ($\delta\epsilon$) and 80 eV for the width ($\delta\Gamma$). These precisions are comparable to those obtained for the kaonic hydrogen by SIDDHARTA.

3 Preliminary to SIDDHARTA-2: the SIDDHARTINO run

During the DAΦNE commissioning phase, preparatory for the kaonic deuterium data taking campaign, the SIDDHARTA-2 experimental apparatus has been installed housing 8 out of 48 SDDs arrays, in a reduced configuration called SIDDHARTINO. During this phase, concluded with the kaonic helium run in July 2021, the main SIDDHARTA-2 functionalities have been successfully tested.
The luminometer continuously monitored the beam quality for all the period, measuring the number of kaons generated in e^--e^+ collisions. Figure 3 (top) shows, as an example, the 2D-plot of the Time-to-Digital Converter (TDC) coincidence signals detected on the scintillators placed respectively on the internal ([TDC1+TDC4]/2) and external ([TDC2+TDC3]/2) side of the Interaction Region (IR). On the diagonal, the signals related to the MIPs are well separated from the kaons: the violet circles highlight the coincidence signals generated by all the particles lost from the e^- and e^+ bunches, while the red circles point out the hits associated to the kaons. The hits of the particles belonging to the bunches out from collision are, instead, distributed outside the diagonal. The projection in time of the diagonal elements allows to determine the number of kaons produced and to obtain a direct indication of the machine background.

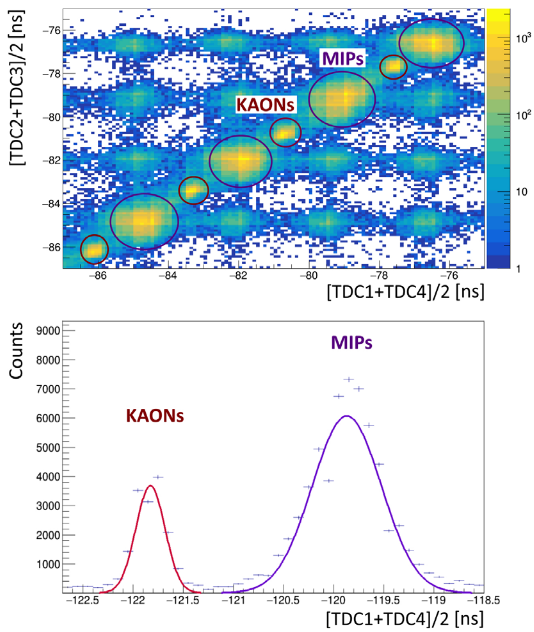

Figure 3. Top: 2D-plot of the TDCs coincidence detected on the internal ([TDC1+TDC4]/2) and external ([TDC2+TDC3]/2) side of the luminometer: red and violet circles indicate, respectively, the kaons and MIPs distributions. Bottom: Gaussian fit of the kaons and MIPs peaks on a timing selection of the 2D-plot diagonal projection.

Figure 3 (bottom) reports an example of the Gaussian fits of the kaons and MIPs signals referring to a selection of the diagonal elements of figure 3 top, used to obtain the number of kaons generated in the collision, compared to the background.
The continuous on-line feedback on the quality of the beams in terms of Kaons-over-MIPs ratio provided by the luminosity monitor, played a key role during all the DAΦNE beams optimization phase.
After having reached a satisfactory condition in terms of kaon signal over background ratio, the SIDDHARTINO data taking campaign has been concluded with the K^-He^4 measurement. Figure 4 reports, the preliminary calibrated spectrum for a subset of 6 pb^{-1} integrated luminosity, applying a 2μs timing cut on the SDDs' X-ray events in coincidence with the Kaon trigger signals to reject the asynchronous background. The calibrated spectrum clearly shows the K^-He^4 peak at around 6.4 KeV and satellite peaks given by the K^- interaction with the elements of the setup, namely the Carbon from the Kapton target walls and the Titanium placed at the top of the target cell.

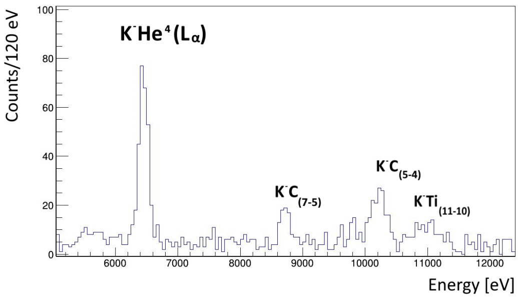

Figure 4. Preliminary calibrated SIDDHARTINO spectrum for 6 pb^{-1} integrated luminosity applying 2μs timing cut on the triggered events.

4 Conclusion

The SIDDHARTA-2 collaboration is prepared to perform the first ambitious kaonic deuterium precision X-ray spectroscopy measurement at the DAΦNE collider of LNF-INFN. In order to achieve this result, a dedicated experimental apparatus has been built and all the integrated systems have been successfully tested during the collider beam optimization phase, concluded with the measurement of the K^-He^4. The SIDDHARTA-2 kaonic deuterium data taking campaign is planned for 2021-2022. In the same time, the collaboration is developing new detector technologies and future proposals dedicated to kaonic atom measurements along the periodic table, for a deeper understanding of the QCD theory, with implications in astrophysics, particle and nuclear physics.

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