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HIGH PRECISION KAONIC ATOMS X-RAY SPECTROSCOPY AT THE DAΦNE COLLIDER: THE SIDDHARTA-2 EXPERIMENT

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Abstract. *X-ray spectroscopic measurements on light kaonic atoms are fundamental tool for the investigation of the low-energy quantum chromodynamics (QCD) in the strangeness sector, being a direct probe of the kaon-nucleus interaction at threshold without the need of an extrapolation at low energy as in the case of scattering experiments. In this framework, after the successful measurement of the kaonic hydrogen X-ray transition to the fundamental level in 2009, the SIDDHARTA-2 Collaboration is now ready to perform the first measurement of kaonic deuterium 2p -> 1s transitions, planned for 2021 – 2022 at LNF-INFN. This paper describes the SIDDHARTA-2 scientific case and the experimental apparatus installed in its reduced form called SIDDHARTINO at the DAΦNE collider, during the preparatory run before the kaonic deuterium data taking campaign.*

Keywords: *Kaonic atoms, Nuclear physics, SIDDHARTA-2 experiment, X-ray spectroscopy*

1. LIGHT KAONIC ATOMS X-RAY SPECTROSCOPY AT THE DAΦNE COLLIDER

A kaonic atom is formed when a negatively charged kaon (K^-) enters a target, it is slowed down through the interaction with the medium and then, after the capture by an atom replacing an electron, is bound to the nucleus by the electromagnetic interaction. Being the kaon mass almost thousand times higher than the electron one, the kaonic atom is formed in a highly excited state; thus, the 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.

This additional interaction introduces a shift on the atomic level binding energy with respect to the purely electromagnetic value given by the Quantum ElectroDynamics (QED). The spectroscopic measurements of the X-ray emissions generated by the de-excitations of kaonic atoms allow to get information on the strong interaction between the hadron and the nucleus, determining the shift (ε) and the width (Γ) of the atomic levels caused by the strong interaction. These observables are fundamental quantities for the understanding of the Quantum ChromoDynamics (QCD) in the non-perturbative regime in the

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strangeness sector, with implications from particle and nuclear physics to astrophysics (equation of state of neutron stars) [1-4].

In 2009, the SIDDHARTA collaboration performed a successful X-ray spectroscopy measurement on kaonic hydrogen (K^-H) at the DAΦNE (Double Annular Φ Factory for Nice Experiments) collider of Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Frascati (LNF-INFN). The results obtained are still the most precise values of shift and width for the K^-H Kα transitions [5-6].

Nowadays, the SIDDHARTA-2 experiment is going to perform, for the first time, the analogous and more challenging measurement of the kaonic deuterium (K^-d). The X-rays emission measurements of the K^-H and K^-d transitions to the fundamental levels, allow to extract the K^-p and K^-d scattering lengths through the Deser-Treumann type formulae with isospin breaking corrections [7-8]. Then, the antikaon-nucleon isoscalar and isovector scattering lengths, fundamental quantities to understand the QCD in the non-perturbative regime in the strangeness sector, can be obtained.

The SIDDHARTA-2 experimental apparatus is presently installed at the DAΦNE collider of LNF-INFN, in its reduced configuration called SIDDHARTINO.

2. THE SIDDHARTA-2 EXPERIMENTAL APPARATUS

DAΦNE is a world-class electron-positron collider at LNF-INFN [9-10], which delivers a unique low-energy and collimated kaon beam, via the decay of Φ-mesons, with a momentum (p) of 127 MeVc^{-1} ($\delta p/p < 0.1\%$). Thus, the kaon produced by the collider is used to generate the kaonic atoms as results of the capture process within the target. The SIDDHARTA-2 experimental apparatus installed at the collider Interaction Region (IR) has been consistently improved with respect to the K^-H experiment, allowing to perform the more challenging K^-d 2p -> 1s transition measurement, characterized by an extremely low yield (≈10% of the analogous K^-H transition to the ground state [5]), with a precision similar to the kaonic hydrogen one. The SIDDHARTA-2 setup increases the signal by gaining in solid angle, thanks to the new Silicon Drift Detectors (SDDs) system geometry, and reduces the background thanks both to the faster SDDs response and to the veto systems.

In detail, the experimental apparatus, shown in Fig. 1, consists of an Aluminum vacuum chamber shaped to fit in the interaction point minimizing the distance between the internal target and beam pipe, allowing the placement of 48 SDDs arrays. The cylindrical shape target cell consists of a high purity aluminum structure with 75µm thick Mylar walls. The target is filled with the deuterium gas and cooled through a closed cycle helium refrigerator below 30 K for a final pressure of 0.4 MPa, optimizing the kaon stopping efficiency. The SDDs system is placed all around the target cell; each 2x4 detector matrix has an active area of 5.12 cm^2 (single cell active area is 0.64 cm^2) and the devices are arranged in a head to head configuration, to maximize the mechanical solidity, the geometrical efficiency and to lower the heat power consumption of the front end electronics. The target refrigeration system cools the detectors below 170 K to improve their spectroscopic response.

The SDDs have been optimized in the laboratory and then the SIDDHARTA-2 SDDs system (detectors and front end readout) has been tested in the collider background experimental condition, proving to be suitable to perform high precision X-ray spectroscopy measurements [11-13].

The scintillators systems (Veto-1 and Kaon trigger) play a fundamental role in terms of background rejection: the L-shaped scintillators [14] arrangement outside the vacuum chamber is an efficient hadronic background rejection system, allowing to identify the high energy particle emitted by kaon nuclear absorption processes with the materials of the setup. Below the vacuum chamber, the system made by a couple of scintillators placed on the vertical direction of the beam pipe, able to detect the K^+K^- pairs emitted by the decay of the Φ meson, acts as trigger allowing an efficient electronic background rejection by applying a timing window selection accordingly to the fast SDDs response.

Fig. 1b shows the Monte Carlo simulation performed through GEANT4 for an acquired luminosity of 800 pb^{-1} after the optimization of each element of the setup, assuming an yield of 0.1%.

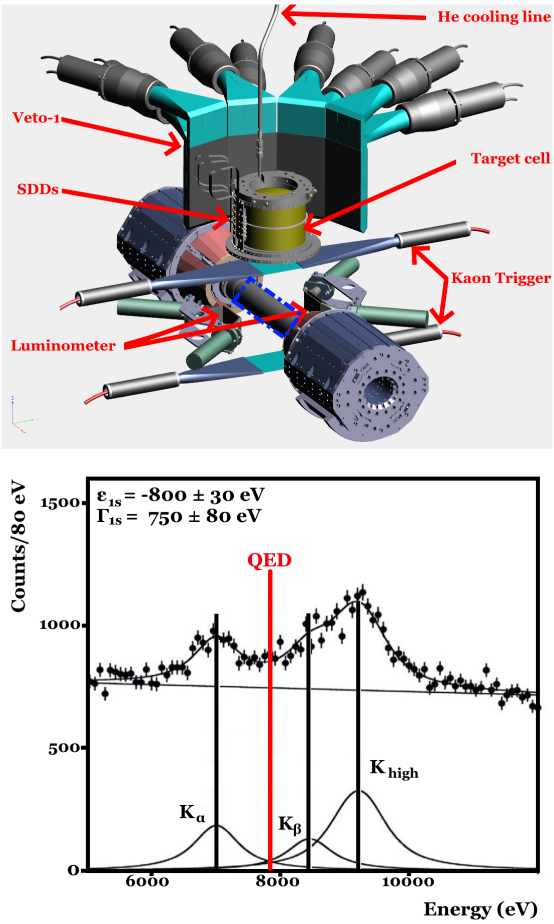

Figure 1. Top: Drawing of the SIDDHARTA-2 setup. The dotted-line box indicates the DAΦNE collider beam pipe. Bottom: expected SIDDHARTA-2 K^-d spectrum for an integrated luminosity of 800 pb^{-1} simulated by GEANT4, considering the theoretical values [8-15] of ε_{1s} = −800 eV and Γ_{1s} = 750 eV. The red line at 7834 eV corresponds to the pure QED K_{α} value.

The fit of K^-d simulated spectrum indicates that both ε_{1s} and Γ_{1s} can be evaluated with a precision comparable to the kaonic hydrogen measurement performed by SIDDHARTA.

Lastly, the luminometer [16] made by a couple of scintillators placed on the lateral side of the beam pipe measures the back – to – back kaons produced by the e^+ - e^- collision at the energy of the Φ-meson resonance. It provides a fast and constant information both on the beam quality (kaons/MIPs) and the luminosity (instantaneous and integrated) delivered by the machine.

3. THE SIDDHARTINO RUN

The SIDDHARTA-2 experimental apparatus has been installed in DAΦNE in a reduced configuration named SIDDHARTINO (8 SDDs arrays out of 48), during the collider e^+ - e^- beams optimization, concluded with the K^-He^4 measurement.

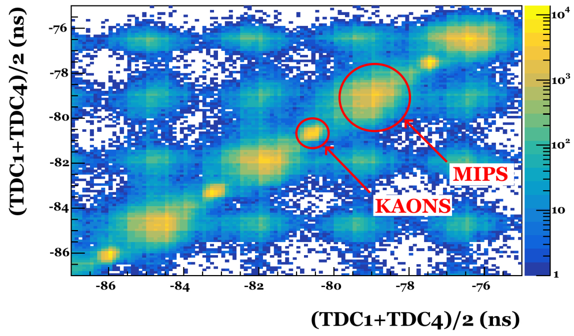

Figure 2. 2D-plot of the TDCs coincidence detected on the boost ([TDC1+TDC4]/2) and anti-boost ([TDC2,TDC3]/2) side of the luminometer.

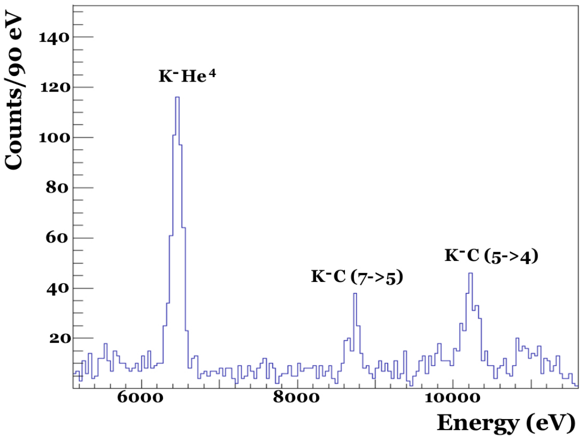

Figure 3 Preliminary SIDDHARTINO spectrum corresponding to 10 pb^{-1} acquired with the target filled with He^4

All the SIDDHARTA-2 systems have been successfully tested. The luminometer continuously monitored the beam quality delivering also fundamental information for the collider operation during the optimization phase. Fig. 2 shows, as an example, the luminometer 2D-plot of the TDC coincidence signals detected on the scintillators placed respectively on the boost ([TDC1+TDC4]/2, internal machine) and anti-boost ([TDC2+TDC3]/2, external machine) sides of the IR. On the diagonal, the MIPs distributions generated by all the particles lost from the e+ and e- bunches, are well separated from the kaons. The distributions out from the diagonal, instead, refer to hits of particles belonging to bunches out from collision.

The SIDDHARTINO data taking campaign has been concluded with the K^-He^4 measurement and Fig. 3 reports, as example, the preliminary spectrum for 10 pb^{-1} integrated luminosity after the rejection of the asynchronous background. The spectrum clearly shows the K^-He^4 peak at around 6.4 KeV, together with satellites peaks given by the K^- interaction with the elements of the setup.

4. CONCLUSIONS

The SIDDHARTA-2 collaboration is going to perform for the first time the challenging kaonic deuterium high precision X-ray spectroscopy measurement. In order to achieve this unprecedented result, a dedicated experimental apparatus has been built and it is now installed at the DAΦNE collider of LNF-INFN. All the experimental apparatus systems have been tested during the collider beam optimization phase, successfully concluded with the measurement of the K^-He^4. Thus, the SIDDHARTA-2 collaboration is now ready to start the kaonic deuterium data taking campaign, planned for 2021-2022.

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