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Towards the first kaonic deuterium measurement with the SIDDHARTA-2 experiment at DAΦNE

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Summary. — The SIDDHARTA-2 experiment is going to perform the long-awaited high precision X-ray measurement of kaonic deuterium, obtaining for the first time the values of the shift and the width induced by the strong interaction on the fundamental level. By combining this unprecedented result with the analogous kaonic hydrogen measurement performed by the SIDDHARTA experiment, it will be possible to extract the isospin-dependent antikaon-nucleon scattering lengths, providing direct information on the Quantum Chromodynamics (QCD) in the non-perturbative Chromodynamics (QCD) in the non-perturbative regime in the strangeness sector. This paper describes the SIDDHARTA-2 experiment, presently installed at the DAΦNE collider of Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati, and the results obtained during the kaonic helium run, preparatory for the kaonic deuterium data taking campaign planned for 2022.

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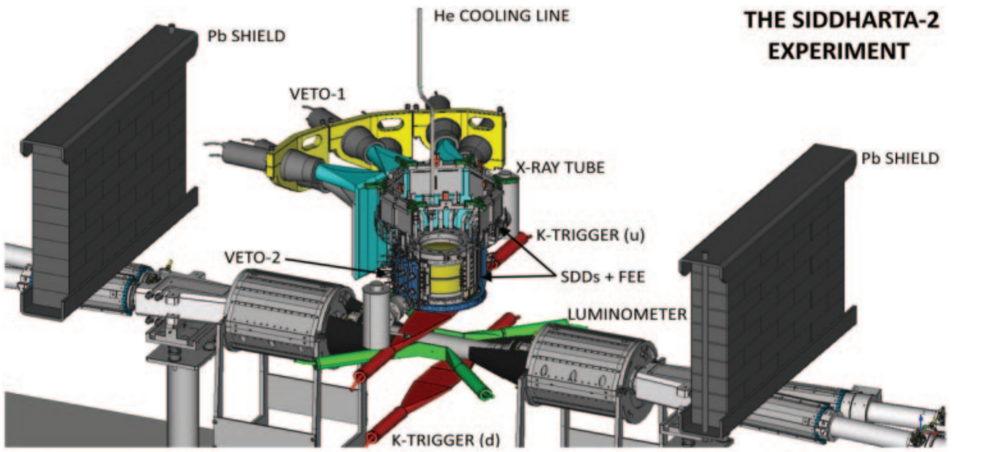

Fig. 1. – Layout of the SIDDHARTA-2 setup installed at the Interaction Region of the DAΦNE collider.

1. – The SIDDHARTA-2 experiment at DAΦNE

In kaonic atoms, a negatively charged kaon (K^-) is captured in a highly excited state, replacing an electron, and is bound to the nucleus by the electromagnetic interaction. In light kaonic atoms such as kaonic hydrogen (K^-H) and kaonic deuterium (K^-d), the de-excitation processes reach the fundamental level, where the strong interaction between the kaon and the nucleus adds up to the electromagnetic one. The precise measurement of the K^-H and K^-d 1s level shift (ε) and width (Γ) induced by the strong interaction allows the direct experimental determination of the isospin-dependent antikaon-nucleon scattering lengths [1], which are fundamental quantities for understanding the Quantum Chromodynamics (QCD) in the non-perturbative regime in the strangeness sector. In this context, after the most precise measurement to date of the K^-H 1s level performed by SIDDHARTA [2], the SIDDHARTA-2 Collaboration aims to perform the analogous, much more challenging kaonic deuterium measurement, with a precision comparable to the kaonic hydrogen one.

Figure 1 shows the layout of the SIDDHARTA-2 setup installed at the DAΦNE collider [3, 4] of Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati (INFN-LNF).

Inside the vacuum chamber, the cryogenic target cell made of Kapton walls and reinforced with aluminium supports is filled with deuterium gas kept at 30 K and 0.4 MPa to optimize the kaons stopping efficiency and X-ray yield. 48 large area Silicon Drift Detectors (SDDs) arrays are placed all around the target cell, covering an active area of 245.8 cm^2. The signals detected by the SDD units are processed by the dedicated low-noise Front End Electronic (FEE), named SFERA [5, 6], which ensures an excellent spectroscopic response in terms of linearity, stability and energy resolution [7]. In order to reject the events generated by the Minimum Ionizing Particles (MIPs) hitting on the detectors borders, a veto-2 system [8] made of plastic scintillators read by Silicon Photo-Multipliers (SiPMs) is placed behind the SDDs.

Outside the vacuum chamber, two systems of plastic scintillators read at both ends by PMs, namely the veto-1 [9] (cyan) and the kaon trigger (red), are used to suppress, respectively, the hadronic background generated by the kaon absorption processes, and the machine electromagnetic background, asynchronous with the $K^- - K^+$ pairs emitted by the ϕ decays in the vertical plane, where the setup is installed.

On the horizontal plane, the luminometer (green), made of plastic scintillators read by PMs, evaluates the collider performances [10]. Lastly, a system consisting of two X-ray tubes shining on a multi-elemental target is employed for the SDDs' *in situ* calibration.

The dedicated GEANT4 simulation [11], performed including all the optimized SIDDHARTA-2 elements, shows that the SIDDHARTA-2 experiment is expected to measure the kaonic deuterium X-ray transitions with a precision comparable to the kaonic hydrogen one for an integrated luminosity of 800 pb^{-1}.

2. – Towards the kaonic deuterium run

During the DAΦNE collider beam optimization phase, the SIDDHARTA-2 main functionalities were tested with a reduced version of the experimental apparatus (8 SDD arrays out of 48), named SIDDHARTINO. Besides the laboratory tests [7, 12], the SDD system has been proved to be suitable to perform high precision kaonic atoms X-ray spectroscopy measurements, thanks to its linear response at the level of few eV and energy resolution compatible with the low-noise Silicon-based detectors, also in the collider hard experimental environment [13]. During this phase, the luminosity monitor constantly provided an on-line feedback on the beam quality (kaons over MIPs ratio) supporting the machine optimization during the process of reaching satisfactory conditions in terms of luminosity and background. The SIDDHARTINO run was concluded in July 2021 with the $\mathrm{K^-He^4L_\alpha}$ transition measurement [14], together with the qualification of the system's spectroscopic response [15] during this first kaonic atom run performed by the SIDDHARTA-2 experiment at the DAΦNE collider.

Figure 2 shows, as an example, the results obtained for a data sample equivalent to $\simeq 1\ \mathrm{pb}^{-1}$ integrated luminosity during the $\mathrm{K^-He^4}$ run performed for the first time with the complete SIDDHARTA-2 experimental apparatus which was installed at DAΦNE in summer 2021. The red circles on the kaon trigger 2D plot (top-right inset), given by the coincidence signals detected on the two scintillators, define the signals associated to the kaons. The $\mathrm{K^-He^4\ L_\alpha}$ line is clearly visible in the spectrum, after having applied a timing cut on the SDD signals synchronous to the K-trigger detected kaons.

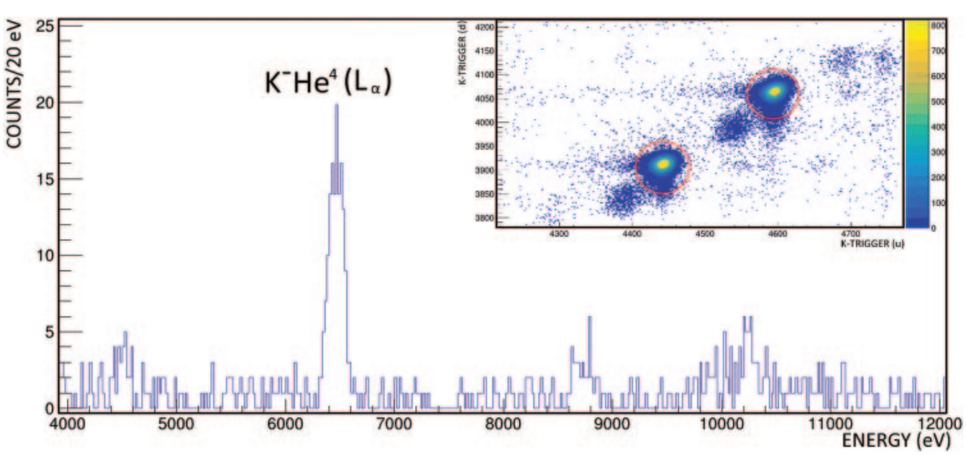

Fig. 2. – Preliminary calibrated spectrum of the first $\mathrm{K^-He^4}$ $\mathrm{L}\alpha$ transition measurement performed with the SIDDHARTA-2 experimental apparatus at the DAΦNE collider. On the top right inset, the kaon trigger 2D plot given by the coincidence signals detected by the scintillators allows the kaon selection (red circles).

3. – Conclusions and outlooks

The SIDDHARTA-2 experiment aims to perform the unprecedented K^-d 2p→1s transition measurement at the DAΦNE collider of INFN-LNF, with a precision comparable to the analogous results for the K^-H one obtained by SIDDHARTA. The solid spectroscopic response of the SIDDHARTA-2 experimental apparatus was demonstrated during the machine commissioning phase, concluded in July 2021 with the successful K^-He^4 L_α measurement performed by SIDDHARTINO. Nowadays, the SIDDHARTA-2 experiment is ready to start the kaonic deuterium data taking campaign, planned for 2022, to obtain the still missing information needed to extract the isospin-dependent antikaon-nucleon scattering lengths.

Meanwhile, the SIDDHARTA-2 Collaboration is proposing and planning new challenging kaonic atom measurements [16] for light and heavy atoms along the periodic table, which would allow deeply investigating the low-energy strangeness QCD in detail, with implications from nuclear and particle physics to astrophysics [17-19].

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