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Low energy kaon-nuclei interaction at DAΦNE: The SIDDHARTA-2 experiment

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Summary. — Light kaonic atoms spectroscopy is a unique tool for the investigation of the low-energy quantum chromodynamics (QCD) in the strangeness sector. The precise measurements of the X-ray emission from light kaonic atoms provide information on the kaon-nucleus interaction at threshold without the need of an extrapolation as in the case of scattering experiments. In 2009, the SIDDHARTA Collaboration performed the most precise measurement of kaonic hydrogen (K^-H) X-ray transition to the fundamental level. Nowadays, the SIDDHARTA-2 Collaboration is ready to perform the more challenging measurement of kaonic deuterium (K^-d) 2p $\rightarrow$ 1s transition. To achieve this unprecedented result, which is fundamental to extract the isospin-dependent antikaon-nucleon scattering lengths, an upgraded experimental apparatus with respect to the SIDDHARTA one was realized. This paper presents an overview on the SIDDHARTA-2 setup installed on the DAΦNE collider of LNF-INFN and the first results obtained during the machine optimization phase, in preparation for the kaonic deuterium data taking campaign planned in 2021–2022.

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1. – Introduction

A kaonic atom is formed when a negatively charged kaon (K^-) is captured in a highly atomic excited state, replacing an electron, being bound to the nucleus by electromagnetic interaction. The excited 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. In the light kaonic atoms, such as the kaonic hydrogen (K^-H) and kaonic deuterium (K^-d), the kaon cascade process reaches the fundamental level, which allows to extract the shift (ϵ) and width (Γ) of the 1s level induced by the strong interaction. The precise measurement of these observables brings to the direct experimental determination of the isospin-dependent antikaon-nucleon scattering lengths [1, 2], which are fundamental quantities for understanding the low energy QCD in the strangeness sector, having also important impact in astrophysics (equation of state of neutron stars).

After the important result achieved by the the SIDDHARTA Collaboration in 2009, the most precise measurement of ϵ and Γ for the K^-H fundamental level, the SIDDHARTA-2 experiment is going to perform the analogous first K^-d measurement. To achieve the goal, given the one order of magnitude lower expected yield of the K^-d [3], the SIDDHARTA-2 Collaboration will take advantage both of a completely upgraded setup with respect to SIDDHARTA and the excellent properties of the kaon beam provided by the upgraded DAΦNE collider [4, 5] at Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati (LNF-INFN), Italy.

2. – The SIDDHARTA-2 experiment at the DAΦNE Collider

The DAΦNE (Double Annular Φ Factory for Nice Experiments) electron-positron collider provides, through the decay of Φ-mesons, a kaon beam with unique properties in terms of low-momentum ($p = 127\,\mathrm{MeV/c}$) and energy spread ($\delta p/p$) below 0.1%.

The cross section layout of the SIDDHARTA-2 apparatus is shown in fig. 1, left. A cryogenic target cell, made by Kapton walls and reinforced with aluminium supports, is operated below 30 K at a pressure of 0.4 MPa (3% LHD), optimizing the kaon stopping efficiency and the X-rays yield. The target cell is shaped to allow the placement of 48 new technology Silicon Drift Detectors (SDDs) arrays [6], for a total active area of 245.8 cm^2. A series of plastic scintillators [7] are placed all around the target cell for an efficient rejection of the experimental background. In detail, the external (Veto-1) and internal (Veto-2) scintillator systems are fundamental to reject the radiation generated by the nuclear processes within the target cell; below the target cell, the plastic scintillators working in coincidence mode on the vertical plane with respect to the beam pipe (kaon trigger), are used to suppress the electromagnetic background.

Each element of the setup has been optimized using a dedicated GEANT4 simulation taking as starting values the theoretical calculations [8, 9] and assuming a yield of 0.1% for the K_α transition [3]. The fit resulting from the Monte Carlo simulation indicates that both ϵ_{1s} and Γ_{1s} can be evaluated with a precision comparable with the K^-H measured by SIDDHARTA.

The SIDDHARTA-2 apparatus is presently collecting data during the DAΦNE commissioning phase, preparatory for the kaonic deuterium data taking campaign. During this phase, the energy response of the SDDs system has been tested in the more stressful and realistic environment with respect to the laboratory tests [6]. Figure 2, left shows a typical calibrated spectrum collected by a SDDs system unit using photons emitted by a multi-elemental target excited by an X-ray tube placed below the SIDDHARTA-2

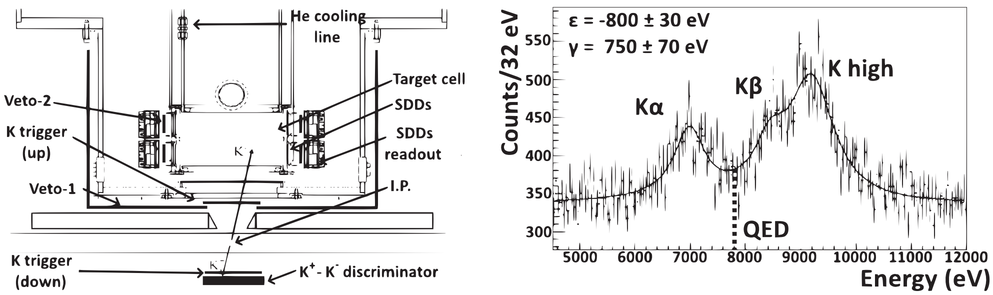

Fig. 1. – Left: cross section layout of SIDDHARTA-2 setup. Right: Monte Carlo simulation of K⁻d corresponding to an integrated luminosity of 800 pb^{-1} (with input $\epsilon_{1s} = -800$ eV, $\Gamma_{1s} = 750$ eV and yield = 0.1%). Dot line at 7834 eV refers to the pure QED K_α value.

vacuum chamber. The energy resolution at 170 K for the Fe K_α line is 166 ± 4 eV, a typical value for the low-noise silicon devices. On the right, the residual plot obtained by the linear ADC-to-eV conversion reveals an uncorrelated distribution equally distributed around zero, differing only few eV from the ideal linear case. The good energy resolution and linear response ($\Delta E/E < 10^{-3}$) of the SDD system, measured with the hard background of the collider, are key features for performing the high-precision K⁻d X-ray spectroscopy measurement.

On the lateral sides of the collider bream pipe, the SIDDHARTA-2 luminometer [10] continuously monitors the quality of the beams during the DAΦNE commissioning phase, providing the luminosity for each collider beam cycle. Figure 3, right reports, as an example, the intensity of the beams registered for three beam cycle during the first tests with the machine configuration in collision mode.

The luminosity in fig. 3, right has been evaluated, considering the overall system efficiency, within time intervals of 2 minutes, excluding the high background condition during the beam injection phase. For each beam cycle the luminosity decreases accordingly to the lifetime of the electron and positron beam currents. The estimated mean luminosity value is $L = 3.3 \times 10^{31}$ cm^{-2} s^{-1}. The luminometer analysis provides a fast feedback on the beam quality, playing an important role during the present beam optimization phase [10].

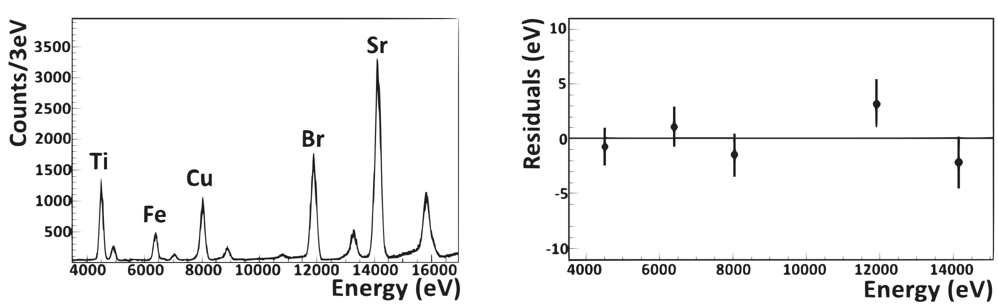

Fig. 2. – Left: example of an SDD calibrated spectrum collected with an X-ray tube, during the DAΦNE beam commissioning phase. Energy resolution at 170 K for the Fe K_α line is 166 ± 4 eV. Right: the linear response of SDDs system is $\Delta E/E < 10^{-3}$ in the range of 4000–14000 eV.

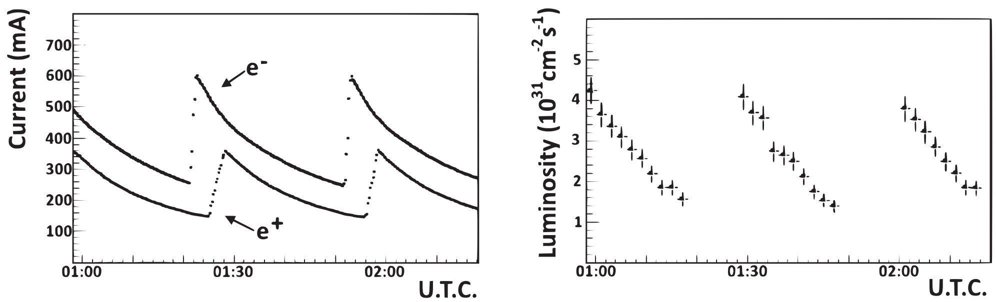

Fig. 3. – Left: beam currents measured by the SIDDHARTA-2 luminometer during the first collision tests. Right: instant luminosity with time intervals of 120 s [10].

3. – Conclusions

The SIDDHARTA-2 experiment aims to perform for the first time the X-ray spectroscopy of the K^-d 2p $\rightarrow$ 1s transition, with a precision comparable to the analogous results of the K^-H one obtained by SIDDHARTA. To achieve this goal, the SIDDHARTA-2 experimental apparatus takes advantage of a new Silicon Drift Detectors system and fast plastic scintillators to increase the signal-over-background ratio of the measurement.

During the DAΦNE commissioning phase, the novel SDDs system developed by the Collaboration has been tested in stressful and realistic conditions, proving to be suitable for high-precision light kaonic spectroscopy thanks to its good energy resolution and linear response ($\Delta E/E < 10^{-3}$). Furthermore, the fast and efficient evaluation of the beam properties given by the SIDDHARTA-2 luminometer plays a key role during the beam optimization phase. The K^-d data taking campaign is planned for 2021–2022. The Collaboration is working also on future plans for other kaonic atoms measurements.

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