LOW-ENERGY KAON NUCLEON/NUCLEI STUDIES AT DAΦNE: THE SIDDHARTA-2 EXPERIMENT*

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The experimental studies of light kaonic atoms offer the unique opportunity to investigate the kaon–nucleus interaction at threshold, performing experiments equivalent to scattering at vanishing relative energies without the need of an extrapolation. In this framework, the SIDDHARTA-2 experiment is going to perform the first measurement of kaonic deuterium $2p \to 1s$ transition, which is fundamental to extract the isospin-dependent antikaon–nucleon scattering lengths. The setup was installed on the DAΦNE collider of LNF-INFN in spring 2019 and is presently in optimization phase. The SIDDHARTA-2 data taking campaign for the kaonic deuterium is planned in 2020–2021.

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1. Introduction

A kaonic atom is a system in which a negatively charged kaon (K^-) is bound to the nucleus by electromagnetic interaction. A kaonic atom is formed when a K^- enters a target, is slowed down by losing its kinetic energy through the interaction with the medium and, lastly, is captured by an atom replacing an electron. Since the kaon mass is 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. It follows that the measurements of the X-ray emissions from de-excitations of kaonic atoms allow to extract 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 non-perturbative QCD (Quantum ChromoDynamics) in the strangeness sector, with implications from particle and nuclear physics to astrophysics.

The SIDDHARTA-2 experiment is going to perform, for the first time, the ϵ and Γ measurement for the kaonic deuterium. Combining them with the analogous results obtained by SIDDHARTA for the kaonic hydrogen in 2009 [1], it is possible to extract the K^-p and K^-d scattering lengths using the Deser–Treumann-type formulae with isospin-breaking corrections [2, 3]

$$\epsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K^-p}\left[1 - 2\alpha\mu(\ln\alpha - 1)a_{K^-p} + \ldots\right] , \tag{1}$$

$$\epsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K^-d}\left[1 - 2\alpha\mu(\ln\alpha - 1)a_{K^-d} + \ldots\right] \tag{2}$$

being: μ: K^-p (K^-d) reduced mass; α: the fine-structure constant.

Thus, the extraction of the antikaon–nucleon isoscalar a_0 and isovector a_1 scattering lengths is given by the following relations:

$$a_{K^-p} = \frac{1}{2}\left[a_0 + a_1\right] ; \qquad a_{K^-n} = a_1 , \tag{3}$$

$$a_{K^-d} = \frac{4\left[m_N + m_K\right]}{\left[2m_N + m_K\right]} Q + C , \tag{4}$$

$$Q = \frac{1}{2}\left[a_{K^-n} + a_{K^-p}\right] = \frac{1}{4}\left[a_0 + 3a_1\right] , \tag{5}$$

where: Q: K^- scattering from each (free) nucleon of deuterium; C: includes the K^-d three-body interaction, which can be studied by solving Faddeev-type equations.

The SIDDHARTA-2 Collaboration is ready to perform the measurement of K^-d. In order to do this, it will take advantage both of a completely upgraded setup with respect to SIDDHARTA, which will be described in the next section, and of the excellent properties of the kaon beam provided by the DAΦNE collider [4–6] at LNF-INFN, Italy. DAΦNE is a world-class electron–positron collider able to generate a kaon beam through the decay of Φ-mesons which is characterized by a low-momentum ($p = 127$ MeVc^{-1}) and a spread $\delta p/p$ below 0.1%.

2. The SIDDHARTA-2 experiment

An exploratory measurement of K^-d has been already performed during the SIDDHARTA data taking campaign, estimating a very low yield ($\simeq 0.1\%$) for the transitions to the ground state [7]. Thus, an improved setup is now ready with the aim to perform the kaonic deuterium measurement with a precision comparable to the kaonic hydrogen one. The main improvements of the new experimental apparatus (figure 1 (top)) with respect to SIDDHARTA are:

— Vacuum chamber. Aluminum vacuum chamber properly shaped to fit in the interaction point allowing the displacement of all the 48 detectors (Silicon Drift Detectors, SDDs). A closed cycle helium refrigerator to keep the target cell between 20 K–30 K and the SDDs stable around 150 K;

— Target cell. Cylindrical shape of diameter = 130 mm and height = 140 mm, its walls are made of 75 μm thick Mylar with aluminum parts for mechanical reinforcement. The working pressure of deuterium gas inside is set at 0.4 MPa;

— Veto-1 system. Scintillators read by PMs sorrounding the vacuum chamber, which acts as an active veto system identifying the hadronic background [8];

— Kaon trigger. Scintillators used as a trigger on K^+K^- pairs from DAΦNE, to suppress the asynchronous background applying a timing window selection according to the timing resolution of the SDDs;

— Veto-2 system. Plastic scintillators read by SiPMS placed behind the SDD devices. These detectors are used for the rejection of the high-energy particles which pass through the SDDs;

— Luminometer. Plastic scintillators read by PMs placed on the lateral (boost and anti-boost) sides of the IR (Interaction Region). They are used to evaluate the luminosity measuring the number of kaons given by the coincidence plots (see figure 2 (top and bottom));

— SDDs and readout electronics. 48 SDD arrays, each containing 8 units placed in a 2×4 matrix (the single cell active area is 0.64 cm^2), will be arranged in a head-to-head configuration, gaining in mechanical solidity and lower heating induced by the heat power consumption from the dedicated readout electronics. The system ensures excellent properties in terms of energy resolution (140 eV at 6 keV), linearity and stability (around 1 eV in the energy range of 4 500–12 000 eV) [9].

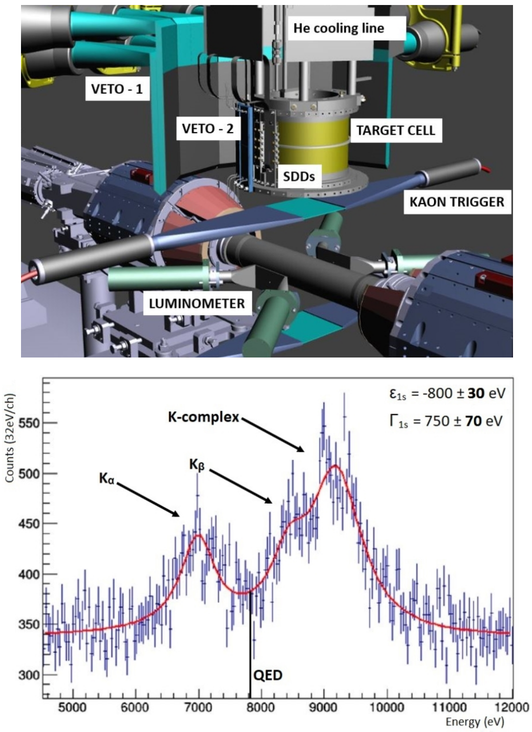

Fig. 1. Top: Schematic view of the SIDDHARTA-2 setup. Bottom: Simulated $K^{-}d$ Monte Carlo spectrum corresponding to an integrated luminosity of 800 pb^{-1}, assuming $\epsilon_{1s} = -800$ eV and $\Gamma_{1s} = 750$ eV, and a yield of 0.1%. The dotted line at 7834 eV corresponds to the pure QED K_{α} value.

Referring to the upgraded setup, a Geant4 simulations have been performed. Figure 1 (bottom) shows the $K^{-}d$ simulated spectrum for an acquired luminosity of 800 pb^{-1}, assuming $\epsilon_{1s} = -800$ eV and $\Gamma_{1s} = 750$ eV, and an yield of 0.1% for the K_{α} transition. The fit indicates that the precision of both ϵ_{1s} and Γ_{1s} evaluation is comparable with the kaonic hydrogen one measured by SIDDHARTA.

The SIDDHARTA-2 apparatus is now installed in the collider in a reduced configuration called SIDDHARTINO during the "DAΦNE commissioning phase", *i.e.* until satisfactory conditions of luminosity and background will be reached. Each element of the setup, using Geant4 simulations, has been tested during the SIDDHARTINO run.

During the "DAΦNE commissioning phase", the luminometer continuously monitors the quality of the beam, measuring the number of kaons generated in e^{+}–e^{-} collisions. Figure 2 (top) shows the 2D-plot of the TDC coincidence signals detected on the scintillators placed respectively on the boost ([TDC1+TDC4]/2) and anti-boost ([TDC2+TDC3]/2) side of the Interaction Region (IR). On the diagonal, we observe the MIPs distributions, which are generated by all the particles lost from the e^{+} and e^{-} bunches, well separated from the kaons. The distributions out from the diagonal, instead, refer to hits of particles belonging to bunches out from collision. The projection in time of the diagonal elements allows to determine the number of kaons produced as well as to obtain a direct indication of the machine background. Figure 2 (bottom) reports, as an example, the histogram referring to the diagonal elements of figure 2 (top). The kaon peaks (grey/red) have been also fitted in order to obtain a preliminary estimate of the number of kaons generated by the collision and, considering the overall efficiency, a preliminary luminosity of about $L = 3.3 \times 10^{31}$ cm^{-2}s^{-1} was estimated.

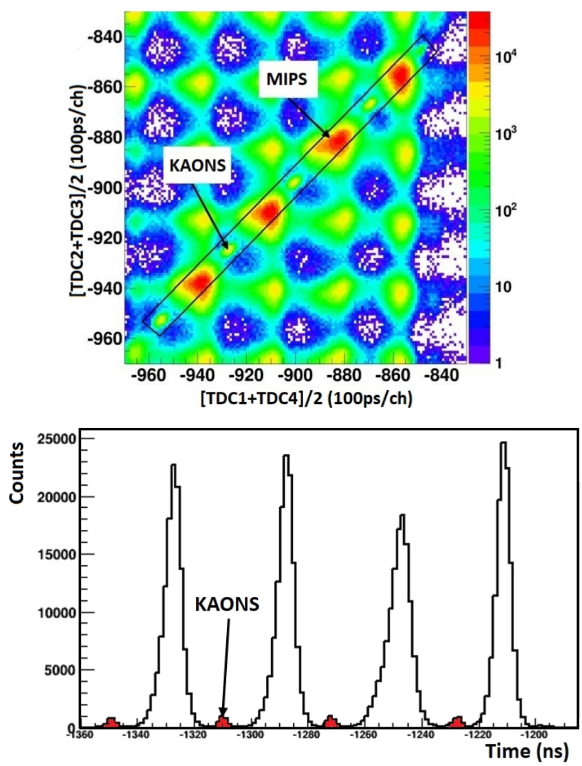

Fig. 2. (Colour on-line) Top: 2D-plot of the TDCs coincidence detected on the boost ([TDC1+TDC4]/2) and anti-boost ([TDC2,TDC3]/2) side of the luminometer. Bottom: Projection on the time coordinate of the 2D-plot diagonal.

The luminometer analysis, thanks to its fast provided feedback, plays an important role during the present beam optimization phase.

3. Conclusions

The SIDDHARTA-2 experiment is going to perform for the first time the measurement of the $K^- d$ $2p \rightarrow 1s$ transition, obtaining the shift (ϵ) and the width (Γ) of the $K^- d$ fundamental level caused by the strong interaction. Combining these values with the analogous results of SIDDHARTA, it will allow to extract fundamental quantities for a better understanding of the non-perturbative QCD in the strangeness sector.

Presently, DAΦNE is in optimization phase with help from SIDDHARTA-2 for the luminosity measurement and background optimization. The $K^- d$ measurement will be done as soon as this optimization will be achieved, in 2020–2021. Meanwhile, the collaboration is working on future plans for other kaonic atoms measurements.

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