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Kaonic Atoms Measurements at DAΦNE: SIDDHARTA-2 and Future Perspectives

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Abstract High precision light kaonic atoms X-ray spectroscopy is a unique tool for performing experiments equivalent to scattering at vanishing relative energies, to determine the antikaon–nucleus interaction at threshold

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without the need of extrapolation to zero energy. The SIDDHARTA-2 collaboration is going to perform the first measurement of kaonic deuterium transitions to the fundamental level, which is mandatory to extract the isospin dependent antikaon–nucleon scattering lengths. The SIDDHARTA-2 experiment is presently installed on the DAΦNE collider of INFN-LNF. The preliminary results obtained during the machine commissioning phase in preparation for the kaonic deuterium data taking campaign, together with future perspectives for extreme precision kaonic atoms studies at DAΦNE are presented.

1 SIDDHARTA-2: The Scientific Case

A kaonic atom forms in a highly excited state, when a negatively charged kaon enters a target, it is slowed down loosing its kinetic energy through the interaction with the medium and then it is captured replacing an electron. Consequently, the kaonic atom cascades down to the low n-states where the strong interaction between the antikaon and the nucleus adds up to the electromagnetic one. As a result, the precise measurements of the shift (ε) and the width (Γ) of the 1s level induced by the strong interaction for kaonic hydrogen and kaonic deuterium bring 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 implications going from particle and nuclear physics to astrophysics [3–6]

The SIDDHARTA Collaboration performed the K^-H ε_{1s} and Γ_{1s} most precise measurement in 2009 [7]. Nowadays, the SIDDHARTA-2 experiment, despite the one order of magnitude lower expected yield of the kaonic deuterium transition to the fundamental level [8] with respect to the analogous kaonic hydrogen one, is ready to perform, for the first time, the more challenging K^-d measurement by using a completely upgraded setup with respect to SIDDHARTA, taking advantage of a new Silicon Drift Detectors (SDDs) system, specially developed to perform high precision X-ray spectroscopy measurements, and of a series of dedicated veto detectors for background reduction.

2 The SIDDHARTA-2 Experiment

The SIDDHARTA-2 experimental apparatus with a reduced (1/6) number of SDDs is presently installed at the DAΦNE collider [9,10] of Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati (INFN-LNF), Italy, which is in commissioning phase.

The cross section layout of the SIDDHARTA-2 apparatus is shown in Fig. 1 left. The target cell, made by Kapton walls reinforced with aluminium supports, operates at a temperature around 22 K and pressure of 0.4 MPa (equivalent to 3%, LHD), to optimize the kaon stopping efficiency and the X-rays yield. The total X-ray detection active area is 245, 8 cm^2, given by the 48 SDDs arrays [11] placed around the target cell and readout by CUBE preamplifiers [12] and SFERA [13] ASICs. The veto system [14] is composed of the

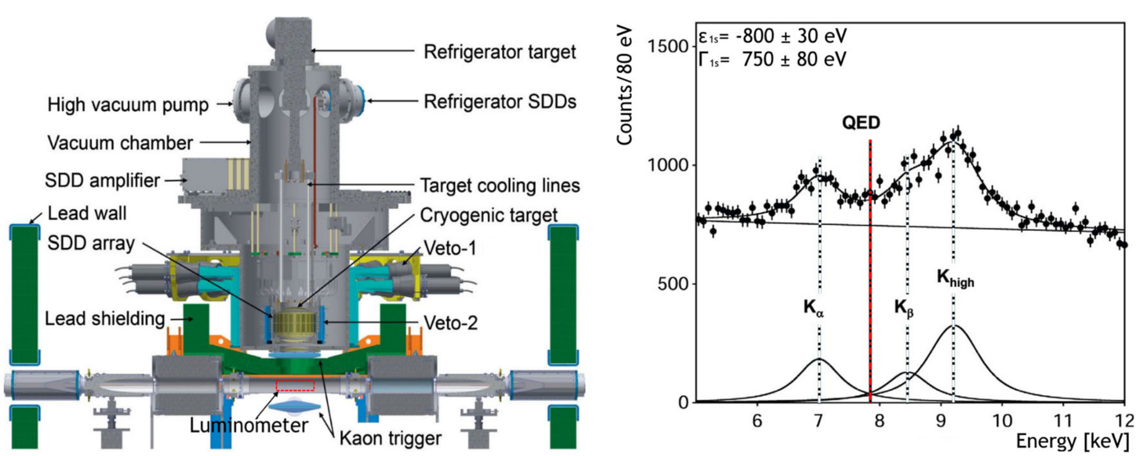

Fig. 1 Left: Cross section layout of the SIDDHARTA-2 experimental apparatus (red dot box refers to the SIDDHARTA-2 luminometer). Right: K^-d MC simulation for an integrated luminosity of 800 pb^{-1} considering $\varepsilon_{1s} = -800\,\mathrm{eV}$, $\Gamma_{1s} = 750\,\mathrm{eV}$ and yield=0.1% as input parameters

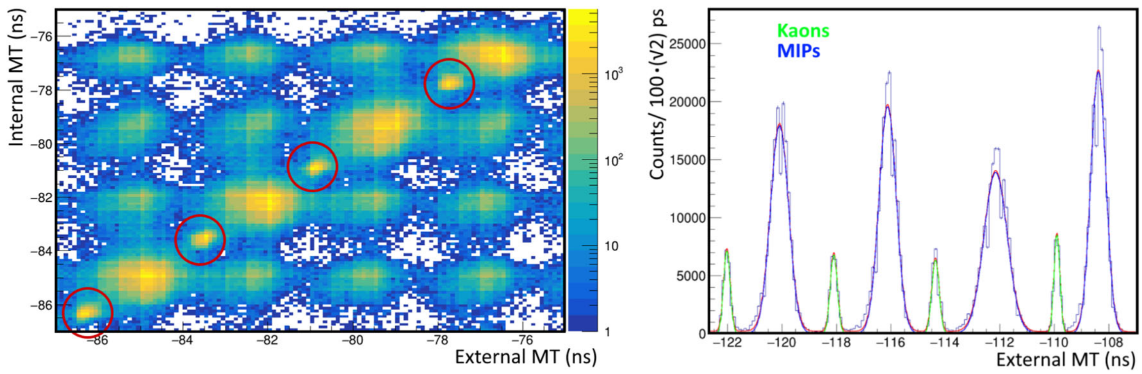

Fig. 2 Left: 2-D plot of the TDCs coincidence between the internal ([TDC1+TDC4]/2) and external ([TDC2,TDC3]/2) luminosity monitor scintillators. Red circles indicate the kaons distribution; Right: Projection on the time coordinate of the 2D plot diagonal

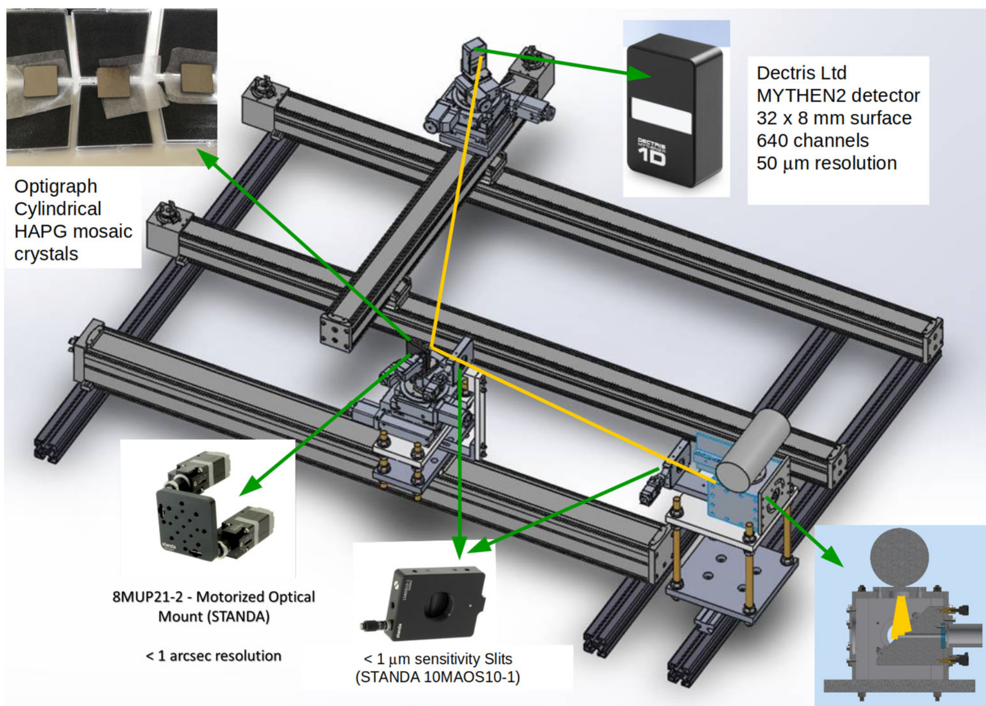

Fig. 3 Sketch of the present VOXES setup [19]

plastic scintillators placed all around the target cell, both external (Veto-1) and internal (Veto-2) to the vacuum chamber, to reject the radiation generated by the nuclear processes within the target cell and the one coming from the machine. The plastic scintillators below and above the beam pipe, working in coincidence mode on the vertical plane (kaon trigger), are used to suppress the electromagnetic background.

A dedicated GEANT4 simulation, taking as input parameters the theoretical calculations [15,16] and an yield of 0.1% for the K_α transition extrapolated from the SIDDHARTA run in 2009 [8], allows the optimization of each single element of the SIDDHARTA-2 experimental apparatus. The fit resulting from the Monte Carlo simulation estimates the precision by which both ε_{1s} and Γ_{1s} are expected to be measured in a run of 800 pb^{-1}, with results comparable to the analogous observables measured by SIDDHARTA during the KH data taking campaign.

The reduced SIDDHARTA-2 apparatus is presently collecting data during the DAΦNE commissioning phase, in preparation for the kaonic deuterium data taking campaign. During this phase, the energy response of the SDDs system has been tested also in the more realistic environment of a particle collider, revealing that its spectroscopic response is preserved even in the high background of the machine, as proved in [17].

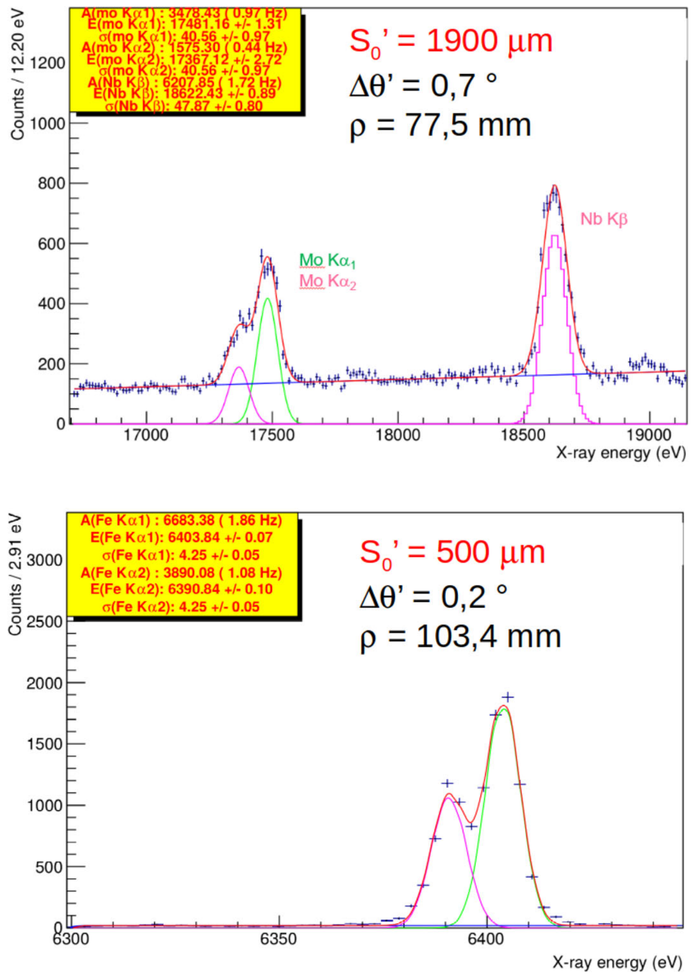

Fig. 4 Example of precisions and resolutions obtained by VOXES

The excellent performances of the SIDDHARTA-2 system, in terms of energy resolution and linearity of the response, are key features for performing the first K^-d X-ray spectroscopy measurement.

Futhermore, the SIDDHARTA-2 luminometer [18], placed on the lateral sides of the collider beam pipe (red dot box in Fig. 1), runs continuously during the DAΦNE commissioning phase, providing a fast feedback on the quality of the beams for each collider beam cycle, playing a key role during the beam optimization. Figure 2 reports, as an example, the plots obtained during the tests of the machine in collision mode configuration. The 2-D plot on the left of Fig. 2 shows the TDC coincidence signals detected on the scintillators placed respectively on the internal ([TDC1+TDC4]/2) and external ([TDC2+TDC3]/2) sides of the Interaction Region (IR). The distribution on the diagonal of the plot corresponds both to the MIPs (particles lost from the e^+ and e^- bunches) and the detected kaons (red circle) generated by the decay of the Φ particle. Outside the diagonal, there are hits of particles not belonging to same RF shot. On the right, the histogram generated by the projection in time of the 2-D plot diagonal elements is shown. The kaon peaks (red) have been fitted to estimate the number of kaons generated by the collision and, consequently, the luminosity.

The SIDDHARTA-2 run for the kaonic deuterium measurement is scheduled to start in autumn 2021 and to proceed through 2022, until the integration of 800 pb^{-1}.

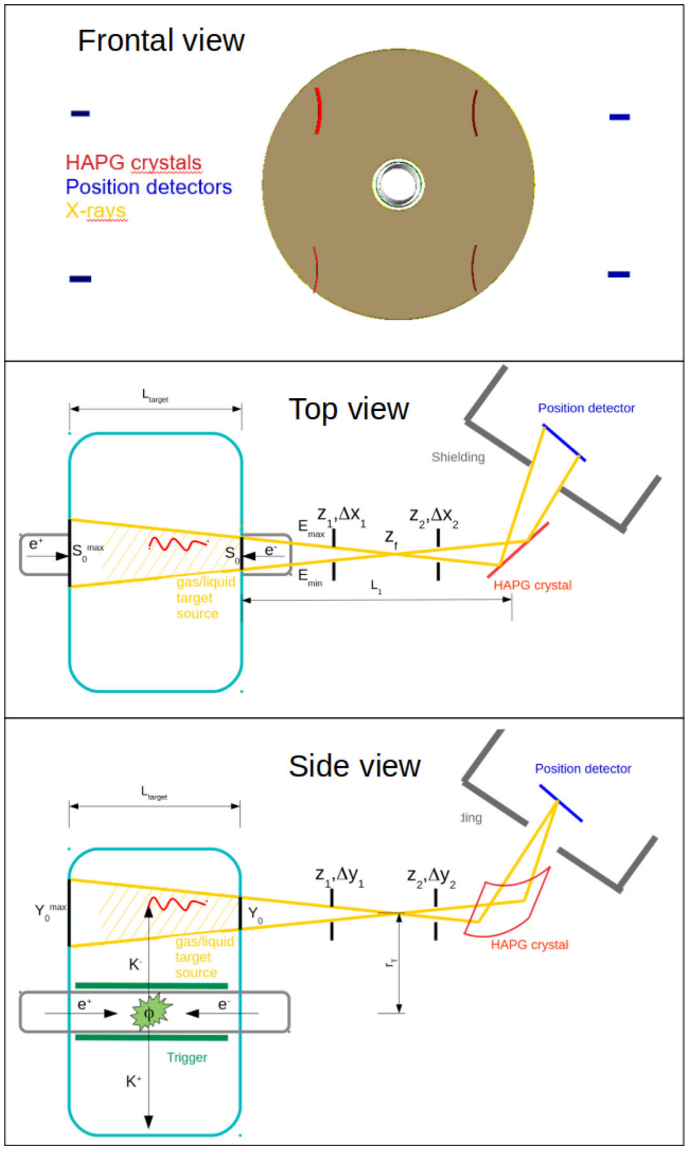

Fig. 5 Sketch of a possible setup of the KA3 experiment (see text for details)

3 Future Perspectives for Extreme Precision Kaonic Atoms Measurements

In the near future, a new exciting possibility in the investigation of kaonic atoms will be represented by extreme (sub-eV) precision measurements of their transition energies, like for example that of the relative difference in the $3d \rightarrow 2p$ transition energies between K^3He and K^4He (known as the *isotopic shift*) and of their widths, whose measurement with a precision below 1 eV might represent a breakthrough in the field [3]. To achieve the required challenging precisions, detectors with $FWHM \simeq 5$–10 eV @ 6–10 keV resolution, namely more than one order of magnitude better than that of the standard large area solid state devices, is required.

The possibility to exploit Bragg reflection to reach such extreme precision has been ruled out until now, by the typical required source sizes of few tens of microns and the extremely low efficiencies. However, exploiting the combined possibilities offered by Highly Annealed Pyrolitic Graphite (HAPG) mosaic crystals and the vertical focus of the Von Hamos configuration, the VOXES collaboration at INFN-LNF [19–21] realised a spectrometer able to maintain a resolution in the order of 0.1% (FWHM/E), for energies below 10 keV, and of 0.3% up to 20 keV, using a source size ranging from 500 μm to 2 mm in the Bragg dispersion plane. The developed experimental setup is shown in Fig. 3. As an example of the outstanding performances in terms

of energy resolution and determination of the peak position, results obtained with targets of Fe, Mo and Nb, activated by an X-ray tube, are shown in Fig. 4. In the lower pad, the extremely good resolutions and the resulting high precisions achieved with a single element target (Fe in the example) is shown, while in the upper one the possibility to have spectra with a larger dynamic range and in the 15–20 keV region with few eV precisions is also demonstrated. In both pads of Fig. 4, the effective source size S_0' for each measurement is reported, representing the real breakthrough of the VOXES spectrometer (see [19] for more details).
A drawing of a possible experimental setup which could be realised to perform extreme precision measurements of kaonic atoms at the DAΦNE collider in Frascati, consisting of 8 spectrometer arms devoted to a specific energy range each, is shown in Fig. 5; frontal (along the collider beam direction), top and side views are depicted in the top, middle and bottom pad, respectively. Kaons emitted from the interaction point are first detected by a scintillator and SiPMs based trigger system, before entering in a cylindrical gaseous target cell surrounding the beam pipe, where they form kaonic atoms; the X-ray photons emitted during the transitions are then measured by a specific energy range spectrometer having a resolution of few eV.
Such an apparatus would provide the possibility to measur X-rays in the 4–20 keV region with few eV resolution from macroscopic sources, with precision on the peak position determination in the sub-eV range, allowing to perform crucial and still missing measurements of kaonic atoms such as kaonic helium 3 and 4, carbon, lithium and beryllium, contributing to a much deeper understanding of the low energy strangeness QCD. This proposal is being put forward to the scientific community in a broader perspective, presented in [22].

4 Conclusions

The SIDDHARTA-2 collaboration is ready to perform the K^-d 2p → 1s transition shift (ε) and width (Γ) measurement. Combining these results with the analogous ones of SIDDHARTA, it will be possible to extract the antikaon–nucleon isoscalar a_0 and isovector a_1 scattering lengths, fundamental quantities for understaning the non-perturbative QCD in the strangeness sector. The upgraded SIDDHARTA-2 experimental apparatus is now installed at the DAΦNE Collider of INFN-LNF during the machine beam commissioning phase, providing fundamental information for the beam optimization in terms of luminosity and background.

The K^-d data taking campaign is scheduled to start in autumn 2021. Meanwhile, the collaboration is preparing future proposals for other kaonic atoms measurements including extreme precision light kaonic atoms spectroscopy.

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