PROCEEDINGS OF SCIENCE

Low-Energy Kaon-Nuclei Interaction studies at the DAΦNE Collider: a Strangeness Odyssey

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Kaonic atoms provide important observables for the study of the low-energy strong interactions with strangeness. Following SIDDHARTA's kaonic hydrogen measurement, the SIDDHARTA-2 collaboration is performing the kaonic deuterium measurement, which will significantly enhance our understanding of kaon-nucleon interactions. Alongside this groundbreaking goal, the collaboration has provided other important measurements of kaonic atom transitions, which are significant not only for understanding low-energy strong interactions but also for studies in Quantum Electrodynamics. The experiment is also testing state-of-the-art X-ray detectors, paving the way for new technologies and future measurements of kaonic atoms with heavier nuclei.

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We dedicate this work to the memory of Prof. C. Guaraldo and Prof. J. Zmeskal, whose contributions were essential to the success of the kaonic atom measurements campaign at the DAΦNE collider. This work would not have been possible without them.

1. Introduction

Exotic atoms are formed when a negatively charged particle – other than an electron, either a lepton or a hadron – is captured into an atomic orbit via electromagnetic interaction with the nucleus, replacing an electron. Once captured, the particle at hand will cascade down towards the energy levels with lower principal quantum number n, whilst emitting Auger electrons and characteristic X-rays. If the exotic particle is a hadron, it will be absorbed at the lowest energy levels due to its strong interaction with the nucleus, ultimately altering the energy levels. Therefore, hadronic atoms can be used to study low-energy Quantum Chromodynamics (QCD) in its non-perturbative regime. When analyzing strong interactions in hadronic atoms, the key observables are the energy level shift (ε) relative to Quantum Electrodynamics (QED) predictions and the broadening (Γ) of these levels. Furthermore, hadronic atoms, are also valuable tools to carry out precision tests of QED and studies of bound-state QED (BSQED) [1]. For the latter, hadronic atoms are much more compact than the corresponding non-hadronic counterpart, thus enhancing BSQED contributions. Another profit that comes when studying kaonic atoms is the possibility to perform a new measurement of the charged kaon mass, which is still an open issue in the framework of particle physics.
The SIDDHARTA-2 experiment [2–4] at the DAΦNE collider of Laboratori Nazionali di Frascati of INFN (INFN-LNF) [5–7] is the world leading experiment for studies of kaonic atoms. DAΦNE delivers clean and low energetic kaon beams; the produced K^- are eventually stopped inside a target where they form kaonic atoms. Silicon Drift Detectors (SDDs) [8, 9] and CdZnTe based detectors [10, 11] are used to detect the X-rays emitted during the cascade process of kaonic atoms. In Section 2, the low-energy strong interaction is discussed; in Section 3, the recent measurement of kaonic neon together with a discussion on the kaon mass problem and the BSQED are presented; in Section 4, the low-energy strong interactions between kaon and heavier nuclei, and the new proposal to measure them are discussed.

2. Kaonic atoms and the low-energy strong interaction

The main goal of the SIDDHARTA-2 experiment is to perform the long-awaited measurement of the shift and width induced by the strong interaction on the $1s$ level of kaonic deuterium. By combining this measurement with that of kaonic hydrogen from the SIDDHARTA experiment [12], the isospin-dependent antikaon-nucleon ($\bar{K}N$) scattering lengths ($a_{I=0,1}$), key quantities for the low-energy QCD, can be extracted. Those quantities are related through the Deser-Trueman formula [13], which, in an improved version by Meißner *et al.* [14, 15], is expressed as:

$$\varepsilon_{1s}^{H} + \frac{i}{2}\Gamma_{1s}^{H} = 2\alpha^3\mu^2 a_{\bar{K}p}\left[1 - 2\alpha\mu(ln\alpha - 1)a_{\bar{K}p} + ...\right] , \quad (1)$$

for kaonic hydrogen and:

$$\varepsilon_{1s}^{D} + \frac{i}{2}\Gamma_{1s}^{D} = 2\alpha^3\mu^2 a_{\bar{K}d}\left[1 - 2\alpha\mu(ln\alpha - 1)a_{\bar{K}d} + ...\right] , \quad (2)$$

for kaonic deuterium. The isospin-dependent scattering lengths are related to the $\bar{K}p$ scattering length through the relation:

$$a_{\bar{K}p} = \tfrac{1}{2}\,(a_0 + a_1)\,. \tag{3}$$

In order to be able to calculate both a_0 and a_1, the measurement of the shift and width of kaonic deuterium is needed. Once the $\bar{K}d$ scattering length $a_{\bar{K}d}$ is known, this relates to the isospin-dependent scattering lengths via the following relations:

$$a_{\bar{K}n} = a_1, \tag{4}$$

$$a_{\bar{K}d} = \frac{4\,[m_N + m_K]}{2m_N + m_K} Q + C\,. \tag{5}$$

where m_N is the mass of the nucleus, the term C takes into account higher-order contributions related to the $\bar{K}d$ three-body problem and:

$$Q = \frac{1}{2}\left[a_{\bar{K}p} + a_{\bar{K}n}\right] = \frac{1}{4}\left[a_0 + 3a_1\right]\,. \tag{6}$$

In Fig. 1 [16] some of the relevant phenomenological models for the $\bar{K}N$ scattering amplitudes are shown. Thanks to the measurement of kaonic hydrogen performed by the SIDDHARTA experiment [12], several theoretical models on the $\bar{K}p$ amplitude at threshold energy agree with each other, since their parameters are fitted to the experimental data in this region. Given the lack of a $a_{\bar{K}n}$ experimental determination, the theoretical predictions for the $\bar{K}n$ amplitude are highly divergent, hence the need of a kaonic deuterium measurement.

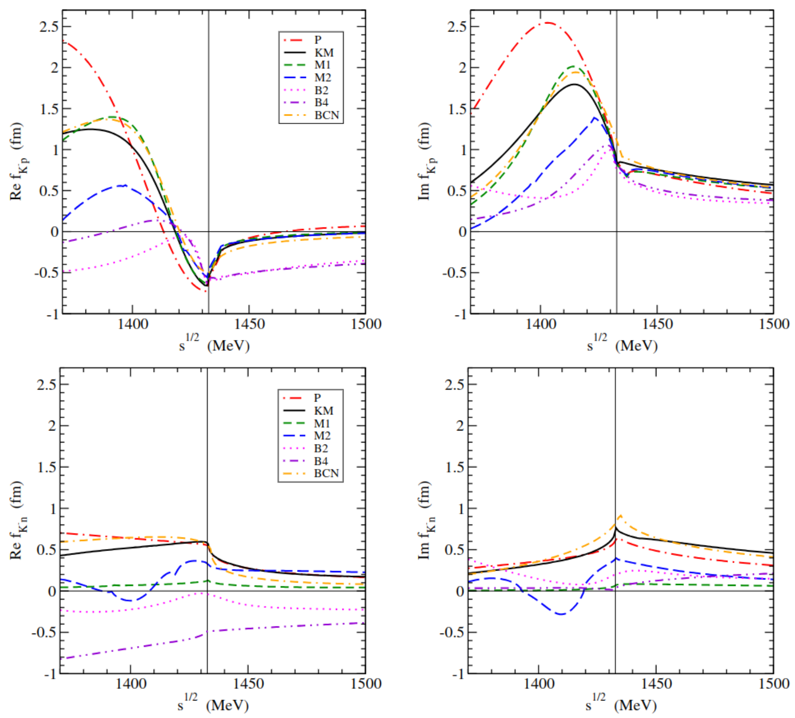

Figure 1: Theoretical models for the real (left) and imaginary (right) parts of the s-wave free-space K^-p (f_{K^-p}) and K^-n (f_{K^-n}) amplitude [16] in the state-of-the-art chiral models. A measurement of the scattering length $a_{\bar{K}n}$ is needed in order to fit the parameter of the theoretical models to the experimental data.

From an experimental point of view the observation of kaonic deuterium X-rays transitions to the fundamental level is very challenging due to their low yield. The X-ray yield for the $2p \rightarrow 1s$ transition is expected to be almost 10 times smaller than that of the corresponding transition for kaonic hydrogen. For this reason, the experimental apparatus of SIDDHARTA has been largely improved into the new SIDDHARTA-2 apparatus, thanks to the development of new Silicon Drift Detector with excellent time and energy resolution and by adding three veto systems for background reduction [3]. A careful optimization of the new detection systems has been performed with an high-yield with an high-yield gaseous target, namely Helium-4 [17]. During the 2023 and 2024 runs, a total amount of $\sim 1000\,\mathrm{pb}^{-1}$ of data with a gaseous deuterium target have been collected and are presently being analyzed to extract the shift and width induced by the strong interaction on the $1s$ level of kaonic deuterium, thus providing a crucial experimental input to all those phenomenological models dealing with $\bar{K}N$ low-energy interaction. In Fig. 2 a scheme of the experimental apparatus for kaonic deuterium measurement is reported.

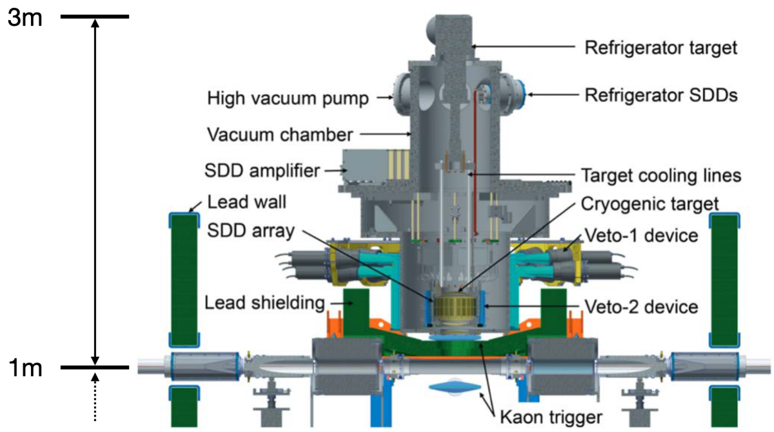

Figure 2: Scheme of the SIDDHARTA-2 apparatus. For an accurate description of the experimental set-up refer to [3]. Picture taken from [17].

3. BSQED and Kaon Mass

Kaonic atoms serve as a crucial experimental tool not only for probing the low-energy regime of QCD but also for conducting precision tests of QED. QED is the best understood quantum field theory and is commonly used to conduct searches for physics beyond the standard model. In particular, BSQED is used to achieve highly precise calculation for few-electron systems [1]. To date, BSQED has been studied with few-electrons highly charged ions (HCI) [18], however, these systems suffer from uncertainties which can be larger than the BSQED effects of interest. To deal with this problem, exotic atoms can be used: as these systems are much more compact, the close proximity of the exotic particle to the nucleus enhances the BSQED contributions to the transition energies. To date, muonic and antiprotonic atoms have been exploited to such end, but using kaonic atoms instead has several advantages: given their larger reduced mass, kaonic atoms exhibit an upgraded sensitivity to BSQED effects with respect to muonic atoms, and while antiprotonic atoms require an high experimental energy resolution to determine the level splitting caused by spin-orbit interactions, kaonic atoms have no such problem. When dealing with kaonic atoms, BSQED information can be extracted by measuring high-n transitions, as these take place far enough from the nucleus for the strong interaction to be neglected and can therefore be considered as purely electromagnetic transitions [19]. SIDDHARTA-2 recently measured several high-n transitions of kaonic neon, a spectrum with a subset of the total data is shown in Fig. 3. For the result of the analysis of the whole dataset we refer to [19].

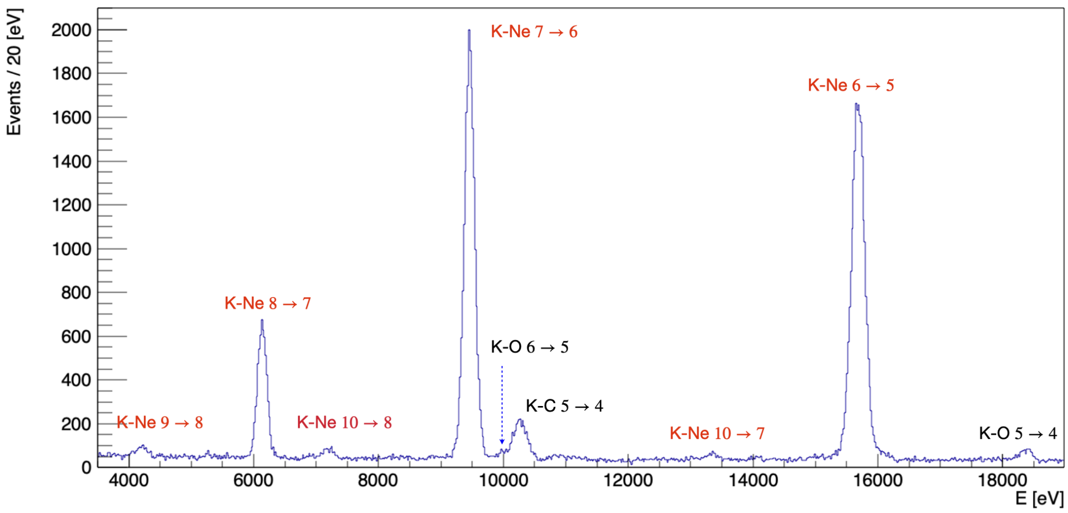

Figure 3: Kaonic neon energy spectrum detected with the SIDDHARTA-2 apparatus. Some contaminant transitions, together with the Kaonic Neon ones, are present.

This measurement of high-n purely electromagnetic transitions of kaonic neon can also be used to pursue another goal, namely to perform a new measurement of the charged kaon mass. This is one of the still unsolved problems of fundamental particle physics: the value reported on the Particle Data Group (PDG) [20] is the outcome of a weighted average of the two most precise measurements to date of the charged kaon mass [21, 22]. However, as shown in Fig. 4, these two measurements are not compatible one with the other. Both measurements were conducted using a solid target, which introduced systematic errors driven by effects such as electron screening and electron refill, which are challenging to account for. These issues, however, do not arise when using a low-Z gaseous target. Therefore, the SIDDHARTA-2 collaboration plans to perform a dedicated kaonic neon data-taking campaign to obtain a new measurement of the charged kaon mass [4].

4. Future Projects: EXKALIBUR

The combined measurement of kaonic hydrogen and kaonic deuterium has a strong impact on the description of the low-energy strong interactions with strangeness, in particular on the kaon interaction with single and double nucleon, while the interaction between a kaon and many nucleons can only be probed by studying heavier systems.

Currently, our understanding of kaon-multinucleon interactions at very low energies is based on experiments conducted over forty years ago, most of which are reported in [23]. Some of these

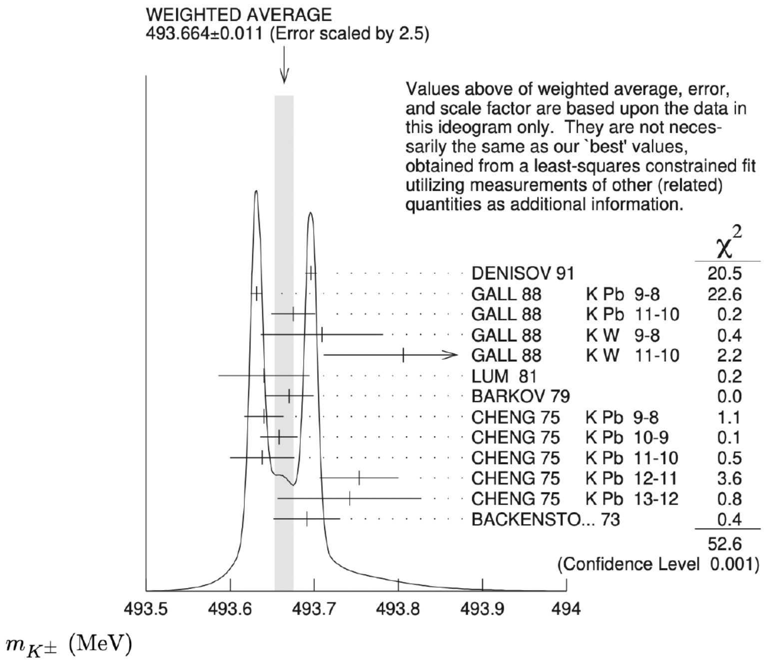

Figure 4: Current state of the charged kaon mass measurements. Taken from [20].

measurements have yielded inconsistent results, and recent kaonic hydrogen [12, 24, 25] and helium [17, 26, 27] measurements made at KEK and DAΦNE have shown discrepancies in the previously reported values for these elements.

The new technologies achieved in the last twenty years in the field of X-rays detection, and the expertise in kaonic atoms spectroscopy gained by the SIDDHARTA-2 group, can be important to overcome this source of uncertainty in the kaon-multinucleon interaction description, with key applications from low-energy strong interactions in particle and nuclear physics, to astrophysics [28].

To address this, the collaboration is exploring the possibility of measuring heavier kaonic atoms at the DAΦNE collider through the EXKALIBUR proposal (EXtensive Kaonic Atoms Research: from LIthium and Beryllium to URanium) [29]. The aim is to measure a wide range of kaonic atoms and obtain a definitive description of kaon interactions with multinucleon nuclei, from lithium to uranium. The collaboration is already working on possible new detectors to measure a wide range of signals, each specialized for a specific region. The EXKALIBUR project will include:

- A new setup optimized for solid targets similar to that of SIDDHARTA-2, along with state-of-the-art 1mm Silicon Drift Detectors (SDDs) [30], shown in Fig. 5, covering an energy range up to 50 keV, to measure the shift and width of light-mass kaonic atoms (Li, Be, B).

- A new detector, shown in Fig. 5, based on the Cadmium-Zinc-Telluride (CZT) semiconductor to measure shifts and widths of intermediate-mass kaonic atoms that have previously shown inconsistent measurements or large uncertainties, such as Al, S, and C (see Table 1 in [23]). A CZT detector system has already been tested for the first time in an e^+-e^- collider by the collaboration [10, 11, 31], showing good performance in terms of stability and linearity.

- A High Purity Germanium (HPGe) detector to measure heavy-mass kaonic atoms and potentially determine the kaon mass independently. A feasibility study demonstrating the capabilities of this detector has already been conducted at the DAΦNE collider [32].

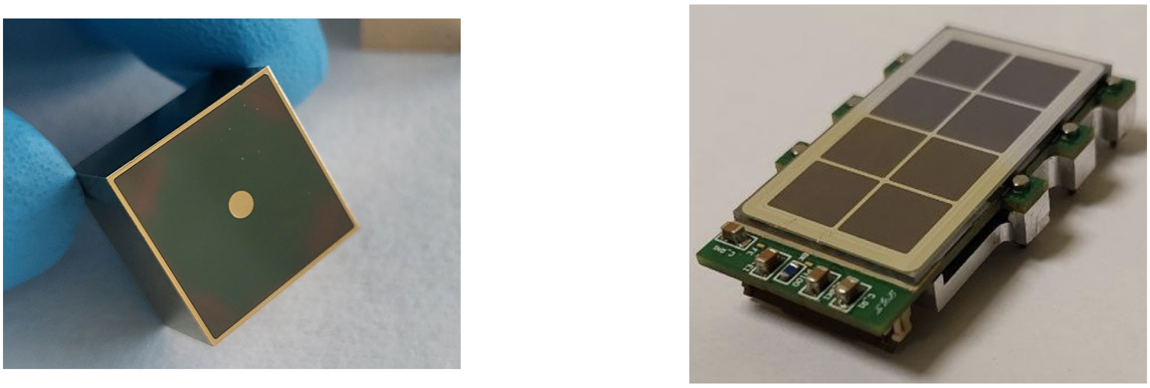

Figure 5: Left: picture of a 10mm x 10mm x 15mm quasi-hemispherical CZT detector [33]. Right: picture of a matrix of 8mm x 8mm new 1mm-thick SDDs [30].

5. Conclusions

The SIDDHARTA-2 experiment aims to achieve the first measurement of the shift and width of kaonic deuterium – one of the most significant measurements in hadronic physics – which will enhance our understanding of kaon interactions with single nucleons at threshold. Together with this main quest, the collaboration is also exploring a multitude of physics studies to be carried out using kaonic atoms spectroscopy, including the kaon mass problem, BSQED and kaon-multinucleon interactions.
The experiment has already performed the measurements of kaonic helium [17] and kaonic neon [19], that have a strong impact in the kaon mass determination and in possible studies of new physiscs in BSQED.
The collaboration is also studying the possibility for new kaonic atoms experiments within the EXKALIBUR proposal, testing beyond state-of-the-art detectors like 1mm SDDs and CZT detectors, and studying the important consequences of these measurements in fields ranging from nuclear physics to astrophysics.

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