PROCEEDINGS OF SCIENCE

Tests of New CZT detectors at DAΦNE collider for Kaonic Atoms Measurements

Francesco Artibani,[a,b,*] **Leonardo Abbene,**[c] **Massimiliano Bazzi,**[a] **Giacomo Borghi,**[e,f] **Damir Bosnar,**[g] **Mario Bragadireanu,**[h] **Antonino Buttacavoli,**[c] **Michael Cargnelli,**[d] **Marco Carminati,**[e,f] **Alberto Clozza,**[a] **Francesco Clozza,**[a,o] **Luca De Paolis,**[a] **Raffaele Del Grande,**[a,i] **Kamil Dulski,**[a] **Carlo Fiorini,**[e,f] **Ivica Friscic,**[g] **Carlo Guaraldo** [†]**,**[a] **Mihail Iliescu,**[a] **Masahiko Iwasaki,**[j] **Aleksander Khreptak,**[k] **Simone Manti,**[a] **Johann Marton,**[d] **Pawel Moskal,**[k,l] **Fabrizio Napolitano,**[a] **Szymon Niedźwiecki,**[k,l] **Hiroaki Ohnishi,**[m] **Kristian Piscicchia,**[n,a] **Fabio Principato,**[c] **Alessandro Scordo,**[a] **Francesco Sgaramella,**[a] **Michal Silarski,**[k] **Diana Laura Sirghi,**[a,h,n] **Florin Sirghi,**[a,h] **Magdalena Skurzok,**[k,l] **Antonio Spallone,**[a] **Kairo Toho,**[m] **Lorenzo G. Toscano,**[e,f] **Marlene Tüchler,**[d] **Johann Zmeskal** [†d] **and Catalina Curceanu**[a]

[a] *Laboratori Nazionali di Frascati, INFN, Via E. Fermi 54, 00044 Frascati, Italy,*
[b] *Dipartimento di Matematica e Fisica, Università di Roma Tre, Via della Vasca Navale, 84, 00146 Roma, Italy*
[c] *Dipartimento di Fisica e Chimica - Emilio Segrè, Università di Palermo, Viale Delle Scienze, Edificio 18, Palermo, 90128, Italy*
[d] *Stefan-Meyer-Institut für Subatomare Physik, Dominikanerbastei 16, Wien, 1010, Austria*
[e] *Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Via Giuseppe Ponzio 34, Milano, 20133, Italy*
[f] *INFN Sezione di Milano, Via Giovanni Celoria 16, Milano, 20133, Italy*
[g] *Department of Physics, Faculty of Science, University of Zagreb, Bijenička cesta 32, Zagreb, 10000, Croatia*
[h] *Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), No. 30, Reactorului Street, Magurele, Ilfov, 077125, Romania*
[i] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Břehová 7, 115 19, Prague, Czech Republic*
[j] *Institute of Physical and Chemical Research, RIKEN, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan*
[k] *Faculty of Physics, Astronomy, and Applied Computer Science, Jagiellonian University, Lojasiewicza 11, Krakow, 30-348, Poland*
[l] *Centre for Theranostics, Jagiellonian University , Kopernika 40, Krakow, 31-501, Poland*
[m] *Research Center for Accelerator and Radioisotope Science (RARIS), Tohoku University, 1-2-1 Mikamine, Taihaku-ku, Sendai, 982-0826, Japan*
[n] *Centro Ricerche Enrico Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Via Panisperna 89A, Roma, 00184, Italy*

[*]Speaker

ISSN 1824-8039. Published by SISSA Medialab. https://pos.sissa.it/

PoS(DISCRETE2024)031

[o] *Dipartimento di Scienze Matematiche Fisiche e Naturali, Università degli studi di Roma Tor Vergata, Via Cracovia, 90, 00133 Roma, Italy*

[†] *Deceased*

E-mail: francesco.artibani@lnf.infn.it

Kaonic atom spectroscopy provides key observables for investigating low-energy strong interactions in strange systems. In this paper, we present an overview of the SIDDHARTA-2 collaboration's activities in the field of kaonic atoms, with a particular focus on the development of a new Cadmium-Zinc-Telluride (CZT) detector system for the study of intermediate-mass kaonic atoms. This novel detection system, applied for the first time in fundamental physics research at a collider, is designed to extend the energy range accessible in kaonic atom spectroscopy. We report on the characteristics of the detector and the results of test measurements conducted at the DAΦNE collider between 2022 and 2024.The tests demonstrated that the detector's energy resolution, efficient background rejection, and good timing performance make it ideal for performing kaonic atom measurements.

The ultimate goal of these developments is to refine our understanding of kaon-multinucleon low-energy strong interactions by providing high-precision measurements of intermediate-mass kaonic atoms.

DISCRETE2024
Ljubljiana
02-06/12/2024

1. Introduction

Kaonic atoms are a type of exotic atoms [1] formed when a negatively charged kaon, after being stopped in matter, replaces an electron in an atomic orbit and binds to the nucleus through electromagnetic interaction. This process occurs when the wave functions of the electron and kaon overlap the most [2], resulting in the creation of a highly excited quantum state. The kaon then undergoes a series of de-excitation processes, which are predominantly radiative in the final stages of the cascade. In the energy levels closer to the fundamental state, the kaon and the nucleus begin to experience strong interaction in addition to the electromagnetic one. In Figure 1, a scheme of the cascade process of kaonic hydrogen atom is reported.

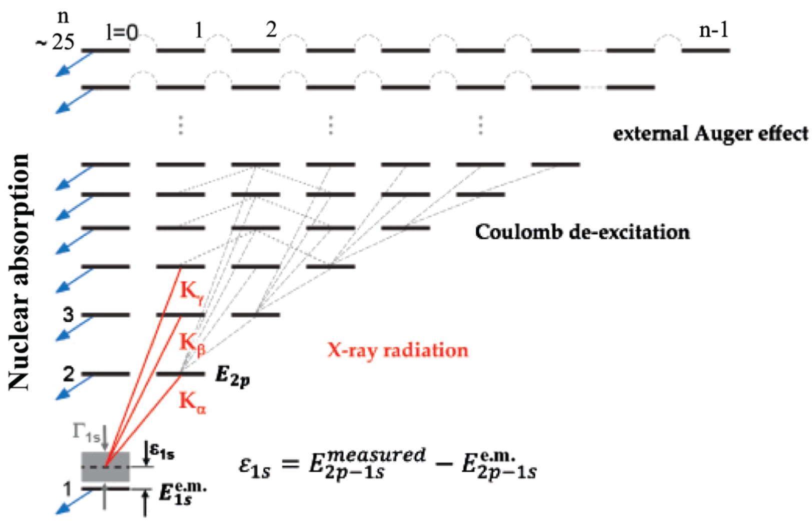

Figure 1: Scheme of Kaonic Hydrogen Cascade process. The shift (ϵ_{1s} and the width (Γ_{1s}) due to the strong interaction in the 1s level are indicated, together with the radiative transitions to the level that can be detected through the spectroscopy (Kα, Kβ, Kγ).

From an experimental perspective, spectroscopic measurements of radiative de-excitation transitions provide a unique method to study at-threshold strong interaction with strangeness in these systems. The effect of the additional interaction, indeed, manifests in a shift (ϵ) of the energy level, and in an intrinsic width (Γ) of the level itself, that causes a broadening of the spectral line [3–5].

These two important observables can be connected to theory through the scattering lengths, key quantities that describe the kaon-nucleon/kaon-multinucleon (K-N/K-multiN) low-energy strong interaction. These quantities are predicted by chiral perturbation theory (χPT), a low-energy extension of Quantum Chromodynamics (QCD) [6, 7]. The experimental values derived from kaonic atoms are a unique observable at-threshold, and can be used to both test and refine theoretical models.

The SIDDHARTA-2 collaboration [3–5] is particularly active in kaonic atom studies at the DAΦNE collider at Frascati National Laboratories (INFN-LNF). A significant contribution in this field comes from the measurements of kaonic hydrogen performed by DEAR [8] and SIDDHARTA [9], as well as the upcoming measurement of kaonic deuterium, the real target of the collaboration.

This new measurement will finally help determine the isospin-dependent scattering lengths and clarify the differences between kaon-proton and kaon-neutron interactions. Besides this important goal, it is also crucial to explore the behavior of strong interactions in multinucleon systems. Moving in this direction, the SIDDHARTA-2 collaboration has already measured the kaonic helium X-ray spectrum [10]. The next step is to study light and intermediate-mass kaonic atoms. To investigate the strong interaction in these systems, it is necessary to extend the energy range beyond that of the current apparatus.

To achieve this, the SIDDHARTA-2 collaboration is pursuing two approaches: developing state-of-the-art detectors for kaonic atom spectroscopy. For light-mass kaonic atoms (K-Li, K-Be, K-B), the collaboration developed new 1mm SDDs [11] with an extended energy range compared to those currently used in the experiment. For intermediate-mass kaonic atoms, A novel Cadmium-Zinc-Telluride (CZT)-based detection system has been successfully developed and tested.

In the following chapter, we will briefly discuss why new measurements of intermediate-mass kaonic atoms are required by the theoretical community, and in the third chapter we will report the results of the CZT detector tests performed at DAΦNE.

2. Intermediate-mass Kaonic Atoms

Until now, theories on kaonic atoms and models of kaon interactions with nucleons have been based on multiple fits to earlier measurements conducted with different target nuclei more than three decades ago. These measurements, along with the detailed connection between the data fits and the model describing K-multiN interactions, are reported in [12].

Among these measurements, conflicting results have been observed in transitions such as kaonic aluminum and kaonic sulfur, while transitions like kaonic carbon suffer from large uncertainties. These discrepancies lead to significant uncertainties in global fits, ultimately limiting our understanding of kaon-nucleus interactions.

Furthermore, recent measurements of kaonic hydrogen [8, 9, 13] and helium [10, 14, 15] have demonstrated that results from older experiments respectively on hydrogen [16–18] and helium [19–21] were incorrect, casting doubt on the current understanding of low-energy strong interactions in kaonic atoms.

Advancements in radiation detector technology over the past thirty years, combined with new methodologies and the expertise of our group, could enable significant new measurements in the field and greatly enhance our understanding of strong interactions in these systems [22].

3. Tests in DAΦNE

To conduct new experiments on intermediate-mass kaonic atoms, the SIDDHARTA-2 collaboration is developing a new CZT detector system. As this is the first application of such a detector in fundamental physics studies at a collider, it must undergo a series of crucial tests to verify its timing performance – essential for kaonic atom studies at DAΦNE –, its resolution, and its resistance to radiation damage. The first two tests were conducted to demonstrate the feasibility of the experiment, as well as to estimate the resolution and background rejection factor. In June 2022, a first prototype of a quasi-hemispherical CdZnTe detector system, with an active surface of 1 cm^2, was placed at the DAΦNE collider, 43 cm from the interaction point [23]. The spectrum of a ^{241}Am source was measured, achieving peak resolutions of 6% at 60 keV and 2.2% at 511 keV. Additionally, a trigger system was developed, based on time-of-flight kaon selection using the luminometer of the SIDDHARTA-2 experiment [24] and on time difference measurements, to exploit the fast readout of the detector and effectively suppress machine-related background. The detector was connected to low-noise charge-sensitive preamplifiers with an equivalent noise charge of 100 electrons and processed by digital electronics. The signals from the CdZnTe detector were acquired by two CAEN DT5724 digitizers, controlled by custom firmware. The signals from the luminometer (LM) were also acquired using the same digitizers for offline data selection when a charged kaon pair was produced. The digital signals from the LM were processed by an ORTEC 566 Time-to-Amplitude Converter (TAC) module. In Figure 2, a spectrum of the TAC, and an estimation of the background rejection after the cuts showing ^{2}41Am spectra with different selections are reported.

A second test was conducted using four custom 13 × 15 × 5 mm^3 quasi-hemispherical CdZnTe detectors provided by Redlen Technologies (Saanichton, BC, Canada) [25], with a setup nearly identical to the first, but placed 22 cm from the DAΦNE interaction point. The main goal of this second test was to observe a time-coincidence peak between the CZT detectors and the luminometer, demonstrating the good timing capability of the detector system and enabling the application of a drift-time-based cut during the physics run, as was done in the SIDDHARTA kaonic hydrogen measurement analysis [9]. The peak observed in the test is shown in Figure 2.

Finally, the last test conducted in 2024 with the same setuop using eight custom 13 × 15 × 5 mm^3 quasi-hemispherical CdZnTe detectors provided by Redlen Technologies and IMEM-CNR, demonstrated the good stability of the apparatus after a long data-taking period at DAΦNE. It also provided a reliable calibration method and a model for the electromagnetic background at DAΦNE to which the CZT detector is exposed [26].

4. Conclusions

The SIDDHARTA-2 collaboration is working towards the measurement of intermediate-mass kaonic atoms, which are important for the understanding of the strong interaction in K-multiN systems. For this purpose, the collaboration has developed a new state-of-art Cadmium-Zinc-Telluride (CZT) detector system, which is being applied for the first time in fundamental physics research at a colliders.

The three tests conducted at the DAΦNE collider have successfully demonstrated the capabilities of the CZT detector system for kaonic atoms spectroscopy. The first test confirmed the detector's excellent resolution and background rejection capabilities. The second test further validated the timing performance of the system, showing the time-coincidence peak between the detector and the luminometer. The third test, provided valuable insights into the stability of the apparatus over long data-taking periods and established a reliable calibration method for the system.

These results indicate that the CZT detector system has the potential to significantly enhance future measurements of intermediate-mass kaonic atoms. This will provide new measurements important for the kaon-nucleon interaction and will contribute to refining the theoretical models that describe low-energy strong interactions with strangeness.

PoS(DISCRETE2024)031

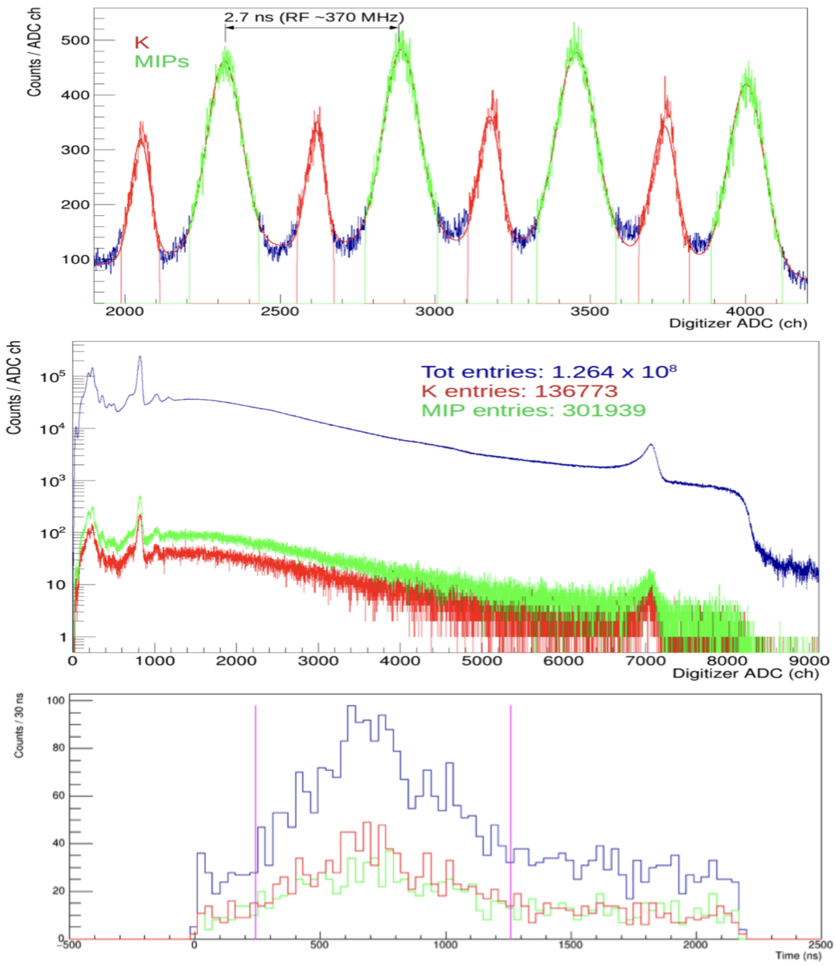

Figure 2: Up: A spectrum of the signal on the luminometer from the first test, and the correspondent kaon selection (red) and minimum ionising particle-related background (green) [23].
Centre: Spectrum of a ^{2}41Am source recorded in the first test, with kaon selection (red) and MIP selection (green), and then correspondent number of events, useful to estimate the background rejection capability [23].
Down: Evidence of a time-coincidence peak between a signal on CZT detector and a signal on luminometer observed in the second test [25].

5. Acknowledgements

We thank H. Schneider, L. Stohwasser, and D. Pristauz-Telsnigg from Stefan Meyer-Institut for their fundamental contribution in designing and building the SIDDHARTA-2 setup. We thank as well the INFN, INFN-LNF and the DAΦNE staff in particular to Dr. Catia Milardi for the excellent working conditions and permanent support. Catalina Curceanu acknowledge University of Adelaide, where part of this work was done (under the George Southgate fellowship, 2024). Part of this work was supported by the Austrian Science Fund (FWF): [P24756-N20 and P33037-N]; the Croatian Science Foundation under the project HRZZ-IP-2022-10-3878; the EU STRONG-2020 project (Grant Agreement No. 824093); the EU Horizon 2020 project under the MSCA (Grant

Agreement 754496); the Japan Society for the Promotion of Science JSPS KAKENHI Grant No. JP18H05402; the SciMat and qLife Priority Research Areas budget under the program Excellence Initiative - Research University at the Jagiellonian University, and the Polish National Agency for Academic Exchange (Grant No. PPN/BIT/2021/1/00037); the EU Horizon 2020 research and innovation programme under project OPSVIO (Grant Agreement No. 101038099). This work was also supported by the Italian Ministry for University and Research (MUR), under PRIN 2022 PNRR project CUP: B53D23024100001.

References

[1] S. Tomonaga and G. Araki, *Effect of the nuclear coulomb field on the capture of slow mesons*, Phys. Rev. **58** (1940) 90.

[2] J. Zmeskal, *From kaonic atoms to kaonic nuclei: A search for antikaon-mediated bound nuclear systems*, Prog. Part. Nucl. Phys. **61** (2008) 512.

[3] C. Curceanu et al., *The modern era of light kaonic atom experiments*, Rev. Mod. Phys. **91** (2019) 025006.

[4] C. Curceanu et al., *Kaonic atoms at the DAϕNE collider: a strangeness adventure*, Front. in Phys. **11** (2023) 1240250.

[5] F. Artibani et al., *The Odyssey of Kaonic Atoms Studies at the DAΦNE Collider: From DEAR to SIDDHARTA-2*, Acta Phys. Polon. B **55** (2024) 5.

[6] A. Cieplý, M. Mai, U.-G. Meißner and J. Smejkal, *On the pole content of coupled channels chiral approaches used for the $\bar{K}N$ system*, Nucl. Phys. A **954** (2016) 17 [1603.02531].

[7] J. Óbertová, E. Friedman, J. Mareš and A. Ramos, *On K^--nuclear interaction, K^--nuclear quasibound states and K^- atoms*, EPJ Web Conf. **271** (2022) 07003.

[8] DEAR collaboration, *Measurement of the kaonic hydrogen X-ray spectrum*, Phys. Rev. Lett. **94** (2005) 212302.

[9] SIDDHARTA collaboration, *A New Measurement of Kaonic Hydrogen X-rays*, Phys. Lett. B **704** (2011) 113 [1105.3090].

[10] F. Sgaramella et al., *Characterization of the SIDDHARTA-2 Setup via the Kaonic Helium Measurement*, Condens. Mat. **9** (2024) 16.

[11] L.G. Toscano et al., *Development of high-efficiency X-ray detectors based on 1 mm thick monolithic SDD arrays*, JINST **19** (2024) P07039.

[12] E. Friedman, A. Gal and C.J. Batty, *Density dependent K- nuclear optical potentials from kaonic atoms*, Nucl. Phys. A **579** (1994) 518.

[13] M. Iwasaki et al., *Observation of the kaonic hydrogen K(alpha) x-ray*, Phys. Rev. Lett. **78** (1997) 3067.

[14] SIDDHARTA collaboration, *Kaonic helium-4 X-ray measurement in SIDDHARTA*, *Phys. Lett. B* **681** (2009) 310.

[15] J-PARC E62 collaboration, *Measurements of Strong-Interaction Effects in Kaonic-Helium Isotopes at Sub-eV Precision with X-Ray Microcalorimeters*, *Phys. Rev. Lett.* **128** (2022) 112503.

[16] J.D. Davies, G.J. Pyle, G.T.A. Squier, C.J. Batty, S.F. Biagi, S.D. Hoath et al., *OBSERVATION OF KAONIC HYDROGEN ATOM X-RAYS*, *Phys. Lett. B* **83** (1979) 55.

[17] M. Izycki et al., *Results of the Search for K Series X-rays From Kaonic Hydrogen*, *Z. Phys. A* **297** (1980) 11.

[18] P.M. Bird, A.S. Clough, K.R. Parker, G.J. Pyle, G.T.A. Squier, S. Baird et al., *KAONIC HYDROGEN ATOM X-RAYS*, *Nucl. Phys. A* **404** (1983) 482.

[19] G.R. Burleson, D. Cohen, R.C. Lamb, D.N. Michael, R.A. Schluter and T.O. White, *Observation of k-mesonic x rays in helium*, *Phys. Rev. Lett.* **15** (1965) 70.

[20] C.J. Batty, S.F. Biagi, S.D. Hoath, P. Sharman, J.D. Davies, G.J. Pyle et al., *MEASUREMENT OF KAONIC AND PIONIC X-RAYS FROM LIQUID HELIUM*, *Nucl. Phys. A* **326** (1979) 455.

[21] S. Baird, C.j. Batty, F.m. Russell, P. Sharman, P.m. Bird, A.s. Clough et al., *MEASUREMENTS ON EXOTIC ATOMS OF HELIUM*, *Nucl. Phys. A* **392** (1983) 297.

[22] F. Artibani, *"new opportunities in kaonic atoms spectroscopy with novel czt detector*, *Frascati Physics Series* **76** (2024) .

[23] L. Abbene et al., *New opportunities for kaonic atoms measurements from CdZnTe detectors*, *Eur. Phys. J. ST* **232** (2023) 1487 [2301.12253].

[24] M. Skurzok et al., *Characterization of the SIDDHARTA-2 luminosity monitor*, *JINST* **15** (2020) P10010 [2008.05472].

[25] A. Scordo et al., *CdZnTe detectors tested at the DAΦNE collider for future kaonic atoms measurements*, *Nucl. Instrum. Meth. A* **1060** (2024) 169060 [2310.15062].

[26] L. Abbene et al., *First Stability Characterization for a CZT Detection System in an e^+e^- Collider Environment*, *Sensors* **24** (2024) 7562 [2410.11294].