Frascati Physics Series Vol. 76 (2024)
8TH YOUNG RESEARCHERS' WORKSHOP 'PHYSICS CHALLENGES IN THE LHC ERA'
May 13 and 16, 2024

NEW OPPORTUNITIES IN KAONIC ATOMS SPECTROSCOPY WITH NOVEL CZT DETECTOR

Francesco Artibani
Laboratori Nazionali di Frascati, INFN, Via E. Fermi 54, 00044 Frascati, Italy
Dipartimento di Matematica e Fisica, Università di Roma Tre, Via della Vasca Navale 84, 00146 Roma, Italy

Leonardo Abbene [2], Manuele Bettelli [4], Antonino Buttacavoli [2], Fabio Principato [2], Andrea Zappettini [4], Massimiliano Bazzi [1], Giacomo Borghi [5,6], Damir Bosnar [7], Mario Bragadireanu [8], Michael Cargnelli [3], Marco Carminati [5,6], Alberto Clozza [1], Francesco Clozza [1], Luca De Paolis [1], Raffaele Del Grande [1,9], Kamil Dulski [1], Laura Fabbietti [9], Carlo Fiorini [5,6], Ivica Friščić [7], Carlo Guaraldo [1†], Mihail Iliescu [1], Masahiko Iwasaki [10], Aleksander Khreptak [11], Simone Manti [1], Johann Marton [3], Pawel Moskal [11,12], Fabrizio Napolitano [1], Szymon Niedźwiecki [11,12], Hiroaki Ohnishi [13], Kristian Piscicchia [14,1], Yuta Sada [13], Francesco Sgaramella [1], Diana Laura Sirghi [1,8,14], Florin Sirghi [1,8], Magdalena Skurzok [11,12], Michal Silarski [11], Antonio Spallone [1], Kairo Toho [13], Lorenzo Toscano [5,6], Marlene Tüchler [3], Johann Zmeskal [3†], Catalina Curceanu [1], Alessandro Scordo [1]

Affiliations.
[1] Laboratori Nazionali di Frascati, INFN, Via E. Fermi 54, 00044 Frascati, Italy
[2] Dipartimento di Fisica e Chimica - Emilio Segrè, Università di Palermo, Viale Delle Scienze, Edificio 18, Palermo, 90128, Italy
[3] Stefan-Meyer-Institut für Subatomare Physik, Dominikanerbastei 16, Wien, 1010, Austria
[4] Istituto Materiali per l'Elettronica e il Magnetismo, Consiglio Nazionale delle Ricerche, Parco Area delle Scienze 37/A, Parma, 43124, Italy
[5] Dipartimento di Elettronica, Informazione e Bioingegneria, Via Giuseppe Ponzio 34, Milano, 20133, Italy
[6] INFN Sezione di Milano, Via Giovanni Celoria 16, Milano, 20133, Italy
[7] Department of Physics, Faculty of Science, University of Zagreb, Bijenička cesta 32, Zagreb, 10000, Croatia
[8] Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), No. 30, Reactorului Street, Magurele, Ilfov, 077125, Romania
[9] Physik Department E62, Technische Universität München, James-Franck-Straße 1, Garching, 85748, Germany
[10] Institute of Physical and Chemical Research, RIKEN, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan
[11] Faculty of Physics, Astronomy, and Applied Computer Science, Jagiellonian University, Łojasiewicza 11, Krakow, 30-348, Poland

[12] Centre for Theranostics, Jagiellonian University , Kopernika 40, Krakow, 31-501, Poland
[13] Research Center for Accelerator and Radioisotope Science (RARIS), Tohoku University, 1-2-1 Mikamine, Taihaku-kun, Sendai, 982-0826, Japan
[14] Centro Ricerche Enrico Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Via Panisperna 89A, Roma, 00184, Italy
† Deceased.

Abstract

Kaonic atoms spectroscopy provides important observables for low-energy strong interactions in strange systems studies. In this paper, an overview of the SIDDHARTA-2 activities in kaonic atoms field is presented.
Particular attention is given to the development of the new cadmium-zinc-telluride detection systems to measure intermediate-mass kaonic atoms. The characteristics of the detector, the results of the two first test measurements in DAΦNE, and some of the physics goals are presented.

1 Introduction

The study of kaonic atoms is crucial to investigate the low-energy regime of the strong interactions with strangeness [1, 2, 3]. Kaonic atoms are systems in which a low energy kaon is trapped by the electromagnetic field of an atoms's nucleus. The kaon, after replacing one of the electrons in the outermost cell, is bounded to the nucleus and forms a kaonic atom. The kaonic atom is created in an highly excited state, and the kaon starts a cascade de-excitation process that, in its last part, is radiative. In the last levels, the kaon and the nucleus are close enough to experience strong interactions together with the electromagnetic one. A schematic image representing these three processes is reported in Figure 1.
The presence of the additional strong interaction, from a spectroscopic point of view, reflects in a shift ϵ on the energy of the level calculated with Quantum-ElectroDynamics (QED) only, and in a widening Γ of the level, caused by the limited lifetime of the level before the kaon is absorbed by the nucleus [4]. These observables are linked to the scattering lengths, that at vanishing relative energy is direcly related to the cross section, relevant for the theories studying the strong interactions at low energy.
The SIDDHARTA-2 collaboration performs high precision kaonic atoms studies. After the important measure of the shift and the width of kaonic hydrogen, done by the SIDDHARTA experiment at DAΦNE [5], the main goal of SIDDHARTA-2 is to measure the shift and width of the kaonic deuterium. Thanks to these two measurements together, it will be possible to extract the isospin-dependent antikaon-nucleon scattering lenghts.
The kaonic atoms data are also important to improve and test new models on the kaon-nucleon (K-N) and kaon-multinucleon (K-multiN) interactions at threshold. Indeed, they provide unique observables at (even below) threshold for the strong interaction, and these observables are direct input to the theory. For this reason, the collaboration is aiming to measure kaonic atoms' shift and width for different mass ranges. Focusing on the light and intermediate mass range, the existing dataset of kaonic atoms measurement [12] reports the results of experiments done in the '70s-'80s, often incompatible between each other.
The SIDDHARTA-2 collaboration is also planning to measure intermediate mass kaonic atoms, exploiting a new cadmium-zinc-telluride (CZT, CdZnTe) detector. In test measurements, this promising semiconductor showed good feature in terms of resolution and efficiency in a wide energy range (from keV to MeV), and, differently from other X-ray detectors, it works at room temperature, making it ideal to build reliable and compact setups [6, 7, 8]. It is the first application of such a technology in a collider experiment, and important tests about the feasibility of a kaonic atoms experiments in a collider paved the way for a new generation of CZT detectors with applications on collider experiments and on particle

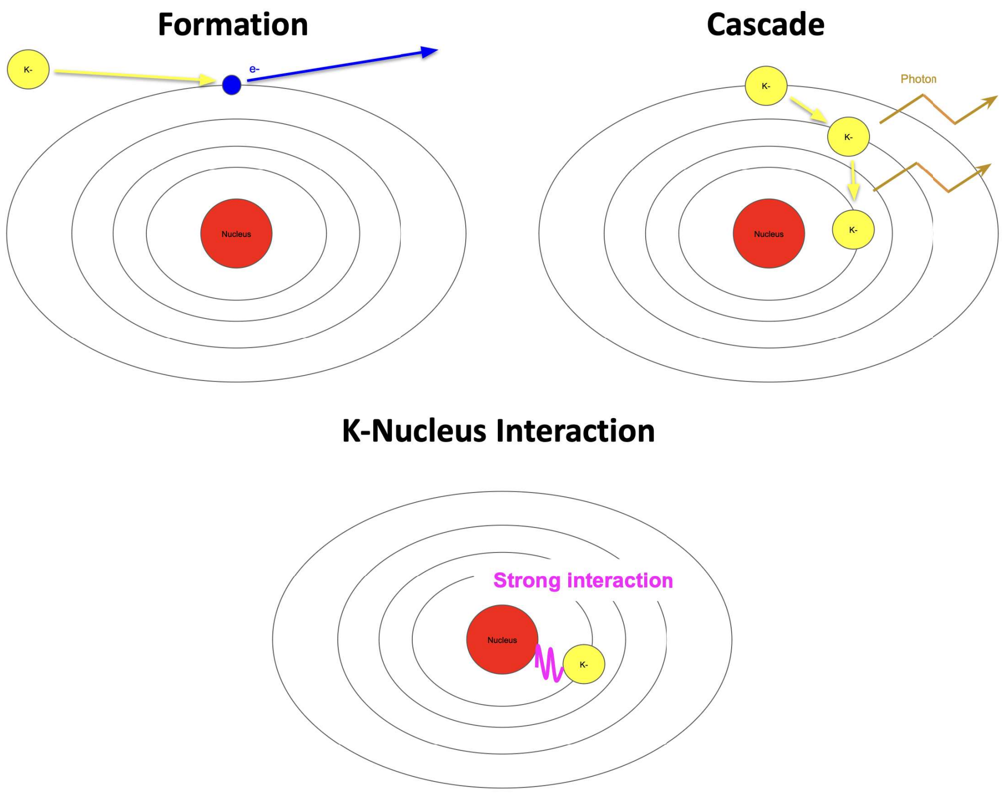

Figure 1: *Schematic representation of the kaonic atom's processes: Formation, Cascade and Strong Interaction. The kaon is represented in yellow, the nucleus in red, the electrons in green, the X-rays coming from the cascade process in orange, and the strong interaction in the last level in purple.*

and nuclear physics. In section 2, the detection system and the first outcomes of the tests in DAΦNE are summarized.

2 The Cadmium-Zinc-Telluride Detector

CZT is a promising material in the field of radiation detectors for X-ray spectroscopy. This compound semiconductor, a ternary compound of cadmium, zinc and tellurium, attracted increasing interest as X-ray and γ-ray detector in the last decades, because of the good performance in terms of resolution, linearity and fast response at room temperature. This unique features are appealing for the possibility to produce incredibly versatile, reliable and compact detectors for the X-ray and γ-ray, without the need of a cooling system.
Following important applications in various research fields, the SIDDHARTA-2 collaboration built a new CZT detector system foreseeing one of the first application of this semiconductor in a collider [9, 10, 11]. The system, in its last configuration, is composed of two modules of eight $13\,\mathrm{mm} \times 15\,\mathrm{mm} \times 5\,\mathrm{mm}$ quasi-hemispherical CZT detectors provided by REDLEN in a thin aluminum box. The detectors present a custom electronics developed within the collaboration to increase the performances: a 3D-printed detector holder with electrical connection to cathode and anode electrodes, Charge Sensitive Preamplifiers (CSPs)

and a Digital Pulse Processing (DPP) system, described accurately in [8, 10]. A view of a module of the detector is reported in Figure 2.

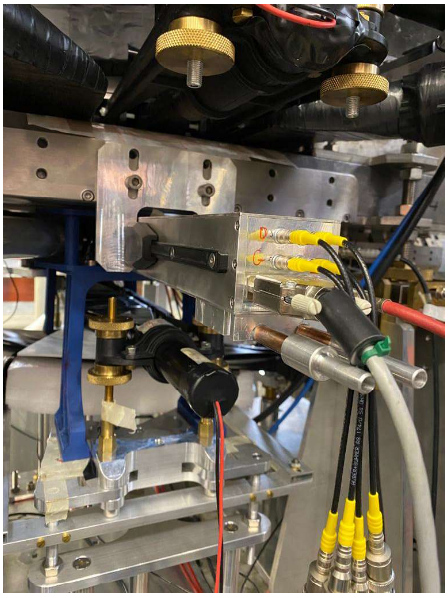

Figure 2: *Photo of the aluminum box containing the four CZT detectors installed near the DAΦNE collider's beam pipe, during a test measurement.*

The collaboration performed two important tests of the detector. These tests represent the first spectroscopic measurements using a CZT detector in a collider environment. The resolution, the linearity and the fast response of the detector were tested, obtaining good results despite the high background of the DAΦNE collider. In Figure 3, a spectrum collected with an Americium (^{2}41Am) source and beam on in the first test in DAΦNE [10] with the CZT detector is reported. Two peaks of the ^{2}41Am source were visible, together with escape peaks. The resolutions resulted to be 6% at 60 keV and of 2.2% at 511 keV. The test confirmed that a CZT detectors can be used in colliders despite the high background. The results on linearity and fast timing are reported in [9].

3 The Physics Case: Intermediate-mass Kaonic Atoms

The CZT detector will be used to perform intermediate-mass kaonic atoms measurements at the DAΦNE collider or elsewhere.
In particular, some kaonic atoms present interesting physics cases and new measurements are requested by the theoretical community:

- **Kaonic Oxygen and Kaonic Carbon.** These two kaonic atoms deserve a particular attention. Indeed, these two measurements exhibit a large uncertainty comparing to the others following the table in [12]. This causes problems in the phenomenological models because they are the boundary elements between light and heavy ones, and more precise results have important implications, for example, on the description of the nuclear density distribution [13].

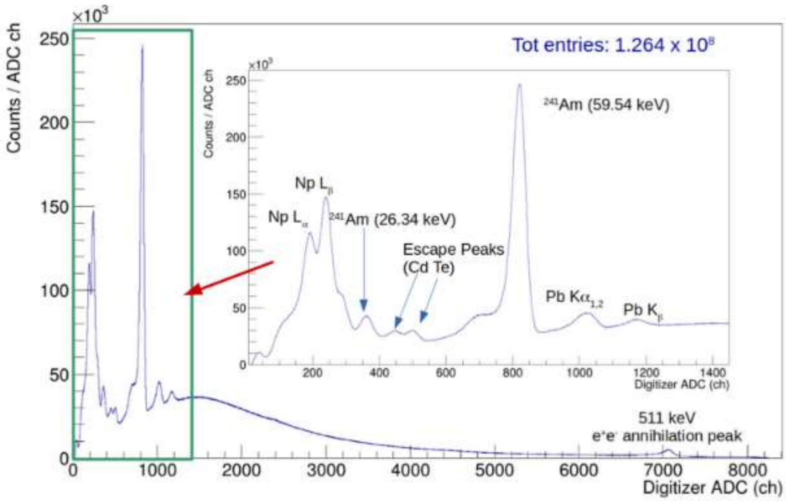

Figure 3: *Spectrum collected with the CZT detector and the DAΦNE beam on during the test described in* [10]*. The annihilation peak at 511 keV and the two peaks coming from the lead shielding scintillation are visible together with the Americium source spectrum. In the box a zoom on the source's peaks around 26 keV and 60 keV is reported.*

- **Kaonic Aluminum, Kaonic Sulfur, Kaonic Copper.** These atoms exhibit two (three in the case of sulfur) incompatible measurements, that reflect in huge uncertainties in the models on K-multiN interactions in that range [14]. A new, precise, measurement, would finally solve this problem.
- **Kaonic Lead.** The kaonic lead, beside the important role in the low-energy strong interactions with strangeness, has also applications in the kaon mass calculation. The kaon mass is one of the open problem in particle physics [15]. A new HPGe detector was arranged by the SIDDHARTA-2 collaboration with the aim of measuring kaonic lead transitions and the kaon mass. The experiment is already providing first results [16], and parallel kaonic lead measurement with CZT detector would help to confirm these results and extend the range of the transitions measured by the collaboration.

In Table 1, a list of kaonic atoms transitions, calculated with relativistic effects based on the calculations in [17], which can be measured by CZT, is reported.

4 Conclusions

New measurements of kaonic atoms are needed by the theoretical community working in the studies of strong interaction at low energies. The SIDDHARTA-2 collaboration, beside the groundbreaking measurement of the kaonic deuterium, which is the main goal of the experiment, is also planning new kaonic atoms measurement from the whole periodic table. To measure intermediate mass kaonic atoms, the collaboration developed an innovative CZT detector system, tested successfully for the first time in the DAΦNE collider.

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 EXOTICA project of the Ministero degli Affari Esteri e della Cooperazione Internazionale, PO22MO03; the Croatian Science Foundation under the project IP-2018–01-8570; 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. C. Curceanu *et al*, Rev. Mod. Phys. **91**, 025006 (2019).
2. F. Artibani, F. Clozza *et al*, Acta Phys. Pol. B **55**, 5-A2 (2024).
3. C. Curceanu *et al*, Front. Phys. **11** (2023).
4. A. Cieplý and M. Mai and Ulf-G. Meißner and J. Smejkal, Nucl. Phys. A **954**, 17-40 (2016).
5. M. Bazzi *et al*, Phys. Lett. B **704**, 113-117 (2011).
6. L. Abbene and G. Gerardi, J. Synchrotron Radiat. **22**, 1190-1201 (2015).
7. L. Abbene *et al*, J. Synchrotron Radiat. **24**, 429-438 (2017).
8. L. Abbene *et al*, J. Synchrotron Radiat. **27**, 319-328 (2020).
9. A. Scordo *et al*, NIM A **1060**, 169060 (2024).
10. L. Abbene *et al*, EPJ ST **232**, 1487-1492 (2023).
11. L. Abbene *et al.* Sensors. **23(17)**, 7328, (2023)
12. E. Friedman and A. Gal and C. J. Batty, Nucl. Phys. A **579**, 518-538 (2024).
13. H. De Vries and C. W. De Jager and C. De Vries, At. Data Nucl. Data Tables **36**, 495-536 (2024).
14. C.J. Batty and E. Friedmann and A. Gal, Phys. Rep. **287**, 385-445 (2024).
15. S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)
16. D. Bosnar *et al*, Kaonic lead feasibility measurement at DAΦNE to solve the charged kaon mass discrepancy, eprint (2024).
17. O. Gorceix *et al* J. Phys. B: Atom. Mol. Phys. **20** 639 (1987)

Table 1: *Table reporting kaonic atoms reference energies in keV.*

Kaonic Aluminum				
Transition	Non - relativistic Transition Energy	Relativistic Effects	**Transition Energy**	Measured Shift
3-2	302.293	1.407	**303.700**	Never Measured
4-3	105.803	0.767	**106.570**	- 0.130 ± 0.050 - 0.076 ± 0.014
5-4	48.9715	0.2585	**49.230**	//
6-5	26.6018	0.1052	**26.707**	//

Kaonic Sulfur				
Transition	Non - relativistic Transition Energy	Relativistic Effects	**Transition Energy**	Measured Shift
4-3	160.753	1.322	**162.075**	- 0.550 ± 0.06 - 0.43 ± 0.12 - 0.462 ± 0.054
5-3	235.158	1.775	**236.933**	Never Measured
5-4	74.4055	0.4525	**74.858**	//
6-5	40.4178	0.1872	**40.605**	//

Kaonic Copper				
Transition	Non - relativistic Transition Energy	Relativistic Effects	**Transition Energy**	Measured Shift
5-4	246.411	2.274	**248.685**	- 0.240 ± 0.022 - 0.377 ± 0.048
6-4	380.264	3.235	**383.499**	Never Measured
6-5	133.853	0.961	**134.814**	//
7-6	80.709	0.464	**81.173**	//
8-7	52.3833	0.2457	**52.629**	//

Kaonic Lead				
Transition	Non - relativistic Transition Energy	Relativistic Effects	**Transition Energy**	Measured Shift
8-7	421.271	4.903	**426.174**	- 0.020 ± 0.012
9-8	288.822	2.800	**291.622**	//
10-9	206.593	1.703	**208.296**	//
11-10	152.855	1.087	**153.942**	//
12-11	116.259	0.720	**116.979**	//
13-12	90.4769	0.4921	**90.969**	//
14-13	71.791	0.344	**72.135**	//
15-14	57.917	0.247	**58.164**	//