IL NUOVO CIMENTO **47 C** (2024) 285
DOI 10.1393/ncc/i2024-24285-6

Communications: SIF Congress 2023

The SIDDHARTA-2 experiment for high precision kaonic atoms X-ray spectroscopy at DAΦNE

F. Sgaramella(1), L. Abbene(2), C. Amsler(3), F. Artibani(1)(4), M. Bazzi(1), D. Bosnar(5), M. Bragadireanu(6), A. Buttacavoli(2), M. Cargnelli(2), M. Carminati(7)(8), A. Clozza(1), F. Clozza(1), G. Deda(7)(8), R. Del Grande(9)(1), L. De Paolis(1), K. Dulski(1)(10)(11), L. Fabbietti(9), C. Fiorini(7)(8), I. Friščić(5), C. Guaraldo(1), M. Iliescu(1), M. Iwasaki(12), A. Khreptak(1)(10), S. Manti(1), J. Marton(3), P. Moskal(10)(11), F. Napolitano(1), S. Niedźwiecki(10)(11), H. Ohnishi(13), K. Piscicchia(14)(1), F. Principato(2), A. Scordo(1), M. Silarski(10), D. Sirghi(14)(1)(6), F. Sirghi(1)(6), M. Skurzok(10)(11), A. Spallone(1), K. Toho(13), M. Tüchler(3), O. Vazquez Doce(1), J. Zmeskal(3) and C. Curceanu(1)

(1) *INFN, Laboratori Nazionali di Frascati - Frascati, Italy*
(2) *University of Palermo, Department of Physics and Chemistry - Palermo, Italy*
(3) *Stefan-Meyer-Institut für Subatomare Physik - Vienna, Austria*
(4) *Università degli Studi di Roma Tre, Dipartimento di Fisica - Roma, Italy*
(5) *Department of Physics, Faculty of Science, University of Zagreb - Zagreb, Croatia*
(6) *Horia Hulubei National Institute of Physics and Nuclear Engineering - Măgurele, Romania*
(7) *Politecnico di Milano, Dip. di Elettronica, Informazione e Bioingegneria - Milano, Italy*
(8) *INFN, Sezione di Milano - Milano, Italy*
(9) *Excellence Cluster Universe, Technische Universität München - Garching, Germany*
(10) *Faculty of Physics, Astronomy, and Applied Computer Science, Jagiellonian University Kraków, Poland*
(11) *Center for Theranostics, Jagiellonian University - Krakow, Poland*
(12) *RIKEN - Tokyo, Japan*
(13) *Research Center for Electron Photon Science (ELPH), Tohoku University Sendai, Japan*
(14) *Centro Ricerche Enrico Fermi, Museo Storico della Fisica e Centro Studi - Roma, Italy*

received 12 March 2024

Summary. — High precision X-ray spectroscopy of light kaonic atoms provides valuable information on kaon-nucleus interaction at threshold, allowing to investigate the strong interaction in the strangeness sector at the low-energy frontier. The SIDDHARTA-2 experiment at the DAΦNE collider of INFN-LNF is performing the challenging measurement of the kaonic deuterium 2p→1 s transition which together with the kaonic hydrogen measurement performed by SIDDHARTA, will allow to extract the isospin-dependent antikaon-nucleon scattering lengths. To achieve this goal, the optimization of the setup to maximize the signal over background ratio is a crucial step. This paper presents the SIDDHARTA-2 experiment and its optimization through the first observation of kaonic neon transitions. The excellent electromagnetic background reduction factor ($\sim 10^4$) paves the way not only to the measurement of kaonic deuterium, but also to a new era of selected kaonic atom measurements along the periodic table.

1. – The physics of kaonic atoms

The strong interaction is fundamental to explain the structure and stability of matter. Governed by Quantum Chromodynamics (QCD), its importance spans from nuclear and particle physics [1, 2] to astrophysics [3, 4] including the structure of neutron stars [5, 6]. Despite significant advances, the low-energy regime of QCD is still not fully understood. The main challenge arises from the non-perturbative nature of QCD at low energies. Hadronic atoms [7, 8], systems where a negatively charged hadron is electromagnetically bound to a nucleus, offer the opportunity to investigate the low-energy QCD with high precision. In this context, kaonic atoms represent an interesting scientific case since kaons are hadrons containing a strange quark. The main effect of the strong interaction between the kaon and the nucleus, is a shift and a broadening of the binding energy of the atomic level with respect to the purely QED calculated value. The shift and width of the energy level reflect, respectively, the nature of strong interaction (repulsive or attractive) and the finite lifetime of the kaon in the atomic orbit, due to the nuclear absorption. These two observables can be precisely measured through X-ray spectroscopy of kaonic atoms, providing the necessary experimental inputs for the development of theoretical models used to describe the kaon-nucleus interaction at low-energy.

2. – The SIDDHARTA-2 experiment

SIDDHARTA-2 aims to perform high precision X-ray spectroscopy of kaonic atoms to investigate the antikaon-nucleon strong interaction in the low-energy regime. In particular, SIDDHARTA-2 will perform the first measurement ever of kaonic deuterium X-ray transitions to the fundamental level. The combined analysis of the kaonic deuterium 1 s level measurement with the kaonic hydrogen one, already performed by the SIDDHARTA experiment [9], will allow to extract the experimental $\overline{K}$-nucleon scattering length. Moreover, it will provide essential inputs to test the various theoretical models used to describe the antikaon-nucleon interaction [10]. This measurement is challenging due to the low yield of the kaonic deuterium transition to the fundamental level, expected to be a factor of about 10 lower than that of kaonic hydrogen. By using new state-of-the-art X-ray detectors, and implementing innovative veto systems for background suppression [11, 12], the SIDDHARTA-2 Collaboration overcomes the difficulty associated with the low kaonic deuterium X-ray yield. The setup is currently installed at the interaction region of the $\mathrm{e}^+\mathrm{e}^-$ DAΦNE collider [13, 14] of INFN-LNF. DAΦNE delivers low momentum (127 MeV/c) charged kaons ($\mathrm{K}^+\mathrm{K}^-$) pairs coming from ϕ meson decay. The kaon trigger (KT) of the experiment consists of two plastic scintillators placed in the vertical plane above and below the e^+e^- interaction region, used to detect the back-to-back emitted $\mathrm{K}^+\mathrm{K}^-$. Once the kaons are triggered, they pass through a thin degrader made of some hundred microns of Mylar sheets and enter a cylindrical cryogenic target cell filled with gas. The degrader's thickness was tuned to maximize the kaons stopped in the gas target [15]. Upon stopping, the K^- is captured into a kaonic atom from which it decays emitting X-rays in the range of several keV before being absorbed by the nucleus. The gaseous cryogenic target is surrounded by 384 Silicon Drift Detectors (SDDs) with a thickness of 450 μm, specifically developed for high precision X-ray spectroscopy. The good energy (160 eV at 6.4 keV), and time (∼500 ns) resolution (FWHM) as well as the excellent linear response of the SDD system are key features for performing the kaonic deuterium measurement with high precision [16, 17]. In addition, the setup is equipped with several veto systems [11, 12] crucial to increase the signal-to-background ratio.

2·1. *Setup optimization.* – In preparation for the kaonic deuterium measurement, the SIDDHARTA-2 setup was optimized using the kaonic neon high-n transition measure-

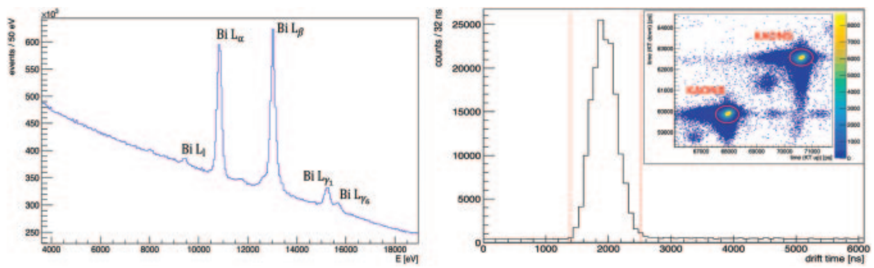

Fig. 1. – Left: inclusive energy spectrum. Right: kaon trigger time distribution given by the mean-time measured from the top (KT up) and bottom (KT down) scintillators.

ments. In particular, the SDDs' time response and the kaon trigger rejection factor have been optimized to reject as much as possible the electromagnetic background generated by particles lost by DAΦNE beams due to the beam-gas interaction and the Touschek effect. Neon was chosen because of its high yield, allowing for a fast tuning. The target cell was filled with neon at the density of 3.6 g/l and kept at 28 K. Figure 1 shows the inclusive energy spectrum obtained by summing all the SDD calibrated data, corresponding to an integrated luminosity of $10\,\mathrm{pb}^{-1}$. Several fluorescence lines are visible above the continuous background. These lines belong to bismuth, present in the setup materials, and activated by the particles lost from the beams. To reduce the electromagnetic background the KT and the SDDs drift time play a crucial role. Only the events synchronous with the KT signal and with a proper drift time (see fig. 1 (right)) are accepted. In addition, the KT measures the Time-of-Flight (ToF) for traversing particles. Given the different ToF between kaons and Minimum Ionizing Particles (MIPs), this feature allows to distinguish the kaon-induced triggers from those caused by MIPs, as shown in fig. 1 (right). More details on the background suppression are reported in [18]. The combined use of KT and SDDs' drift time allowed to drastically reduce the continuous electromagnetic background and the fluorescence lines by a factor $\sim 10^4$. The resulting preliminary energy spectrum is shown in fig. 2 (left), where the kaonic neon lines (K-Ne) are clearly visible in the energy region from 4 keV to 16 keV. Together with kaonic neon, others lines belonging to kaonic carbon (K-C), oxygen (K-O), and titanium (K-Ti) are present. These lines are coming from the kaons stopped in the Mylar window and in the titanium foil at the top of the target cell. This measurement represents the first observation of the kaonic neon transitions. It demonstrates the good performances of the SIDDHARTA-2

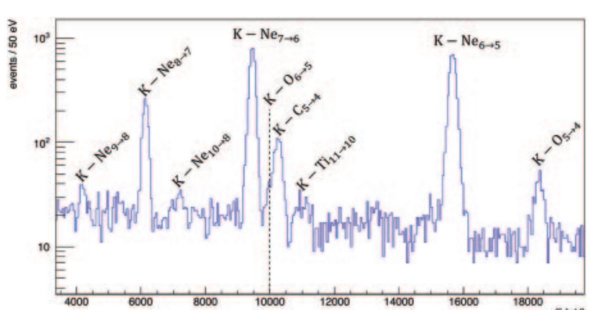

Fig. 2. – Kaonic neon energy spectrum after background suppression. The kaonic neon (K-Ne), carbon (K-C), oxygen (K-O), and titanium (K-Ti) transitions are highlighted.

apparatus, and represents in itself a new source of information, that will allow to better understand the physics of kaonic atoms.

3. – Conclusion and future perspectives

After the optimization phase performed through the kaonic neon measurement, the SIDDHARTA-2 Collaboration initiated (presently ongoing) the data acquisition campaign dedicated to the first measurement of kaonic deuterium. This measurement represents an important step in the exploration of QCD at low energies with strangeness. The good spectroscopic response of the SIDDHARTA-2 apparatus was demonstrated with the first observation of the kaonic neon transitions. Moreover, the excellent background rejection factor and the unique ability of the DAΦNE collider to provide low-energy kaons pave the way for new and more challenging measurements beyond kaonic deuterium. For this reason, the SIDDHARTA-2 Collaboration is planning new measurements of light and heavy atoms along the periodic table, as described in the EXKALIBUR proposal [19,20], which will allow to investigate in depth the kaon-nucleons interaction, and probe the non-perturbative QCD in the strangeness sector.

* * *

We thank C. Capoccia from LNF-INFN and 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 DAΦNE staff for the excellent working conditions and permanent support. Part of this work was supported by the Austrian Science Fund (FWF): P24756-N20 and P33037-N; the EXOTICA project of the Minstero degli Affari Esteri e della Cooperazione Internazionale, PO21MO03; the EU STRONG-2020 project (Grant Agreement No. 824093); the EU Horizon 2020 project under the projects MSCA (Grant Agreement No. 754496) and OPSVIO (Grant Agreement No. 101038099); the Polish Ministry of Science and Higher Education grant No. 7150/E-338/M/2018 and the Polish National Agency for Academic Exchange (grant No. PPN/BIT/2021/1/00037); the Croatian Science Foundation project IP-2022-10-3878.

REFERENCES

[1] Curceanu C. *et al.*, *Rev. Mod. Phys.*, **91** (2019) 025006.
[2] Curceanu C. *et al.*, *Symmetry*, **12** (2020) 547.
[3] Pietri D. *et al.*, *Astrophys. J.*, **881** (2019) 122.
[4] Merafina M. *et al.*, *Phys. Rev. D*, **102** (2020) 083015.
[5] Akaishi Y. and Yamazaki T., *Phys. Lett. B*, **774** (2017) 522.
[6] Drago A., Moretti M. and Pagliara G., *Astron. Nachr.*, **340** (2019) 189.
[7] Tomonaga S. and Araki G., *Phys. Rev.*, **58** (1940) 90.
[8] Conversi M., Pancini E. and Piccioni O., *Phys. Rev.*, **71** (1947) 209.
[9] Bazzi M. *et al.*, *Phys. Lett. B*, **704** (2011) 113.
[10] Cieplý A., Mai M., Meissner U.-G. and Smejkal J., *Nucl. Phys. A*, **954** (2016) 17.
[11] Bazzi M. *et al.*, *JINST*, **8** (2013) T11003.
[12] Tüchler M. *et al.*, *JINST*, **18** (2023) P11026.
[13] Milardi C. *et al.*, presented at *9th IPAC2018, Vancouver BC Canada* (2018).
[14] Zobov M. *et al.*, *Phys. Rev. Lett.*, **104** (2010) 174801.
[15] Sirghi D. *et al.*, *J. Phys. G: Nucl. Part. Phys.*, **49** (2022) 055106.
[16] Miliucci M. *et al.*, *Meas. Sci. Technol.*, **33** (2022) 095502.
[17] Sgaramella F. *et al.*, *Phys. Scr.*, **97** (2022) 114002.
[18] Sgaramella F. *et al.*, *Eur. Phys. J. A*, **59** (2023) 56.
[19] Curceanu C. *et al.*, arXiv:2104.06076 (2021).
[20] Curceanu C. *et al.*, *Front. Phys.*, **11** (2023).