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KAONIC HELIUM-4 L-SERIES YIELD MEASUREMENT AT 2.25 g/l DENSITY BY SIDDHARTA-2 at DAΦNE*

F. Sgaramella[a], M. Bazzi[a], A. Clozza[a], C. Curceanu[a]
L. De Paolis[a], K. Dulski[a], C. Guaraldo[a], M. Iliescu[a]
A. Khreptak[a], S. Manti[a], F. Napolitano[a], A. Scordo[a]
F. Sirghi[a], A. Spallone[a], M. Miliucci[a,b] F. Artibani[a,c]
F. Clozza[a,c], M. Cargnelli[d], J. Marton[d], M. Tüchler[d]
J. Zmeskal[d], L. Abbene[e], A. Buttacavoli[e], F. Principato[e]
D. Bosnar[f], I. Friščić[f], M. Bragadireanu[g], G. Borghi[h]
M. Carminati[h], G. Deda[h], C. Fiorini[h], R. Del Grande[i,a]
M. Iwasaki[j], P. Moskal[k,l], S. Niedźwiecki[k,l], M. Silarski[k,l]
M. Skurzok[k,l], H. Ohnishi[m], K. Toho[m], C. Yoshida[m]
D. Sirghi[n,a], K. Piscicchia[n,a]

[a]Laboratori Nazionali di Frascati INFN Frascati, Italy
[b]ASI, Agenzia Spaziale Italiana, Roma, Italy
[c]University of Rome La Sapienza, Italy
[d]Stefan-Meyer-Institut für Subatomare Physik, Vienna, Austria
[e]Department of Physics and Chemistry (DiFC) — Emilio Segrè
University of Palermo, Palermo, Italy
[f]Department of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia
[g]Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH)
Măgurele, Romania
[h]Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria
Milano, Italy
[i]Excellence Cluster Universe, Technische Universiät München Garching, Germany
[j]RIKEN, Tokyo, Japan
[k]Faculty of Physics, Astronomy, and Applied Computer Science
Jagiellonian University, Kraków, Poland
[l]Center for Theranostics, Jagiellonian University, Kraków, Poland
[m]Research Center for Electron Photon Science (ELPH), Tohoku University
Sendai, Japan
[n]Centro Ricerche Enrico Fermi — Museo Storico della Fisica e Centro Studi
e Ricerche "Enrico Fermi", Roma, Italy

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This article presents the results of the kaonic helium-4 measurement conducted by the SIDDHARTA-2 experiment, aiming to provide crucial insights into the low-energy strong interaction in the strangeness sector. High-precision X-ray spectroscopy is used to examine the interaction between negatively charged kaons and nuclei in atomic systems. The SIDDHARTA-2 setup was optimized through the kaonic helium-4 measurement in preparation for the challenging kaonic deuterium measurement. The kaonic helium-4 measurement at a new density of 2.25 g/l is reported, providing the absolute and relative yields for the L-series transitions, which are essential data for understanding kaonic atom cascade processes.

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1. Introduction

Light kaonic atoms are a unique tool to investigate the low-energy strong interaction in the strangeness sector with implications from nuclear and particle physics to astrophysics [1–4]. A kaonic atom is an atomic system consisting of a negatively charged kaon (K^-) and a nucleus bound by the electromagnetic interaction. The K^- is captured in a highly-excited state, replacing one of the electrons of the atom, and decays to lower-energy levels where the strong interaction between the kaon and the nucleus provokes a shift and a broadening of the energy level. Precise measurements of X-ray emission from kaonic atoms provide crucial information on the kaon–nucleus interaction at the threshold without the need for extrapolation as required in scattering experiments. In particular, the measurement of the kaonic hydrogen (K^-H) and deuterium (K^-d) $1s$ energy level shift and width induced by the strong interaction will allow to set constrains on the theoretical models [5–9] used to describe the K^-N interaction at a low energy. In 2009, the SIDDHARTA Collaboration performed the most precise measurement of kaonic hydrogen $2p \to 1s$ transition [10], providing a fundamental constrain for the K^-p scattering length. In contrast, the much more challenging kaonic deuterium measurement is still missing. Since the expected kaonic deuterium $2p \to 1s$ X-ray yield is at least a factor 10 lower than the kaonic hydrogen yield, the SIDDHARTA-2 Collaboration developed a new experimental apparatus to face the challenging kaonic deuterium $2p \to 1s$ measurement.

The optimization and characterization of the X-ray detectors, trigger and veto systems of the SIDDHARTA-2 apparatus were mandatory to establish the optimal working condition in the view of the kaonic deuterium measurement. The commissioning phase was conducted through the measurement of kaonic helium $3d \to 2p$ transition, taking advantage of its high X-ray yield. Moreover, the analysis of the kaonic helium-4 data allows to obtain new information to investigate the de-excitation processes of kaonic atoms. In this paper, we report on the kaonic helium-4 measurement, providing the X-ray yield for the L-series transitions at a new density (2.25 g/l).

2. The SIDDHARTA-2 experiment

The schematic layout of the SIDDHARTA-2 setup is shown in Fig. 1. The apparatus is currently installed at the interaction region of the DAΦNE [11] collider of Istituto Nazionale di Fisica Nucleare — Laboratori Nazionali di Frascati (INFN-LNF). DAΦNE delivers low-momentum (127 MeV/c) charged K^+K^- pairs coming from the ϕ meson decay. The apparatus has been developed to face the very small kaonic deuterium X-ray yield [12] and the difficulty to perform X-ray spectroscopy in a high radiation environment, like that of a collider. The trigger of the experiment consists of two plastic scintillators placed in the vertical plane above and below the beam pipe to detect the two charged kaons. Once the kaons are triggered, they pass through a thin degrader [13] made of a few hundred microns of mylar sheets and then enter in a cylindrical target cell made of high-purity aluminium frames and 150 μm thick Kapton. The target cell can be filled with different

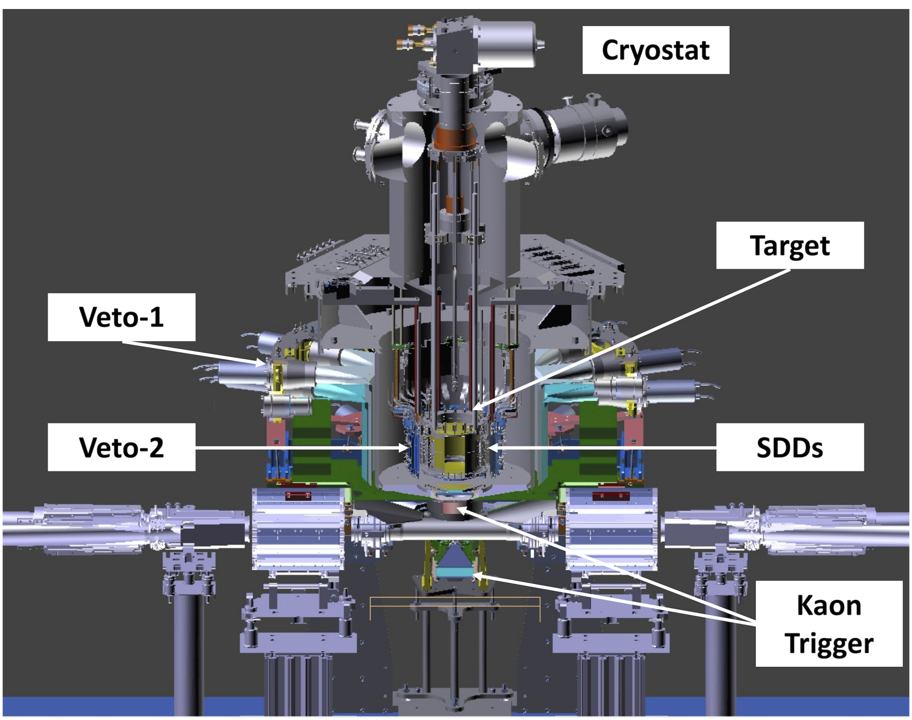

Fig. 1. Schematic layout of the SIDDHARTA-2 apparatus.

types of gases to study the kaon–nucleus interaction for different atoms. The cryogenic system is used to cool down the gas, increasing its density, and consequently, the probability of stopping the kaons. Upon stopping, a K^- is captured into a kaonic atom that emits X-rays in the range of several keV before being absorbed by the nucleus. The gaseous cryogenic target is surrounded by 384 state-of-the-art Silicon Drift Detectors (SDDs) developed specifically for high-precision light kaonic atoms X-ray spectroscopy. The good energy and time resolution, 158 eV at 6.4 keV and 450 ns, respectively, as well as the excellent linear response of the SDD system are key features for performing the kaonic deuterium measurement with high precision [14–16]. In addition, the setup is equipped with several veto systems [17, 18] crucial to increase the signal-to-background ratio. Moreover, a luminosity monitor [19], made with plastic scintillators based on the J-PET technology, is used to monitor the beam quality and luminosity in real-time.

3. The kaonic helium L-series X-ray yield at 2.25 g/l density

There are two main interests in kaonic helium X-ray measurements; one is the shift and width induced by strong interaction between the kaon and the nucleus [13], the other is the intensities of the X-rays transitions for each kaon stopped in the target, also known as the absolute yields. The experimental results for the absolute yields are fundamental to test and develop the cascade model [20–22] which consists of several processes that describe the de-excitation of a kaonic atom starting from the capture of a kaon to its final absorption by the nucleus. The X-ray emission is one of the main processes during the transitions to lower levels, but not all kaons reach the fundamental level. Other processes, such as the Stark effect [23], can induce the kaon nuclear absorption from high-energy levels, drastically reducing the X-ray yields. Since the Stark effect becomes more prevalent with density, experimental values of X-ray yield at new densities are the key to comprehend the kaonic atom cascade processes.

In Spring 2023, The SIDDHARTA-2 Collaboration performed the kaonic helium-4 measurement at the density of 2.25 ± 0.11 g/l.

The kaonic helium-4 energy spectrum for 12 pb^{-1} is shown in Fig. 2. The kaonic helium L-series transitions are clearly visible at 6.4 keV (L_α), 8.7 keV (L_β), and 9.7 keV (L_γ). Other kaonic atom lines, such as the kaonic carbon (KC) high-energy transitions, are present due to the interaction of kaons with the Kapton entrance windows of the target cell.

The kaonic helium-4 L_α absolute yield is determined by the following equation:

$$Y = \frac{\epsilon^{\mathrm{exp}}}{\epsilon^{\mathrm{MC}}} = \frac{N^{\mathrm{exp}}_{\text{X-ray}}/N^{\mathrm{exp}}_{\mathrm{KT}}}{N^{\mathrm{MC}}_{\text{X-ray}}/N^{\mathrm{MC}}_{\mathrm{KT}}}\,, \tag{1}$$

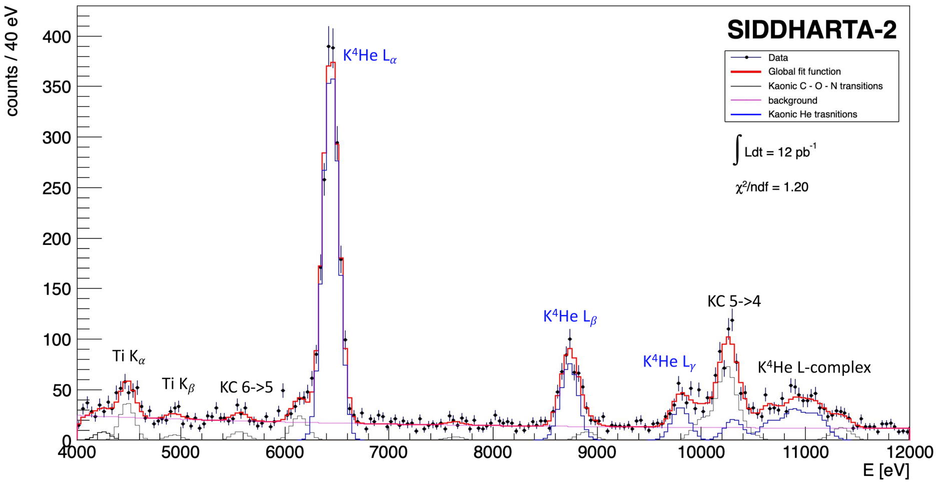

Fig. 2. Kaonic helium-4 energy spectrum. The kaonic helium L-series transitions are visible together with the kaonic carbon high-n transitions (KC $6 \to 5$ and KC $5 \to 4$). The red solid line shows the fit function of the spectrum. The blue line shows the L-series kaonic helium-4 transitions.

where $N^{\mathrm{exp}}_{\mathrm{X-ray}}$ is the number of the L_α events detected, normalized to the number of kaons triggered ($N^{\mathrm{exp}}_{\mathrm{KT}}$). The denominator represents the detection efficiency estimated from the Monte Carlo simulation using Geant 4. The simulation takes into account the geometry of the SIDDHARTA-2 apparatus and the features of the K^+K^- pairs delivered by DAΦNE. For each K^- stopped in the helium target, an L_α X-ray is generated isotropically.

While the $N^{\mathrm{exp}}_{\mathrm{KT}}$ is directly provided by the kaon trigger, the number of L_α events was extracted by the fit of the energy spectrum. The L-series transitions were described through a Voigt function to account for the intrinsic line width due to the possible presence of the strong interaction. The other peaks have been fitted by a Gauss function since the widening induced by strong interaction is known to be negligible [24].

A first-degree polynomial was used to reproduce the continuous background below the peaks.

The absolute yields for the kaonic helium-4 L_α transition and the relative yield for the L_β and L_γ transitions are reported in Table 1 with their statistical uncertainties. The main source of systematic uncertainty is related to the determination of the gas density. The density is determined by the measurement of the gas temperature and pressure. The uncertainties induced by the temperature and pressure sensors lead to a density uncertainty of $\pm 5\%$. This systematic error is purely added to the value provided for the helium gas density. This result adds a new data point for the study of the kaonic helium cascade process, and combined with the measurements of SIDDHARTA [25] and SIDDHARTINO [26] will allow to investigate the de-excitation processes of kaonic atoms along the density scale.

Table 1. The absolute yields of the kaonic helium-4 L_α transition and the relative yields of L_β and L_γ transitions.

Density	2.25 ± 0.11 g/l
L_α $(3d \to 2p)$ yield	0.076 ± 0.003
L_β $(4d \to 2p)/L_\alpha$ $(3d \to 2p)$	0.190 ± 0.027
L_γ $(5d \to 2p)/L_\alpha$ $(3d \to 2p)$	0.082 ± 0.012

4. Conclusions

The kaonic helium-4 measurement at 2.25 g/l density offers new crucial information to refine our knowledge of kaonic atoms and interaction dynamics between kaons and nuclei. The absolute and relative yields of the kaonic helium-4 L-series transitions obtained through precise X-ray spectroscopy provide new data for testing cascade models used to describe the kaonic atom de-excitation processes. This result, combined with previous measurements of SIDDHARTA and SIDDHARTINO, paved the way for an exhaustive investigation of the kaonic atom cascade model along the density scale. Moreover, this measurement demonstrates the potential of the SIDDHARTA-2 apparatus in the view of the challenging kaonic deuterium measurement.

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REFERENCES

[1] C. Curceanu *et al.*, *Rev. Mod. Phys.* **91**, 025006 (2019).

[2] C. Curceanu *et al.*, *Symmetry* **12**, 547 (2020).

[3] M. Merafina *et al.*, *Phys. Rev. D* **102**, 083015 (2020).

[4] A. Drago, M. Moretti, G. Pagliara, *Astron. Nachr.* **340**, 189 (2019).

[5] A. Cieplý, M. Mai, U.-G. Meißner, J. Smejkal, *Nucl. Phys. A* **954**, 17 (2016).

[6] Y. Ikeda, T. Hyodo, W. Weise, *Nucl. Phys. A* **881**, 98 (2012).

[7] M. Mai, U.-G. Meißner, *Eur. Phys. J. A* **51**, 30 (2015).

[8] Z.-H. Guo, J.A. Oller, *Phys. Rev. C* **87**, 035202 (2013).

[9] A. Feijoo, V. Magas, A. Ramos, *Phys. Rev. C* **99**, 035211 (2019).

[10] M. Bazzi *et al.*, *Phys. Lett. B* **704**, 113 (2011).

[11] C. Milardi *et al.*, in: «Proceedings of 9$^{\text{th}}$ International Particle Accelerator Conference (IPAC'18)», *TRIUMF*, Vancouver, BC, Canada April 29–May 4, 2018, pp. 334–337.

[12] SIDDHARTA Collaboration (M. Bazzi *et al.*), *Nucl. Phys. A* **907**, 69 (2013).

[13] SIDDHARTA-2 Collaboration (D. Sirghi *et al.*), *J. Phys. G: Nucl. Part. Phys.* **49**, 055106 (2022).

[14] M. Miliucci *et al.*, *Measur. Sci. Tech.* **32**, 095501 (2021).

[15] M. Miliucci *et al.*, *Measur. Sci. Tech.* **33**, 095502 (2022).

[16] F. Sgaramella *et al.*, *Phys. Scr.* **97**, 114002 (2022).

[17] M. Bazzi *et al.*, *J. Instrum.* **8**, T11003 (2013).

[18] M. Tüchler *et al.*, *J. Phys.: Conf. Ser.* **1138**, 012012 (2018).

[19] M. Skurzok *et al.*, *J. Instrum.* **15**, P10010 (2020).

[20] T. Koike, Y. Akaishi, *Nucl. Phys. A* **639**, 521 (1998).

[21] S.Z. Kalantari, S.S. Hajari, M.D. Kelisani, *Hyperfine Interact.* **209**, 145 (2012).

[22] S. Berezin *et al.*, *Nucl. Phys. B* **16**, 389 (1970).

[23] T.E.O. Ericson, F. Scheck, *Nucl. Phys. B* **19**, 450 (1970).

[24] E. Friedman, A. Gal, C.J. Batty, *Nucl. Phys. A* **579**, 518 (1994).

[25] M. Bazzi *et al.*, *Eur. Phys. J. A* **50**, 91 (2014).

[26] D.L. Sirghi *et al.*, *Nucl. Phys. A* **1029**, 122567 (2023).