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CdZnTe detectors tested at the $DA\Phi NE$ collider for future kaonic atoms measurements

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ABSTRACT

The SIDDHARTA-2 collaboration at the INFN Laboratories of Frascati (LNF) aims to perform important measurements on kaonic atoms. In parallel to the groundbreaking kaonic deuterium measurement, presently running on the DAΦNE collider at LNF, we plan to install additional detectors. The aim is to perform further kaonic atoms' studies, taking advantage of the unique low energy and low momentum spread K^- beam delivered by the at-rest decay of the ϕ meson.

CdZnTe devices are ideal for detecting transitions toward both the upper and lower levels of intermediate-mass kaonic atoms, like kaonic carbon and aluminium. Measuring these transitions can have an important impact on the strangeness sector of nuclear physics.

We present the results obtained in two preliminary tests conducted at DAΦNE in view of measurements foreseen in 2024, with the twofold aim to tune the timing window required to reject the extremely high electromagnetic background, and to quantify the readout saturation effect due to the high rate when placed close to the Interaction Region (IR). In the first test we used a RITEC device and electronics, while for the second one commercial REDLEN detectors were coupled to a frontend electronics customized at the University of Palermo.

The results confirmed the possibility of finding and matching a proper timing window to identify the signal events and proved the better performance in terms of energy resolution of the REDLEN technology with a custom frontend electronics. In both cases, strong saturation effects were confirmed, accounting for a loss

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of almost 90% of the events, which will be overcome by a dedicated shielding structure foreseen for the final experimental setup.

1. Introduction

The energies of the radiative transitions of kaonic atoms, and in particular of those towards their innermost levels where the strong interaction is not negligible, represent ingredients on which the present knowledge on low energy strangeness nuclear physics is built [1]. They have been widely investigated in the 1970's and 1980's, when a systematic study of such systems for a wide set of atoms along the periodic table has been performed. This allowed to set up a dataset [2] which served, until nowadays, as the main experimental input for the development of many theoretical models.

The energies and the widths of such transitions span over a very wide range, going from a few keV up to almost 1 MeV, depending on the Z of the selected atom and on the two levels among which the transition occurs. The choice of the proper detector to measure the kaonic atoms of interest is then crucial, and it has to be taken as a function of many factors, like their efficiency in a given energy range, an energy resolution able to resolve the lines of interest with their natural linewidths, excellent linearity, well-known calibration function, and the capability to work in typically high background environments like particle accelerators, where kaons are produced [1,3–8].

The most recent results on light kaonic atoms, however, cast a shadow on the aforementioned database, since they are not reproducing the results obtained in the past. Furthermore, many of the earliest measurements of the strong interaction-induced shift and width of the lower levels in atoms like carbon, aluminium and sulphur suffer from very large uncertainties [9–12] and, in some cases, they are hard to reproduce with the most recent theoretical models [13]. All these facts renewed the interest in performing a systematic study of kaonic atoms, and the DAΦNE collider at LNF [14,15], with its unique low momentum and low dispersion kaon beam, is the most suitable facility in the world to pursue this scope.

The SIDDHARTA-2 collaboration aims to perform, in parallel with the measurement of kaonic deuterium at DAΦNE, additional measurements on intermediate mass kaonic atoms like KC, KAl and KS, which are strongly demanded by the theoretical community. The transitions of interest for such systems lie in the 30–300 keV range, where CdZnTe devices are the radiation detectors best fulfilling the high efficiency and high-resolution requirements demanded to measure the emitted X-rays with precisions of a few tens of eV, thus improving and testing the results of the older experiments. Moreover, with their excellent performances at room temperature, CdZnTe detectors allow to realize small and compact detection systems, which are easy and fast to be installed and integrated with the existing SIDDHARTA-2 apparatus. The behaviour of CdZnTe devices in high electromagnetic background environments is not, however, well known and ad-hoc crystals and detectors have to be realized to maintain a high efficiency in the whole energy range, without worsening the spectroscopic resolution. Also, it is crucial to define a perfect timing window for the data acquisition to reject the huge amount of background events typical of accelerator environments like DAΦNE.

In 2022, the SIDDHARTA-2 collaboration already performed preliminary tests [16,17] with a small ($1\,\mathrm{cm}^2$) CdZnTe detector installed 45 cm away from the IR. Very promising results in terms of linearity, resolution and high-rate capability were obtained, which triggered the realization of a bigger experimental setup for the physics measurement to be performed in 2024.

In this paper, we present the outcomes of two additional tests performed in the first half of 2023 with CdZnTe devices installed at a few tens of cm from the Interaction Point, aiming at tuning the time selection window for the signal identification and investigating the impact of the high electromagnetic background.

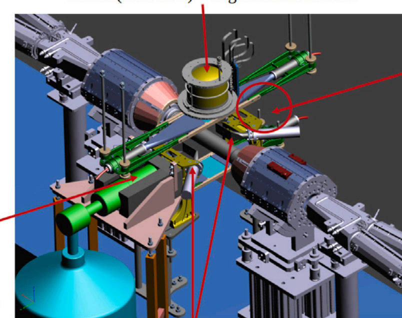

Fig. 1. Top: Schematic of the main components of the SIDDHARTA-2 experimental apparatus where on one side, in the horizontal plane, the setups for the two CdZnTe tests were installed (not in scale).

2. Experimental setup

2.1. The SIDDHARTA-2 luminosity monitor as a trigger system for the CdZnTe measurements

Kaonic atoms are formed when a K^- is stopped in a selected target after its production and back-to-back emission with a K^+ from the Φ decay. Subsequently, the X-rays isotropically emitted during the atomic cascade process [18–20] can be measured by the radiation detector. However, the background of the DAΦNE machine plays a crucial role when the detector needs to be placed close to the Interaction Region (IR), where rates up to $\mathrm{MHz/cm}^2$ level can be reached. The main components of this background are two: a first one, synchronous with the kaonic atoms signal and coming from Minimum Ionized Particles (MIPs) produced within the e^+e^- collision events and releasing energy in the detector, and a second one, asynchronous with the signal and mostly due to particles lost from the beam by Touscheck and beam-gas effects. The hardware rejection of these backgrounds is crucial for the success of the measurements.

To this end, we plan to exploit the already existing SIDDHARTA-2 Luminosity Monitor (LM) as a trigger system for the CdZnTe detectors, which is installed in the SIDDHARTA-2 apparatus at DAΦNE to assess the integrated luminosity [21]. It consists of two plastic scintillators, each read by a pair of PhotoMultipliers (PMTs), placed $\simeq 7.5$ cm away from the IR on the two opposite sides of the beam pipe (see Fig. 1).

The final trigger is given by a quadruple coincidence of the four PMTs, with an additional request of a coincidence with the DAΦNE radiofrequency clock. In this way, a clear signature of an event occurring in time with a collision is obtained. The SIDDHARTA-2 LM allows for a very effective reduction of the acquisition rate, since the $\simeq$ MHz individual rates for the four PMTs reading the signals in the two scintillators drop below 1 kHz when the quadruple coincidence is requested. The individual signals from the two scintillators of the LM provide additional Time-Of-Flight analysis to clearly distinguish between MIPs, mostly coming from the electromagnetic showers created in the magnets before the IR, and a K^+K^- pair (see [21]).

2.2. The CdZnTe detectors

The CdZnTe detectors were placed after the LM scintillator in the anti boost direction of the DAΦNE machine [21], $\simeq 7.5$ cm away from the IR (see Fig. 1), in a position corresponding to a distance between the detectors and the IR of 22 cm.

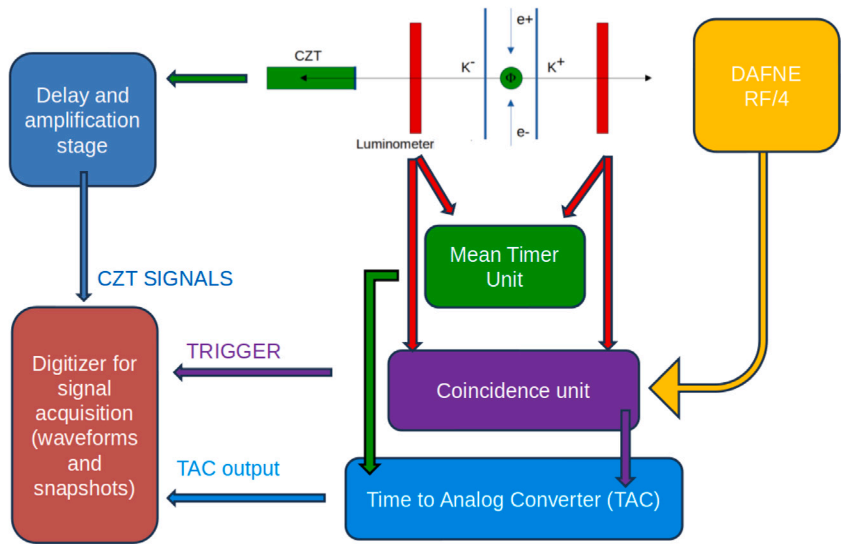

Fig. 2. Schematic of the DAQ logic for the two CdZnTe tests.

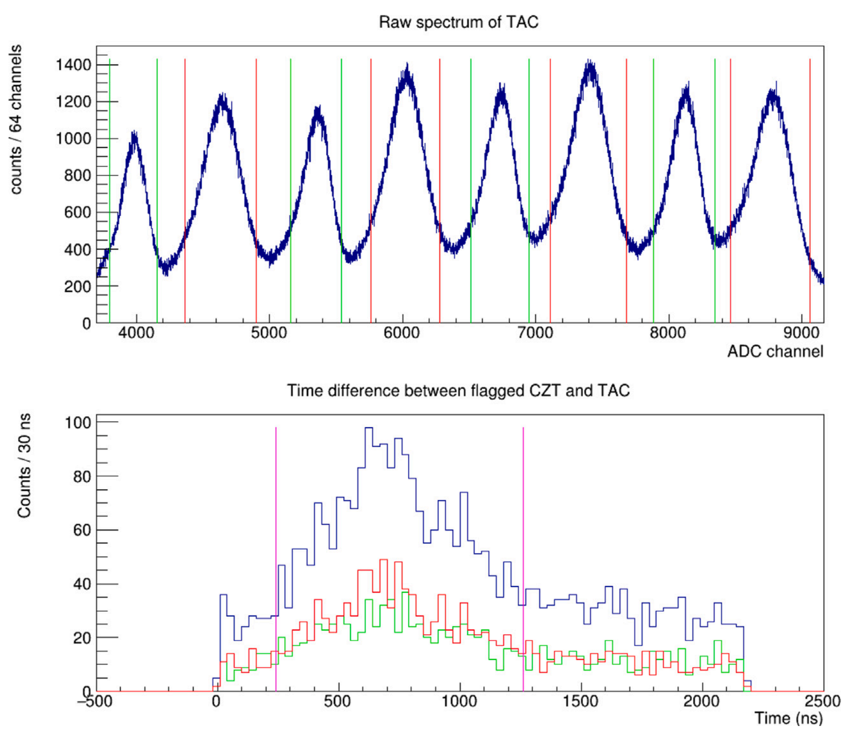

Fig. 3. Top: SIDDHARTA-2 LM TOF spectrum, where windows for Kaons (green) and MIPs (red) time selection are highlighted. Bottom: Timing spectrum of the CdZnTe with respect to the SIDDHARTA-2 LM (blue) with further selection of Kaons (green) and MIPs (red).

The first test was conducted with a RITEC CZT/500 detector system, a hemispherical CdZnTe device of 0.5 cm^3 active volume equipped with a commercial PA101C RITEC preamplifier.

The second test was conducted using four $13 \times 15 \times 5\,mm^3$ quasi-hemispherical CdZnTe detectors provided by Redlen Technologies (M1535) coupled to analogue charge-sensitive preamplifiers (CSPs) and digital pulse processing (DPP) based readout electronics. The four channels of the detection system were AC coupled to hybrid CSPs, developed at DiFC of the University of Palermo, and processed by a 64-channel DPP electronics. The preamplifiers were characterized by an equivalent noise charge (ENC) of about 100 electrons (equivalent to about 1 keV FWHM for CZT detectors) and equipped with a resistive feedback circuit with exponential decay and time constant of 100 μs.

2.3. The DAQ logic

The schematic of the DAQ logic used for both the tests is visible in Fig. 2, and it is very similar to what we used in our previous work [16,17].

The signals from the two scintillators of the LM are processed by an ORTEC 935 Constant Fraction Discriminator (CFD) and then sent to a CAEN N93B Mean Timer unit. The Mean Timer output is then sent to an ORTEC 566 Time-to-Analog Converter (TAC) module as stop signal,

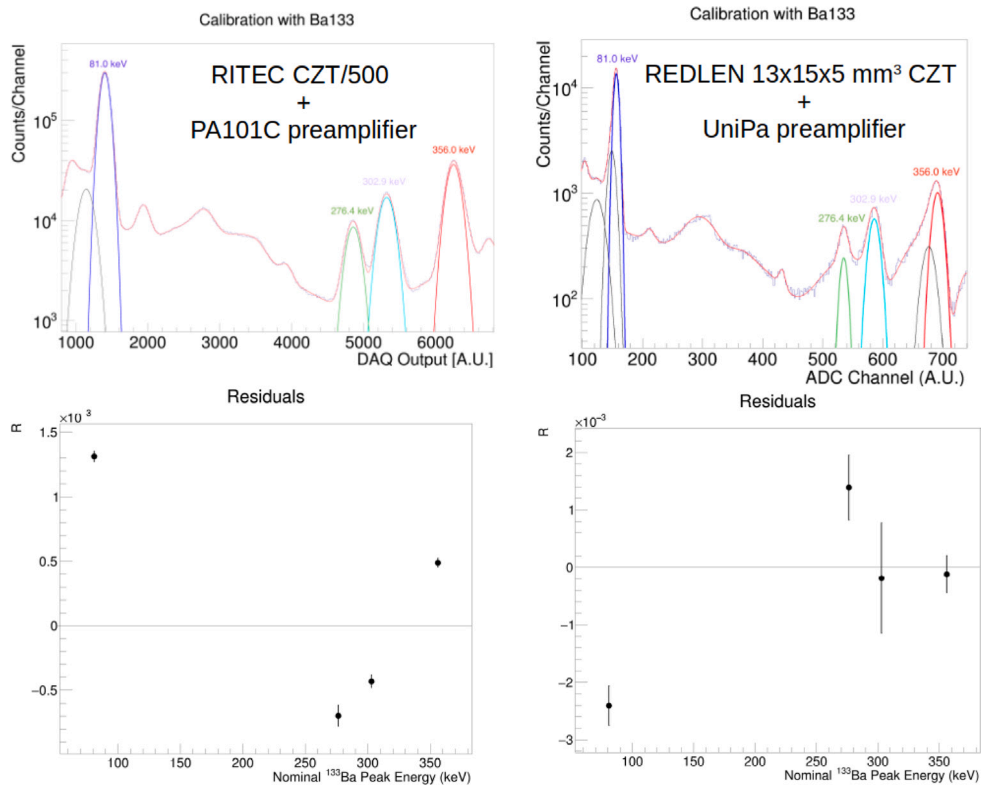

Fig. 4. Top: fitted energy spectra are shown for the CZT/500 (left) and for one of the REDLEN M1535 detectors (right). The gaussians corresponding the four main peaks used for the energy calibration are shown in colours, while the auxiliary ones are shown in black (see text). Bottom: relative deviations of the mean energy values obtained from a fit on the energy calibrated spectra and the nominal ones for the CZT/500 (left) and the REDLEN M1535 CdZnTe system (right).

while the start is given by the triple coincidence between the DAΦNE RF/4 clock signal and the two LM scintillators provided by a CAEN N455 Coincidence Unit module. The TAC output is a signal with an amplitude which is proportional to the start–stop time difference and it is sent to the same digitizer which is acquiring the CdZnTe signals, so resulting in the ADC spectrum shown in the upper part of Fig. 3. Finally, the TAC output and the CdZnTe signals were sent to a CAEN DT5780 and V2740 digitizer for the two tests with the RITEC and REDLEN detectors, respectively. In the latter case, the digitizer was driven by an original firmware developed at the University of Palermo. Both the digitizers also provided the arrival time of the signals with respect to the TAC one. The energy of the CdZnTe signals are obtained from an offline analysis of the individual waveforms acquired by the digitizers.

In the first test, the data were acquired for 30 h, from 30/05/2023 to 31/05/2023, with average electron and positron currents of 793 mA and 507 mA, respectively. The average rate on the SIDDHARTA2 LM was of 18.1 Hz, with a K/MIP ratio of 0.64.

In the second test the data were acquired for 48 h, from 12/07/2023 to 14/05/2023, with average electron and positron currents of 841 mA and 503 mA, respectively. The average rate on the SIDDHARTA2 LM was of 31.5 Hz, with a K/MIP ratio of 0.65.

3. Results

The goal of the first test was to tune the correct timing window for the CdZnTe signals' acquisition in coincidence with the SIDDHARTA-2 LM. The main results are presented in Fig. 3.

In the upper pad, we show the digitizer-converted TOF spectrum obtained from the processing of the LM signals through the TAC module (see Section 2.3 and Fig. 2). The 8 peak structures are due to an hardware limitation; CFD units are limited to work with signals below 200 MHz; thus, it is not possible to use them to discriminate the $\simeq$ 370 MHz radiofrequency (RF) of the DAΦNE collider. The RF/4 is instead used, at a frequency of $\simeq$ 90 MHz. As a consequence, every coincidence event in the LM discriminators can be associated in time with one of the four collisions; this is reflected in the four double structures of Fig. 3 [16,17,21]. The four peaks within the green lines correspond to K^- interacting in the plastic scintillators, while those within the red ones are produced by MIPs. In the lower pad of Fig. 3, the distribution of the time difference between the TAC and the CdZnTe signals is shown in blue, while in red and green the same quantity is shown with the additional kaons (green) or MIPs (red) selection. Similar statistics between kaons and MIPs are expected because of the high flux of MIPs generated in the horizontal plane from the quadrupole magnets placed just before the IR (see Fig. 1). Since the TAC is providing the trigger to the DAQ, there is always a TAC signal in each event; on the contrary, not every TAC signal is followed by a CdZnTe one within the acceptance timing window, and this explains the difference in statistics between the figures in the upper and lower pads. These distributions show how, within a 1 μs timing window, a clear peak of events which occur in time with the LM can be found. It is worth reminding that in this specific test, where no target was present to stop the kaons, both kaons and MIPs reached the detector and could give a signal as clearly visible by the two coloured distributions. The evidence of a time-coincidence peak is a very important result since it confirms the good timing capabilities of CdZnTe and the possibility of using them in kaonic atom measurements.

Another key parameter to monitor was the saturation of the readout electronics induced by the very high rate on the detector. Since the energy of the CdZnTe signals are obtained from an offline analysis of the individual waveforms acquired by the digitizer, the resulting waveform could be not properly analysed if the high rate induces a superposition of several signals. In the first test, due to the limitations of the electronics, these saturating events were hardware-removed, preventing a proper quantification. During the second test such a quantification was instead allowed by the new front-end and readout electronics realized in Palermo. A quantitative analysis performed on

Table 1
Summary of the results obtained with the two systems employed during the tests (see text for more details).

	RITEC CZT/500		REDLEN M1535	
^{133}Ba Peak (keV)	R (10^{-3})	FWHM/E	R (10^{-3})	FWHM/E
81.0	1.3	0.110	−2.4	0.064
276.4	−0.7	0.048	1.4	0.028
302.9	−0.4	0.046	−0.2	0.036
356.0	0.5	0.037	−0.1	0.030

the acquired data revealed how almost 90% of the events recorded by the CdZnTe detectors were showing this saturation effect, which will be overcome in the final setup employing a Pb shielding system.

During both tests, the detectors were calibrated with a ^{133}Ba source while beams were circulating, and their linearity and energy resolution were measured. In the upper part of Fig. 4, the fitted energy spectra are shown for the CZT/500 (left) and for one of the REDLEN M1535 detectors (right). The linear calibration was obtained using four of the ^{133}Ba characteristic lines, for which the individual gaussians resulting from the fit are shown in colour together with the overall fitting function. Some of the peaks showed a more evident Compton tail reported in black. It was accounted for by including additional gaussians at lower energies with respect to the main one. In the case of the REDLEN detector, an additional characteristic peak at 79.6 keV is visible, also shown in black, while in the RITEC one the worse energy resolution prevented from distinguishing it. The residuals (R) shown in the lower pads of Fig. 4 represent the relative deviations of the positions of the four peaks obtained from a fit of the energy-calibrated spectra with respect to the nominal ones for the RITEC (left) and REDLEN (right) system; such residuals reveal a linearity of the systems better than 2×10^{-3}. The different sizes of the error bars are due to the different amount of data collected during the two tests.

As an additional result, we report how the energy resolutions obtained with the REDLEN detection system are better than those obtained with the RITEC one, confirming the good performances of the frontend electronics realized in Palermo. A summary of the obtained results can be found in Table 1.

4. Conclusions

In this paper, we reported the results of two preliminary tests conducted with two different CdZnTe detection systems on the DAΦNE collider at INFN Laboratories of Frascati. The aim was the assessment of the saturation effect due to the high machine background and at tuning the timing window for the acquisition of the detector signal in coincidence with the trigger given by the SIDDHARTA-2 Luminosity Monitor. These tests showed how, within a 1 μs timing window, a clear peak of events can be found, occurring in time with the LM. This represents a crucial test proving how the good timing resolution of such devices allows to employ them in kaonic atoms measurements. Finally, we demonstrated that the energy resolutions obtained with the REDLEN detection system are better than those obtained with the RITEC one, confirming the good performances of both the detectors and the frontend electronics realized in Palermo. Dedicated measurements of selected kaonic atoms like KC, KAl and KS, will be performed in 2024 by the SIDDHARTA-2 collaboration on the DAΦNE collider, in parallel with the ongoing measurement of the kaonic deuterium.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] C. Curceanu, et al., The modern era of light kaonic atom experiments, Rev. Modern Phys. 91 (2019) 025006, http://dx.doi.org/10.1103/RevModPhys.91.025006, URL https://link.aps.org/doi/10.1103/RevModPhys.91.025006.

[2] E. Friedman, A. Gal, C.J. Batty, Density dependent K- nuclear optical potentials from kaonic atoms, Nuclear Phys. A 579 (1994) 518–538, http://dx.doi.org/10.1016/0375-9474(94)90921-0.

[3] M. Iwasaki, et al., Observation of Kaonic hydrogen K_α X Rays, Phys. Rev. Lett. 78 (1997) 3067–3069, http://dx.doi.org/10.1103/PhysRevLett.78.3067.

[4] S. Okada, et al., Precision measurement of the 3d —> 2p x-ray energy in kaonic He-4, Phys. Lett. B 653 (2007) 387–391, http://dx.doi.org/10.1016/j.physletb.2007.08.032.

[5] M. Bazzi, et al., SIDDHARTA Collaboration, A New Measurement of Kaonic Hydrogen X-rays, Phys. Lett. B 704 (2011) 113–117, http://dx.doi.org/10.1016/j.physletb.2011.09.011, arXiv:1105.3090.

[6] M. Bazzi, et al., SIDDHARTA Collaboration, Kaonic helium-4 X-ray measurement in SIDDHARTA, Phys. Lett. B 681 (2009) 310–314, http://dx.doi.org/10.1016/j.physletb.2009.10.052.

[7] M. Bazzi, et al., SIDDHARTA Collaboration, First measurement of kaonic helium-3 X-rays, Phys. Lett. B 697 (2011) 199–202, http://dx.doi.org/10.1016/j.physletb.2011.02.001, arXiv:1010.4631.

[8] M. Bazzi, et al., SIDDHARTA Collaboration, Measurements of the strong-interaction widths of the kaonic 3He and 4He 2p levels, Phys. Lett. B 714 (2012) 40–43, http://dx.doi.org/10.1016/j.physletb.2012.06.071, arXiv:1205.0640.

[9] G. Backenstoss, J. Egger, H. Koch, H. Povel, A. Schwitter, L. Tauscher, Intensities and strong interaction attenuation of kaonic X-rays, Nuclear Phys. B 73 (2) (1974) 189–201, http://dx.doi.org/10.1016/0550-3213(74)90014-5, URL https://www.sciencedirect.com/science/article/pii/0550321374900145.

[10] C. Batty, S. Biagi, M. Blecher, S. Hoath, R. Riddle, B. Roberts, J. Davies, G. Pyle, G. Squier, D. Asbury, A. Clough, Measurement of strong interaction effects in kaonic atoms, Nuclear Phys. A 329 (3) (1979) 407–428, http://dx.doi.org/10.1016/0375-9474(79)90384-1, URL https://www.sciencedirect.com/science/article/pii/0375947479903841.

[11] P. Barnes, R. Eisenstein, W. Lam, J. Miller, R. Sutton, M. Eckhause, J. Kane, R. Welsh, D. Jenkins, R. Powers, A. Kunselman, R. Redwine, R. Segel, Measurement of kaonic X-rays from Al, Si, Ni and Cu, Nuclear Phys. A 231 (3) (1974) 477–492, http://dx.doi.org/10.1016/0375-9474(74)90511-9, URL https://www.sciencedirect.com/science/article/pii/0375947474905119.

[12] C.E. Wiegand, G.L. Godfrey, Measurements of x rays and γ rays from stopped kaons, Phys. Rev. A 9 (1974) 2282–2305, http://dx.doi.org/10.1103/PhysRevA.9.2282, URL https://link.aps.org/doi/10.1103/PhysRevA.9.2282.

[13] J. Óbertová, E. Friedman, J. Mareš, First application of a microscopic k–nn absorption model in calculations of kaonic atoms, Phys. Rev. C 106 (6) (2022) 065201, http://dx.doi.org/10.1103/PhysRevC.106.065201, arXiv:2208.14946.

[14] M. Zobov, et al., Test of crab-waist collisions at DAFNE Phi factory, Phys. Rev. Lett. 104 (2010) 174801, http://dx.doi.org/10.1103/PhysRevLett.104.174801.

[15] C. Milardi, et al., DAΦNE commissioning for SIDDHARTA-2 experiment, JACoW IPAC2021 (2021) TUPAB001, http://dx.doi.org/10.18429/JACoW-IPAC2021-TUPAB001.

[16] L. Abbene, et al., New opportunities for kaonic atoms measurements from CdZnTe detectors, Eur. Phys. J. ST 232 (10) (2023) 1487–1492, http://dx.doi.org/10.1140/epjs/s11734-023-00881-x, arXiv:2301.12253.

[17] L. Abbene, et al., Potentialities of CdZnTe quasi-hemispherical detectors for hard X-ray spectroscopy of kaonic atoms at the DAΦNE collider, Sensors 23 (17) (2023) 7328, http://dx.doi.org/10.3390/s23177328.

[18] T. Koike, Y. Akaishi, Stark mixing in the exotic helium atom cascade process, in: D.J. Millener, R.E. Chrien (Eds.), Nuclear Phys. A 639 (1998) 521–524, http://dx.doi.org/10.1016/S0375-9474(98)00320-0.

[19] S.Z. Kalantari, S.S. Hajari, M.D. Kelisani, Calculation of cascade processes rates and simulation of the transitions in Kaonic ^{4}He atom, Hyperfine Interact. 209 (1–3) (2012) 145–149, http://dx.doi.org/10.1007/s10751-011-0537-8.

[20] S. Berezin, G. Burleson, D.P. Eartly, A. Roberts, T.O. White, Muonic, pionic, kaonic and sigma- x rays, atomic de-excitation cascades and nuclear absorption rates in the light elements, Nuclear Phys. B 16 (1970) 389–398, http://dx.doi.org/10.1016/0550-3213(70)90255-5.

[21] M. Skurzok, et al., Characterization of the SIDDHARTA-2 luminosity monitor, JINST 15 (10) (2020) P10010, http://dx.doi.org/10.1088/1748-0221/15/10/P10010, arXiv:2008.05472.