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A NEW MEASUREMENT OF THE KAONIC HELIUM L-LINES WITH SIDDHARTA-2 AT DAΦNE

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Abstract

The ultimate goal of the SIDDHARTA-2 experiment at the LNF-INFN is to perform the first ever measurement, via X-ray spectroscopy, of the width and shift induced by the strong interaction to the $2p \to 1s$ energy transition of kaonic deuterium. Such a measurement has not been performed yet due to its high difficulty level; in fact, this transition exhibits an extremely low X-ray yield. For this reason, before starting the kaonic deuterium data taking campaign, an accurate and thorough characterisation of the experimental apparatus is of primary importance to gauge its performance. To finalize such a task the best candidate is Helium-4, since the $3d \to 2p$ transition of kaonic helium-4 exhibits a much higher yield of X-rays. This work reports the results of the characterisation of the SIDDHARTA-2 apparatus in preparation for the kaonic deuterium measurement. This is done by measuring the shift and width for the $3d \to 2p$ transition of kaonic helium-4. The measured values are $\varepsilon_{2p} = 2.0 \pm 1.2(\text{stat}) \pm 1.5(\text{syst})\,\text{eV}$ and $\Gamma_{2p} = 1.9 \pm 5.7(\text{stat}) \pm 0.7(\text{syst})\,\text{eV}$. The result shows a net enhancement of the performance of the apparatus when compared to the previous measurement done by the SIDDHARTA experiment $\varepsilon_{2p} = 0 \pm 6(\text{stat}) \pm 2(\text{syst})\,\text{eV}$, thus providing strong evidence of the potential to perform the kaonic deuterium measurement.

1 Scientific case

An exotic atom 1) is an atomic system in which a negatively charged particle, either a lepton or an hadron, replaces an electron when captured into an atomic orbit by its electromagnetic interaction with the nucleus. The values of the energy levels of the electromagnetic interaction between the negatively charged particle and the nucleus are calculated with great accuracy by Quantum Electrodynamics (QED). Therefore, small deviations in the energy of the atomic levels with respect to the solely QED-calculated ones, contain additional information on the interaction occurring between the captured particle and the nucleus. In this framework, hadronic atoms play a crucial role: when present, the strong interaction manifests itself in the lowest energy levels before nuclear absorption occurs. Transitions to these low-lying energy levels are concurrent with the emission of radiation, namely X-rays. These can be detected via X-ray spectroscopy and, given that the relative energy between the captured hadron and the nucleus is the binding energy of the system, of the order of some keV for light kaonic atoms, this allows us to perform a direct measurement of the strong interaction at low energy. Among hadronic atoms, kaonic atoms offer a unique opportunity to directly probe the strong interaction of particles with strangeness in the non-perturbative regime of Quantum Chromodynamics (QCD). From the measurement of the shift and the width induced by the strong interaction on the $1s$ level of the kaonic hydrogen and kaonic deuterium, the isospin-dependent antikaon-nucleon (anti$K$-N) scattering lengths can be obtained 2, 3). Hence, the outcome of the kaonic deuterium measurement will contribute to the understanding of the anti$K$–N interaction in the non-perturbative regime of QCD and will be a test field for several theoretical models 4, 5, 6, 7, 8, 9, 10). The SIDDHARTA experiment 11) successfully measured the kaonic hydrogen in 2009, while the kaonic deuterium measurement is still to be performed. This is a very challenging measurement due to the extremely low yield of X-rays of the transitions to the fundamental level, which is expected to be about one order of magnitude lower than that of kaonic hydrogen. To perform such a measurement it is therefore of key importance that the experimental apparatus is thoroughly characterized using a high X-ray yield gaseous target. Helium-4 is an excellent candidate to fulfill this purpose since the $3d \to 2p$ transition has a yield roughly 100 times larger than that of kaonic deuterium. This kind of measurement has already been performed by the SIDDHARTA experiment 12) in 2009, hence its result in terms of the shift of the $2p$ level can be compared to the new one obtained with the SIDDHARTA-2 experimental apparatus. The new measurement of the kaonic helium L-lines, presented in this work, proves the excellent performance of the SIDDHARTA-2 apparatus, which qualifies as the state-of-the-art instrument for the challenging measurement of kaonic deuterium.

2 The SIDDHARTA-2 Setup on DAΦNE

DAΦNE is an electron-positron collider at the INFN-LNF working with center of mass energy centered on the mass of the ϕ meson (1.02 GeV). The ϕ mesons are produced at threshold and decay into K^+/K^- pairs with a branching ratio of 48.9%. The produced charged kaons have low energies, with a momentum of only 127 MeV/c, hence are easily stopped inside a gaseous target. The SIDDHARTA-2 experiment is installed above the interaction point (IP) of the DAΦNE collider. The setup is shown in Figure 1. Above and below the IP, a pair of plastic scintillators, read by two Photo-Multiplier Tubes (PMTs) each, act as a Kaon Trigger (KT) exploiting the specific time of flight (TOF) of the slow kaons. The purpose of the KT is to select the kaons which are emitted back-to-back from the ϕ decay in the IP and are directed towards the target, and is used to suppress the background asynchronous with the collisions. The vacuum chamber is located above the IP and contains the cryogenic target cell. High purity titanium–copper strips are placed on dedicated holders on the target cell walls for calibration purposes. The charged kaons travel through the vacuum chamber window, then enter the target cell and interact with the gas, forming kaonic atoms and subsequently emitting X-rays. Surrounding the target, silicon drift detectors (SDDs) 13, 14, 15, 16, 17, 18) are used to detect the X-rays coming from the de-excitation of the kaonic atoms. To suppress the background component synchronous with the collisions, two different veto systems are placed outside the vacuum chamber, the Veto-1 system 19), and around the SDDs, the Veto-2 system 20, 21). A system made of two X-ray tubes is employed for the in situ calibration of the SDDs. More information regarding the experimental setup and its components can be found in 22).

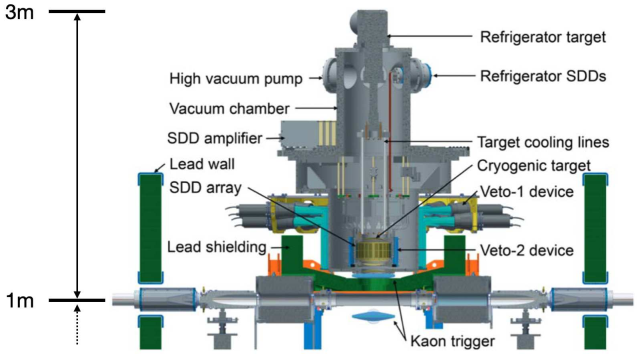

Figure 1: *Schematic view of the SIDDHARTA-2 experimental setup. The whole system is installed at the* e^+e^- *IP in DAΦNE.*

3 SDDs calibration and data selection

The characterization of the experimental setup was carried out using a helium-4 gaseous target at 1.5% of liquid helium-4 density.

3.1 SDDs Calibration in DAΦNE

The energy calibration of the detectors inside the DAΦNE hall is one of the most crucial aspects of the data analysis procedure. Given the slight differences between the SDDs, individual calibrations are mandatory. The calibration was carried out using two X-ray tubes and a ^{55}Fe source. The X-ray tubes are used to induce the characteristic fluorescence emission lines of the high-purity titanium and copper strips placed on the target cell walls; the ^{55}Fe decays via electron capture to an excited state of ^{55}Mn, which then emits an X-ray during the de-excitation process. Hence, we identified in the spectrum the peaks associated with the TiK$_{\alpha}$, the CuK$_{\alpha}$, and the MnK$_{\alpha}$ X-ray emissions. To describe each peak, a Gaussian function summed up to a tail component, to account for the low energy contributions due to incomplete charge collection, is used 23). Once the individual calibrations are done with, the calibrated spectra of each detector are summed up together into a final spectrum, shown in Figure 2, which is then analyzed. By analyzing the difference between the measured energy value and the nominal one of the TiK$_{\alpha}$, CuK$_{\alpha}$, and MnK$_{\alpha}$ peaks, shown in Figure 2, we obtained a gauge of the calibration accuracy, which is of the order of 1.5 eV at $\sim$6 keV. From the fit can also be extracted a good estimate of the energy resolution of the apparatus at $\sim$6 keV from the FWHM of the MnK$_{\alpha}$ peak, resulting in a value of (170.97 ± 0.69) eV FWHM 24).

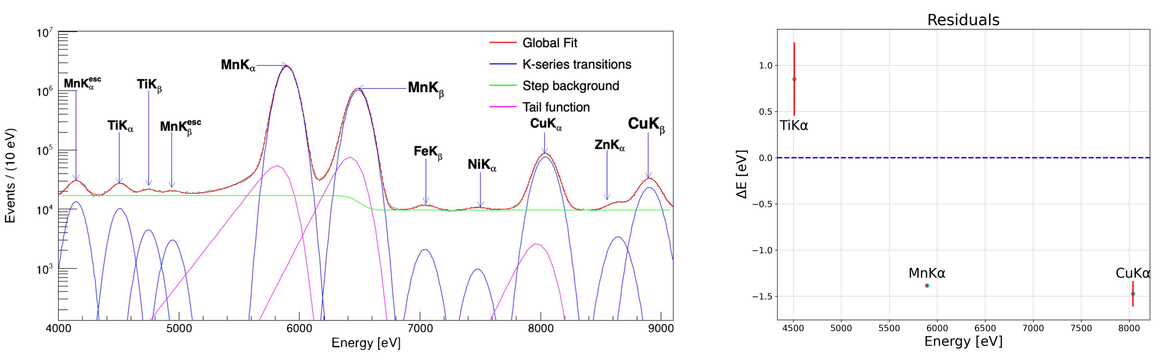

Figure 2: *a) Final calibration spectrum given by the sum of all the calibrated spectra of each SDD; b) Distribution of the residuals of the energy of the TiK$_{\alpha}$, MnK$_{\alpha}$, and CuK$_{\alpha}$ lines from their nominal energy. Adapted from* 24).

3.2 Data selection

To perform the measurement of kaonic helium-4, a total integrated luminosity of $\sim$31 pb^{-1} was collected. The energy spectrum initially presents a high continuous background component hindering the direct observation of the kaonic helium lines; therefore, background rejection cuts were applied to the experimental data. The asynchronous component of the background can be heavily suppressed by using the KT. A 5 µs time window in coincidence with the KT signal is set, thus rejecting a major portion of the background. Aside from this background source, MIPs, generated by the beam–beam and beam–gas interactions resulting in particle losses, can produce a fake signal in the trigger. To reject such triggers, the TOF signature was used by measuring the time difference between the trigger signal and the DAΦNE radio-frequency (RF). From the mean time of the PMTs signal of the upper scintillator and that of the lower one, the timing information of the trigger is extracted and referenced to the RF. Figure 3 shows the time distributions measured by the two KT scintillators and the cut used to reject the MIPs-induced triggers. Furthermore, the time difference between the X-ray detection and the KT signal (Figure 3), was evaluated. Events inside the red lines are related to hits on the SDDs in coincidence with the KT signals, while the flat distribution on the two sides comes from uncorrelated events which therefore are rejected.

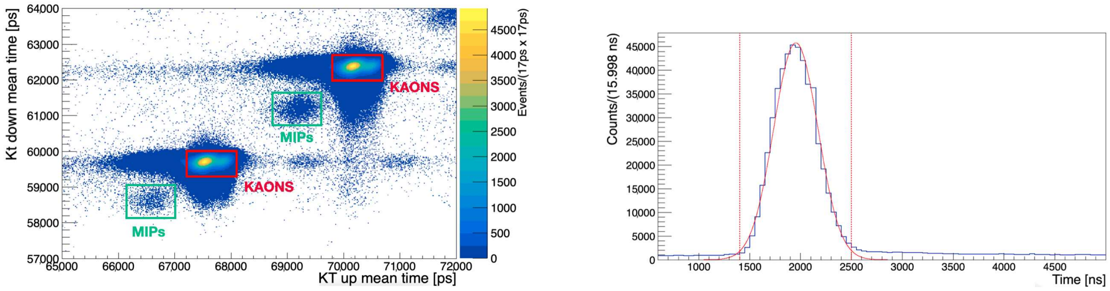

Figure 3: *a) Two-dimensional scatter plot of the mean time distributions measured by the two KT scintillators; b) Distribution of the time differences between the KT signal and the detection of the X-ray with the temporal cut to reject the background. Adapted from* [24].

4 The Kaonic Helium-4 Energy Shift and Width

The final spectrum, with the fit to it, is shown in Figure 4; after the data selection, the kaonic helium-4 L-series lines are clearly visible and were fitted to extract their energies. To account for the intrinsic line width ($\mathbf{\Gamma}$) induced by the strong interaction, the kaonic helium peaks were fitted with a Voigt function, *i.e.* a convolution of a Lorentzian function with a Gaussian.

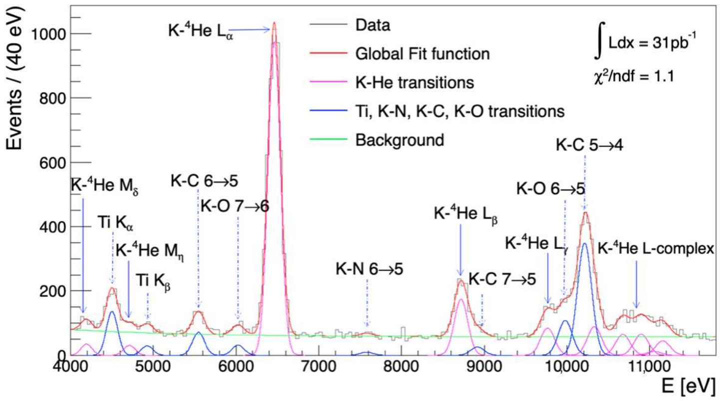

Figure 4: *X-ray energy spectrum and fit to the data after the data selection. The lines of kaonic helium transitions are fitted with a Voigt function, and the other lines are fitted with a Gaussian. Adapted from* [24].

The measured value of the shift of the $\mathbf{2p}$ level and its measured intrinsic width induced by the strong interaction are $\boldsymbol{\varepsilon_{2p}} = \mathbf{2.0 \pm 1.2}$(stat)$\pm$**1.5**(syst) eV and $\mathbf{\Gamma_{2p}} = \mathbf{1.9 \pm 5.7}$(stat)$\pm$**0.7**(syst) eV [24]. Both the shift and the width induced by the strong interaction are compatible with null values inside the error bars, in agreement with the theoretical models, which exclude the presence of a significant shift, and with the previous results obtained by SIDDHARTA $^{12)}$. The new measurement of the kaonic helium $\boldsymbol{3d \rightarrow 2p}$ transition, compared to the value of the shift measured by SIDDHARTA $\boldsymbol{\varepsilon_{2p} = 0 \pm 6}(\mathrm{stat}) \pm \boldsymbol{2}(\mathrm{syst})$ eV, exhibits an improvement in terms of resolution, with a statistical uncertainty six times less than the SIDDHARTA one.

5 Conclusions

The main goal of the SIDDHARTA-2 experiment at the DA**Φ**NE collider of INFN-LNF is to perform the first ever measurement of the shift and width induced by the strong interaction to the $\boldsymbol{1s}$ level of kaonic deuterium. This work displays the result of the characterization campaign of the SIDDHARTA-2 experimental setup. The run was realised using a gaseous helium-4 target operating at a density of **1.5%** of the liquid helium-4 density, which features an X-ray yield nearly 100 times higher than that expected from kaonic deuterium. A new measurement of the L-series lines of the kaonic helium-4 was performed to gauge the performance of the new apparatus. A total amount of $31\,\mathrm{pb}^{-1}$ were collected. The analysis of the collected data yielded a shift and a width of the $\boldsymbol{2p}$ level of kaonic helium-4 of $\boldsymbol{\varepsilon_{2p} = 2.0 \pm 1.2}(\mathrm{stat}) \pm \boldsymbol{1.5}(\mathrm{syst})$ eV and $\boldsymbol{\Gamma_{2p} = 1.9 \pm 5.7}(\mathrm{stat}) \pm \boldsymbol{0.7}(\mathrm{syst})$ eV $^{24)}$, thus excluding a large shift, in good agreement with the theoretical models and with the previous experimental results. The improved accuracy of the measurement of the shift with respect to the one done by the SIDDHARTA experiment $^{12)}$ is a clear validation of the capability of the new apparatus to perform the challenging measurement of kaonic deuterium.

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References

1. Sin-itiro Tomonaga and G. Araki, Phys. Rev. **58**, 90 (1940).
2. U-G Meißner, U. Raha and A. Rusetsky, Eur. Phys. J.-Part. Fields **35**, 349–357 (2004).
3. U-G Meißner, U. Raha and A. Rusetsky, Eur. Phys. J.-Part. Fields **47**, 473–480 (2006).
4. M. Mai, U-G Meißner, Nucl. Phys. A **900**, 51–64 (2013).
5. Z.H. Guo, J.A. Oller, Phys. Rev. C **87**, 035202 (2013).

6. Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A **881**, 98–114 (2012).

7. A. Cieply, E. Friedman, A. Gal, D. Gazda, J. Mares, Phys. Lett. B **702**, 402–407 (2011).

8. A. Cieply, E. Friedman, A. Gal, D. Gazda, J. Mares, J, Phys. Rev. C **84**, 045206 (2011).

9. Z.W. Liu, J.J. Wu, D.B. Leinweber, A.W. Thomas, Phys. Lett. B **808**, 135652 (2020).

10. J. Révai, Phys. Rev. C **94**, 054001 (2016).

11. M. Bazzi, G. Beer, L. Bombelli, A. Bragadireanu, M. Cargnelli, G. Corradi, C. Curceanu, C. Fiorini, T. Frizzi, F. Ghio *et al*, Phys. Lett. B, **704**, 113–117 (2011).

12. M. Bazzi, G. Beer, L. Bombelli, A. Bragadireanu, M. Cargnelli, G. Corradi, C. Curceanu, A. d'Uffizi, C. Fiorini, T. Frizzi *et al*, Phys. Lett. B, **681**, 310–314 (2009).

13. E. Gatti, P. Rehak, Nucl. Instrum. Methods Phys. Res. **225**, 608–614 (1984).

14. E. Gatti, P. Rehak, J.T. Walton, Nucl. Instrum. Methods A **226**, 129–141 (1984).

15. M. Miliucci, A. Scordo, D. Sirghi, A. Amirkhani, A. Baniahmad, M. Bazzi, D. Bosnar, M. Bragadireanu, M. Carminati, M. Cargnelli *et al*, Meas. Sci. Technol. **32**, 095501 (2021).

16. M. Miliucci, M. Iliescu, F. Sgaramella, M. Bazzi, D. Bosnar, M. Bragadireanu, M. Carminati, M. Cargnelli, A. Clozza, C. Curceanu *et al*, Meas. Sci. Technol. **33**, 095502 (2022).

17. F. Sgaramella, M. Miliucci, M. Bazzi, D. Bosnar, M. Bragadireanu, M. Carminati, M. Cargnelli, A. Clozza, G. Deda, L. De Paolis *et al*, Phys. Scr. **97**, 114002 (2022).

18. M. Skurzok, A. Khreptak, Bio-Algorithms Med-Syst. **19**, 74–79 (2023).

19. M. Bazzi, C. Berucci, C. Curceanu, A. d'Uffizi, M. Iliescu, E. Sbardella, A. Scordo, M. Shi, F. Sirghi, H. Tatsuno *et al*, J. Instrum. **8**, T11003 (2013).

20. M. Tüchler, C. Amsler, M. Bazzi, D. Bosnar, M. Bragadireanu, M. Cargnelli, A. Clozza, G. Deda, R.D. Grande, L.D. Paolis *et al*, J. Instrum. **18**, P11026 (2023).

21. M. Tüchler, J. Zmeskal, A. Amirkhani, M. Bazzi, G. Bellotti, C. Berucci, D. Bosnar, A. Bragadireanu, M. Cargnelli, C. Curceanu *et al*, In Proceedings of the 10th International Conference on Precision Physics of Simple Atomic Systems, Vienna, Austria, 14–18 May 2018; IOP Publishing: Bristol, UK, **1138**, 012012 (2018).

22. F. Sirghi, F. Sgaramella, L. Abbene, C. Amsler, M. Bazzi, G. Borghi, D. Bosnar, M. Bragadireanu, A. Buttacavoli, M. Carminati *et al*, arXiv:2311.16144 (2023)

23. M. Van Gysel, P. Lemberge, P. Van Espen, X-ray Spectrom. Int. J. **32**, 434–441 (2003)

24. F. Sgaramella, F. Clozza *et al*, Condens. Matter, **9**, 16 (2024).