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Experimental studies of the kaon-nucleus interaction at low energy with x-ray spectroscopy of kaonic atoms

H Shi ¹, M Bazzi ¹, G Beer ², G Bellotti ^{3,4}, C Berucci ^{5,1},
A M Bragadireanu ^{1,6}, D Bosnar ⁷, M Cargnelli ⁵, C Curceanu ¹,
A D Butt ^{3,4}, R Del Grande ¹, L Fabietti ⁸, C Fiorini ^{3,4}, F Ghio ⁹,
C Guaraldo ¹, R S Hayano ¹⁰, M Iliescu ¹, T Ishiwatari ⁵,
M Iwasaki ¹¹, P Levi Sandri ¹, J Marton ⁵, M Miliucci ¹, S Okada ¹¹,
D Pietreanu ^{1,6}, K Piscicchia ^{1,12}, A Romero Vidal ¹³, A Scordo ¹,
D L Sirghi ^{1,6}, F Sirghi ^{1,6}, H Tatsuno ^{14,15}, I Tucakovic ¹,
O Vazquez Doce ⁸, E Widmann ⁵, S Wycech ¹⁶ and J Zmeskal ⁵
(SIDDHARTA, SIDDHARTA-2 Collaboration)

¹INFN, Laboratori Nazionali di Frascati, Via E. Fermi 40, I-00044 Frascati(Roma), Italy

²Department of Physics and Astronomy, University of Victoria, P.O. Box 1700 STN CNC, Victoria BC V8W 2Y2, Canada

³Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Milano, Italy

⁴INFN Sezione di Milano, Via Celoria 16 - 20133 Milano, Italy

⁵Stefan-Meyer-Institut für Subatomare Physik, Boltzmannngasse 3, 1090 Wien, Austria

⁶IFIN-HH, Institutul National pentru Fizica si Inginerie Nucleara Horia Hulubbei, Reactorulul 30, Magurele, Romania

⁷Department of Physics, Faculty of Science, University of Zagreb, Bijenicka 32, HR-10000 Zagreb, Croatia

⁸Excellence Cluster Universe, Technische Universität München, Boltzmannstraße 2, D-85748 Garching, Germany

⁹INFN Sezione di Roma I and Istituto Superiore di Sanita, I-00161 Roma, Italy

¹⁰Department of Physics, School of Science, The University of Tokyo, Bunkyo-ku Hongo 7-3-1, Tokyo, Japan

¹¹RIKEN, Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako, Saitama 251-0198, Japan

¹²Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, Piazza del Viminale 1-00184 Roma, Italy

¹³Universidade de Santiago de Compostela, Casas Reais 8, 15782 Santiago de Compostela, Spain

¹⁴National Institute of Standards and Technology (NIST), Boulder, CO, 80303, USA

¹⁵High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan

¹⁶National Center for Nuclear Studies, 00-681 Hoza 69, Warsaw, Poland

E-mail: hexishi@lnf.infn.it

Abstract. In the exotic atoms in which one electron is replaced by a negatively charged kaon, the kaon-nucleus hadronic interaction introduces an energy shift and broadening of the low-lying states of the kaonic atoms. The shift and width can be determined with high precision from the atomic x-ray spectroscopy, and this experimental method provides unique information to understand the low energy kaon-nucleus interaction at the production threshold.



1. Introduction

There are two experimental approaches to probe the kaon-nucleus strong interaction. One is by studying the scattering and the reaction channels between the kaon and the nucleus, to directly search for bound states and extract the potential of the strong interaction. The other method of the precision x-ray measurement of the kaonic atoms, measures the shift and broadening of the energy levels of the atomic states, caused by the kaon-nucleus strong interaction. The method is of significant importance, since it is the unique laboratory that gives the information of the kaon-nucleus system at their production threshold.

In an exhaustive review in 1997 and the references therein, C. J. Batty and colleagues analyzed all the published results of kaonic atom x-ray measurements with nuclei from Li to U [1]. They fitted the full data set with an optical potential with an imaginary part that presents the absorption of the kaon by the nucleus, and a real part as the depth of the potential. The analysis concluded with an attractive and absorptive kaon-nucleus potential, however due to the limit in the precision of the experimental data, the real part of the potential can vary from about -40 MeV to -200 MeV, depending on the choice of phenomenological models. The indication of a very deep potential motivated the subsequent theoretical and experimental searches of deeply bound kaon-nucleus state, which remains be an open question today.

In this context, precision x-ray spectroscopy of the $Z=1,2$ kaonic atoms as the simplest kaon-nucleus systems is fundamental to understand the low-energy interaction between the kaon and the nucleus. Firstly, in case of kaonic hydrogen which is the simplest kaonic atom, the strong interaction induced shift and width of the $1s$ state can be deduced from the K -series x-rays, and they are related to the s -wave K^-p scattering length a_{K^-p} through the Deser-Trueman formula [2]. This scattering length consists of two isospin dependent components of a_0 ($I=0$) and a_1 ($I=1$), which are among the most fundamental parameters for the low-energy $\bar{K}N$ interaction, and which can only be derived experimentally from x-ray spectroscopy. To disentangle these two components, we need also the precise measurement of the kaonic deuterium $1s$ shift and width, further taking into account higher order contributions from the three-body interaction [3]. Experimentally this measurement is extremely difficult mainly due to the small x-ray yield and the broad width of the $1s$ level. Until now an unambiguous detection of the kaonic deuterium x-rays has not been achieved and the measurement remains to be the major challenge of upcoming experiments.

For the $Z=2$ kaonic atoms, there had been a long-standing discrepancy between the theoretical and the measured strong-interaction induced shift of the $2p$ level of kaonic helium-4. This “kaonic helium puzzle” was solved by the KEK E570 experiment which showed the $2p$ level shift was $2 \pm 2(\text{stat.}) \pm 2(\text{syst.})$ eV [4], refuting the previous average shift of about -40 eV from three early experiments [5][6][7]. More essentially, the precise measurement of the kaonic helium $2p$ level shift is a test ground for possible deeply-bound kaonic nuclear states predicted by Akaishi and Yamazaki [8][9]. A combination of electronvolt precision measurement of the shift and the width of the $2p$ level for both kaonic helium-3 and kaonic helium-4 atoms can effectively narrow down the allowed range of the nuclear potential of kaon in the search of deeply-bound states.

In the next section measurements performed in the SIDDHARTA experiment will be introduced in detail.

2. The SIDDHARTA experiment

2.1. Experimental method

The experiment made use of the K^+K^- pairs coming from the ϕ decays with a 49% branching ratio, at the DAΦNE e^-e^+ collider in Laboratori Nazionali di Frascati (LNF), Italy. As the beam energies are tuned to produce ϕ (1020) resonance at rest in the lab frame, the K^+K^- pair has a fairly good back-to-back configuration which could be identified by the kaon detectors

made of two plastic scintillators placed above and below the interaction point as illustrated in Figure 1. The kaons are distinguished from the minimum ionizing particles using the time of flight information at the kaon detectors, and the coincidence of the two scintillators defines the kaon trigger, which marks the timing of the incident kaons.

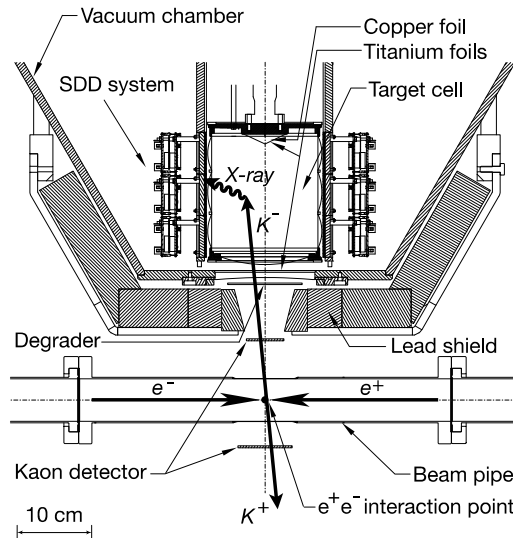


Figure 1: A schematic cutaway view of the SIDDHARTA setup at the DAΦNE interaction point. The charged kaon pairs are identified with two plastic scintillators, and the K^- induced x-rays detected by the SDDs are identified from the time correlation to the kaon pair events.

A fraction of the negatively charged kaons that made the kaon trigger will stop inside the volume of the gaseous target placed about 20 cm above the interaction point to form kaonic atoms. With the time correlation between the subsequent x-rays detected by the Silicon Drift Detectors (SDDs) and the kaon trigger, one can distinguish the kaon origin x-rays from the background coming from the processes that are asynchronous to the kaon pair production.

The SDDs had a total active area of 144 cm^2 , covering about 10% of the solid angle around the target cell. The energy calibrations of the SDDs were done with an interval of few hours, using the K_α lines of Ti (4.5 keV) and Cu (8.0 keV) to determine the scale of the energy spectra. The energy resolution at 6 keV was stable at about 150 eV (FWHM) throughout our measurement. At the operating temperature of 140 K, the SDDs showed a timing resolution of 700 ns FWHM, with which we effectively rejected the asynchronous background by four orders of magnitude. More details about the configuration and the performance of the detectors can be found in previous publications of the SIDDHARTA experiment [10][11][12].

We accumulated data during the data taking in 2009 with gaseous targets of hydrogen (1.3 g/l), deuterium (2.50 g/l), helium-3 (0.96 g/l), and helium-4 (1.65 g/l and 2.15 g/l), and obtained physics results for all the measurements.

2.2. Kaonic hydrogen and deuterium

With the precise measurement of the kaonic hydrogen K -series x-rays as the main objective of the SIDDHARTA experiment, most of the beam time was dedicated to the hydrogen target

measurement to a total integrated luminosity of 340 pb^{-1} . A total amount of 100 pb^{-1} integrated luminosity was dedicated to the first exploratory kaonic deuterium measurement.

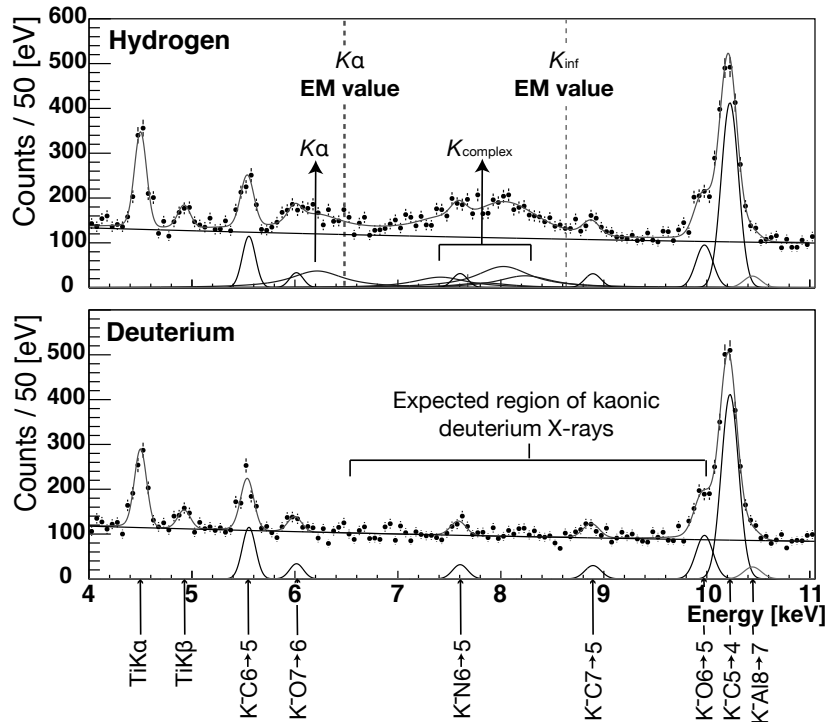


Figure 2: Result of the hydrogen and deuterium targets measurement in SIDDHARTA.

To derive the $1s$ shift ϵ_{1s} and width Γ_{1s} , as well as the x-ray yield of kaonic hydrogen, we performed a combined analysis of the hydrogen and deuterium targets measurement, by fitting simultaneously the kaonic x-ray spectra from the two data sets. Since the yield of the kaonic deuterium K -series x-rays is more than one order of magnitude smaller than that of the kaonic hydrogen, the spectrum from the deuterium target measurement helped determining the background x-rays from other kaonic atoms when the K^- stopped inside the target cell made of Kapton, as shown in Figure 2 [13]. This combined analysis contributed to reduce the systematic errors in the kaonic hydrogen results, which achieved the best precision up to date for the $1s$ shift $\epsilon_{1s} = -283 \pm 36$ (stat.) ± 6 (syst.) eV and for the width $\Gamma_{1s} = 541 \pm 89$ (stat.) ± 22 (syst.) eV [12]. The results solved the discrepancy between two recent kaonic hydrogen x-ray experiments KpX in KEK [14][15] and DEAR at DAΦNE [16], in that the two results do not overlap with each other within their error bars. The improved precision presents more stringent constraints to the theoretical study of the low-energy QCD near the K^-p threshold.

Together with a full Monte Carlo simulation of the setup, we determined the absolute yields of kaonic x-rays for a negatively charged kaon stopped inside a hydrogen gaseous target at the density of 1.3 g/l to be $0.012_{-0.003}^{+0.004}$ for K_α and $0.043_{-0.011}^{+0.012}$ for all the K -series transitions K_{tot} [13]. This is the second data point of the kaonic hydrogen x-ray yield from an experiment, and is necessary to improve the kaonic atom cascade model which is verified by comparing the prediction of the absolute x-ray yields to the experimental values. For the deuterium target spectrum which showed no significant amount of signal of kaonic deuterium x-rays, we evaluated an upper limit for the yield of the kaonic deuterium K_α x-ray as $Y(K_\alpha) < 0.0039$ (C.L. 90%) [17]. It presents a solid reference to plan for the future precision measurement of kaonic deuterium x-rays.

Table 1: Results on the energy shifts (ΔE_{2p}) and widths (Γ_{2p}) of the kaonic helium-3 and kaonic helium-4 $2p$ states [10][11][18].

Target	ΔE_{2p} [eV]	Γ_{2p} [eV]
helium-4	$+5 \pm 3$ (stat.) ± 4 (syst.)	14 ± 8 (stat.) ± 5 (syst.)
helium-3	-2 ± 2 (stat.) ± 4 (syst.)	6 ± 6 (stat.) ± 7 (syst.)

2.3. Kaonic helium-3 and helium-4

The strong interaction induced $2p$ level shift and width are measured for both kaonic helium-3 and helium-4 atoms [10][11][18], and it is the first time that kaonic helium-3 x-rays are measured. The results of the shift as listed in Table 1 are consistent with the results of E570 [4], thus a zero-compatible shift of the $2p$ level from experiment is established, which is in agreement with the theoretical estimations in [7][19]. We have not found abnormally large widths which can directly support the estimations made in conjunction with the prediction of a deeply-bound kaon states [8][9].

A decisive measurement that will give a conclusion to this topic is under preparation at J-PARC [20], in which the transition-edge sensor micro-calorimeter as the x-ray detector will be used to reach the precision requirement of sub-electronvolt.

3. Future perspectives

As a continuation of the SIDDHARTA experiment which successfully applied the timing capability in addition to the excellent energy resolution of the SDDs, the extended SIDDHARTA-2 collaboration is preparing a series of modifications and upgrades of the apparatus and experimental configurations, aiming to measure the kaonic deuterium x-rays with a precision compatible with that achieved in the hydrogen target measurement [21]. The main upgrades include the development of the new SDD chips with larger effective area to increase the acceptance and the application under temperature below 50 K to reach the best timing resolution to improve the signal to background ratio. The first precision measurement result of the kaonic deuterium x-ray from SIDDHARTA-2 will finally determine the isospin dependent components of the s-wave scattering lengths of the $\bar{K}N$ interaction, which are the missing building blocks for the Chiral SU(3) based effective field theories of the low-energy kaon-nucleus interaction.

A promising future perspective from the precision point of view comes from a recent publication on the measurement of exotic atom x-rays using the transition-edge sensor micro-calorimeters in a hadronic beam line [22]. The exploratory experiment done at the π M1 pion beam line at Paul Scherrer Institute successfully measured the x-ray transitions of pionic atoms, with an absolute energy uncertainty of 0.1 eV in the 6 keV region. This breakthrough demonstrated the feasibility of the application of the microcalorimeter for high precision spectroscopy at high energy particle beamlines. It is also a milestone towards the realization of the decisive high precision measurement of the kaonic helium-3 and helium-4 x-rays to be performed at J-PARC.

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