PROCEEDINGS OF SCIENCE

Kaonic Atoms – final results of the SIDDHARTA experiment

Johann Zmeskal for the SIDDHARTA Collaboration [1]
Stefan Meyer Institute for Subatomic Physics
Boltzmanngasse 3, Vienna, Austria
E-mail: johann.zmeskal@oeaw.ac.at

The study of the antikaon nucleon system at very low energies plays a key role for the understanding of the strong interaction between hadrons in the strangeness sector. At the DAΦNE electron positron collider of Laboratori Nazionali di Frascati with SIDDHARTA kaonic atoms with Z=1 and Z=2 were studied with up to now unrivalled precision, taking advantage of the low-energy charged kaons from ϕ-mesons decaying nearly at rest. The SIDDHARTA experiment used X-ray spectroscopy to determine the strong interaction induced shift and width of the experimentally accessible level: 1s for kaonic hydrogen atoms and 2p for kaonic helium. Shift and width are connected to the real and imaginary part of the scattering length.

The results of the SIDDHARTA measurements performed at DAΦNE are discussed in this paper.

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[1] SIDDHARTA Collaboration: M. Bazzi[a], G. Beer[b], C. Berucci[c,a], L. Bombelli[d], A.M. Bragadireanu[e], M. Cargnelli[c], C. Curceanu (Petrascu)[a], A. d'Uffzi[a], C. Fiorini[d], T. Frizzi[d], F. Ghio[f], C. Guaraldo[a], R. Hayano[g], M. Iliescu[a], T. Ishiwatari[c], M. Iwasaki[h], P. Kienle[c,i], P. Levi Sandri[a], A. Longoni[d], J. Marton[c], S. Okada[h], D. Pietreanu[e], A. Romero Vidal[j], E. Sbardella[a], A. Scordo[a], H. Shi[g], D.L. Sirghi[a,e], F. Sirghi[a,e], H. Tatsuno[a], A. Tudorache[e], V. Tudorache[e], O. Vazquez Doce[i], E. Widmann[c], J. Zmeskal[c]
[a]INFN, Laboratori Nazionali di Frascati, Italy; [b]University of Victoria, Canada; [c]Stefan-Meyer-Institut für subatomare Physik, Austria; [d]Politecnico di Milano, Italy; [e]IFIN-HH, Romania; [f]INFN Sez. Roma, Italy; [g]University of Tokyo, Japan; [h]RIKEN, Japan; [i]Excellence Cluster Universe TUM, Germany
[j]Universidade de Santiago de Compostela, Spain

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1.Introduction

One of the outstanding fundamental problems in hadron physics today is the question of the origin of the large hadron masses made up of light quarks. The current mass of the up (u) and down (d) quarks is two orders of magnitude smaller than a typical hadron mass of about 1 GeV. This extraordinary phenomenon is proposed to originate from spontaneous breaking of chiral symmetry of mass-less quarks in strong interaction physics [1].

Precision X-ray spectroscopy of kaonic atoms represents an excellent tool to study the chiral symmetry breaking scenario [2,3,4]. Kaonic atoms are QED bound systems in which the heavier, negatively charged particle replaces an electron, for example a kaonic hydrogen (K^-p) atom could be formed. In general, studies of exotic mesonic atoms have provided important information on strong interaction (hadron) physics.

Effective field theories (EFTs) provide a crucial framework for analyzing the properties and interactions of hadrons and nuclei. These theories describe low-energy hadron physics implementing the symmetries of the underlying theory, QCD, using effective Lagrangians for the relevant degrees of freedom, which leads to observable effects in the spectrum of exotic hadronic atoms.

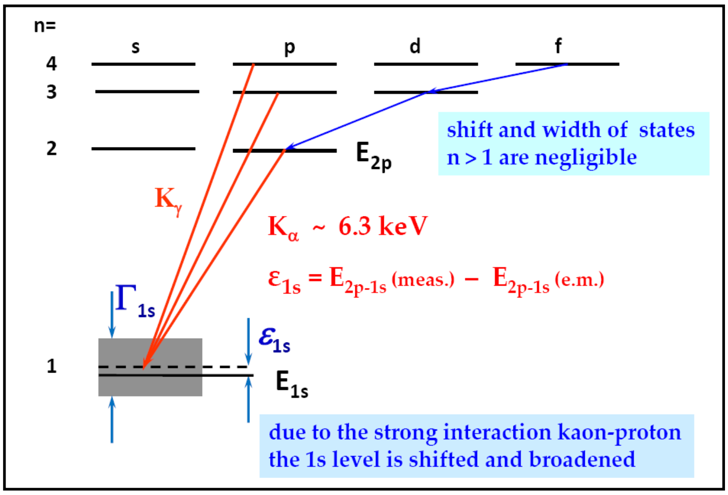

Figure 1: Indicated are X-ray transitions to the ground state of kaonic hydrogen atoms. The 1s ground state is shifted and broadened due to strong interaction.

For light atoms, most likely, a detectable energy shift of the ground state will be observed (with respect to the pure QED value, see Figure 1) as well as a broadened ground state level, caused by nuclear absorption, will be seen. By measuring these observables the s-wave hadron-hadron scattering lengths at zero energy could be extracted, which are a sensitive measure of the chiral and isospin symmetry breaking pattern in QCD.

Using a Deser [5] type formula with correction terms included [6] the strong interaction shift and widths could be expressed by the complex K^-p scattering length $\alpha_{K\text{-}p}$, with α the fine structure constant and μ_c the reduced mass of K^-p system:

$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2\alpha_{K^-p}(1 - 2\alpha\mu_c(\ln\alpha - 1)\alpha_{K^-p})$$

2. The SIDDHARTA project

With the SIDDHARTA (**SI**licon **D**rift **D**etector for **H**adronic **A**tom **R**esearch with **T**iming **A**pplication) project the kaonic hydrogen system [7,8] was studied and precise data on the $K^{-}p$ interaction at threshold became available. In addition SIDDHARTA has performed measurements of $K^{-4}He$ [9] and for the first time on $K^{-3}He$ [10], as well as an exploratory measurement on $K^{-}d$ [11].

2.1 The DAΦNE kaon factory

DAΦNE, the ϕ-factory at Laboratori Nazionali di Frascati, operates at the centre-of-mass energy (m=1019.413 MeV) of the ϕ mesons via e^+e^- collisions. The ϕ meson is produced almost at rest and decays to about 50%, back-to-back, into a K^+K^- pair with a kaon momentum of 127 MeV/c. During the SIDDHARTA beam time period the average ϕ production rate was in the order of $R_{\phi}=2.5\text{x}10^{3}\ s^{-1}$.

2.2 The SIDDHARTA experimental setup

The kaons leave the interaction point through the SIDDHARTA beam pipe, are degraded in energy and enter a gaseous hydrogen (helium) target placed above the beam pipe where the negative kaons are stopped (Figure 2).

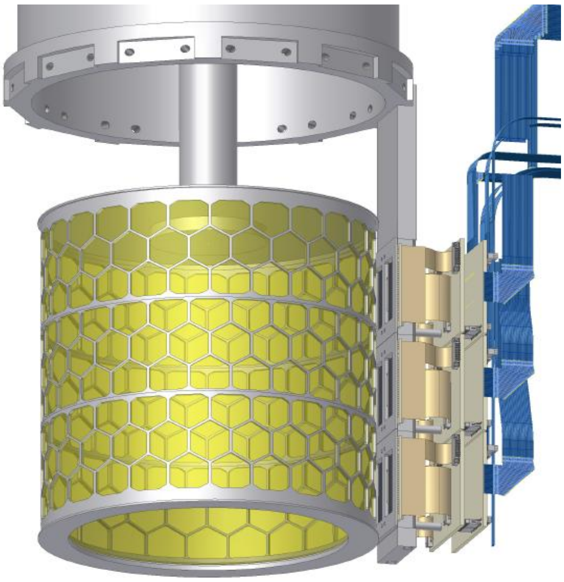

Figure 2: Sketch of the light-weight cryogenic target cell, with one SDD detector module mounted.

A light-weight cryogenic target was built, consisting of aluminium (top-plate and entrance-ring), Kapton (side wall and entrance window) and a hexagonal support structure also made of aluminium to minimize fluorescence X-rays produced in the target material. The target cell was cooled to 25 K with a two stage closed-cycle helium refrigerator. A working pressure of 0.3 MPa was achieved, which leads to a hydrogen gas density of 3.5 g/l (corresponding to 3% of Liquid Hydrogen Density). The vacuum requirement is fulfilled using a wide range turbo molecular pump (TMP) and an oil-free diaphragm pump.

For SIDDHARTA we have developed a special X-ray detector with excellent energy resolution (FWHM ~ 150 eV @6 keV) and timing capability in the order of μs, namely large area Silicon Drift Detectors (SDDs) [12,13]. Using the X-ray signal from the SDDs in coincidence with the K^+K^- pair a triple coincidence could be set up (see Figure 3). With this coincidence method we are able to suppress the continuous background, as well as fluorescence X-rays by almost three orders of magnitude compared to the DEAR case.

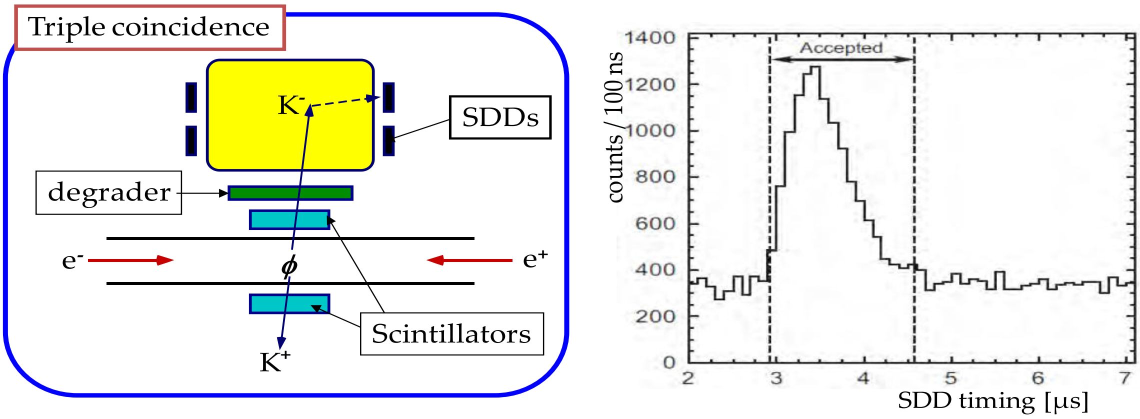

Figure 3: Sketch of the triple coincidence of the charged kaon pair with the X-ray (left); time spectrum of the drift time of measured X-rays within the SDDs, indicated the used time window for the analysis procedure(right).

3.The SIDDHARTA results

The new trigger-able SDD detectors, developed for the SIDDHARTA project, allowed an improved measurement of energy and time resolution compared to past experiments, resulting in much lower background and in addition permits a better control on systematic. The determination of shift and width allows more precise evaluation of the antikaon nucleon scattering lengths which yields vital constraints on low-energy QCD [14,15].

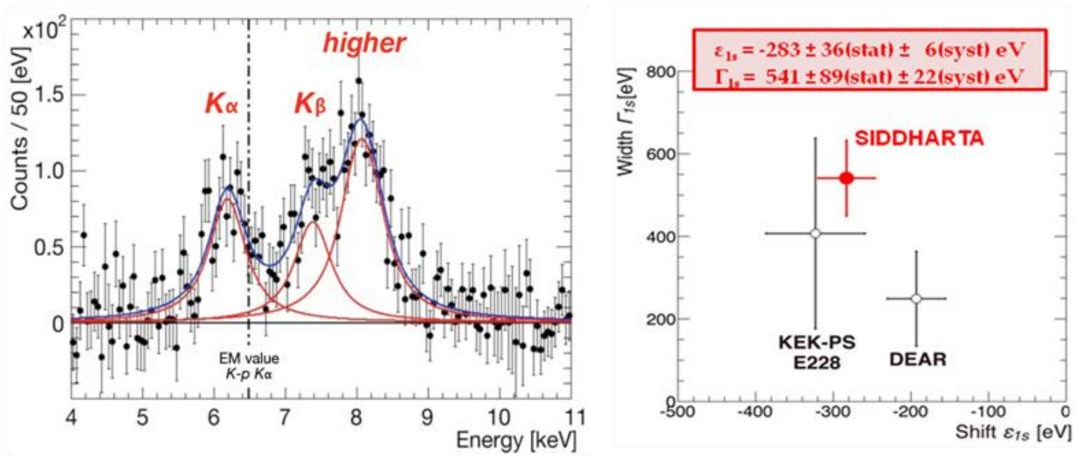

Figure 4: Kaonic hydrogen X-ray spectrum, the dashed-dotted line indicates the value of the "pure" electromagnetic interaction (QED calculation). The shift due to strong interaction of the Kα-line is clearly visible (left). The result of SIDDHARTA is compared with KEK-PS E228 and DEAR (right).

3.1Kaonic hydrogen

Figure 4 (left) shows the final kaonic hydrogen spectrum with kaonic and fluorescence X-ray lines subtracted together with the continuous background. The position of the "pure" electromagnetic interaction is indicated (dashed-dotted line). The shift of the Kα-line, due to strong interaction is clearly visible.

Figure 4 (right) shows the SIDDHARTA result together with the results of KEK-PS E228 (KpX) [16] and DEAR [17].

3.2 Kaonic deuterium

To determine the “isospin-dependent” antikaon nucleon interaction, it is crucial to measure the strong-interaction 1*s*-energy-level shift and width of kaonic deuterium. The result of a first-ever exploratory measurement of kaonic-deuterium X-rays is shown in Figure 5. Although there is no clear evidence of a signal corresponding to K-series of K^-d X-rays, it was possible to extract a 1.7 sigma hint of a signal if the shift and width of the K-series transitions are taken from theory.

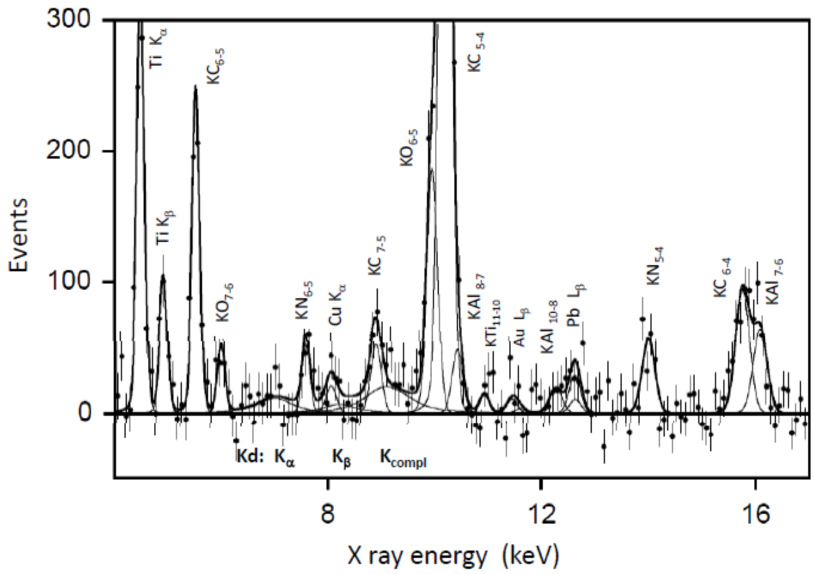

Figure 5: Kaonic deuterium X-ray spectrum with the fitted continuous background already subtracted. Fit with fixed K^-d transition shift and width (–805 eV, 750 eV) and fixed yield ratio of the individual K-transitions. The lines from kaonic X-rays and from X-ray fluorescence lines are indicated. Note the excess of events in the region of a possible signal.

3.3 Kaonic helium

The strong-interaction induced shift was measured for the kaonic ^{3}He and ^{4}He 2p levels with an accuracy of several eV. For the first time the measurements were performed using gaseous targets. In addition it was the world first observation of kaonic ^{3}He X-rays.

Figure 6 (left) shows the X-ray energy spectrum of kaonic ^{3}He [10]. The position of the kaonic helium X-ray transition from 3d $\rightarrow$ 2p is indicated in the figure, as well as the fluorescence line of titanium and kaonic transitions in carbon, oxygen and nitrogen. The later lines were used for calibration purpose and stability check of the SDDs. Figure 6 (right) shows the X-ray energy spectrum of kaonic ^{4}He [9].

In addition the 2p state width of K^{-3}He and K^{-4}He could be determined with an order of magnitude better precision [18] as compared to the old measurements:

$\Gamma_{2p}(^3\text{He})$ = 6 ± 6 (stat.) ± 7 (syst.) eV and $\Gamma_{2p}(^4\text{He})$ = 14 ± 8 (stat.) ± 5 (syst.) eV.

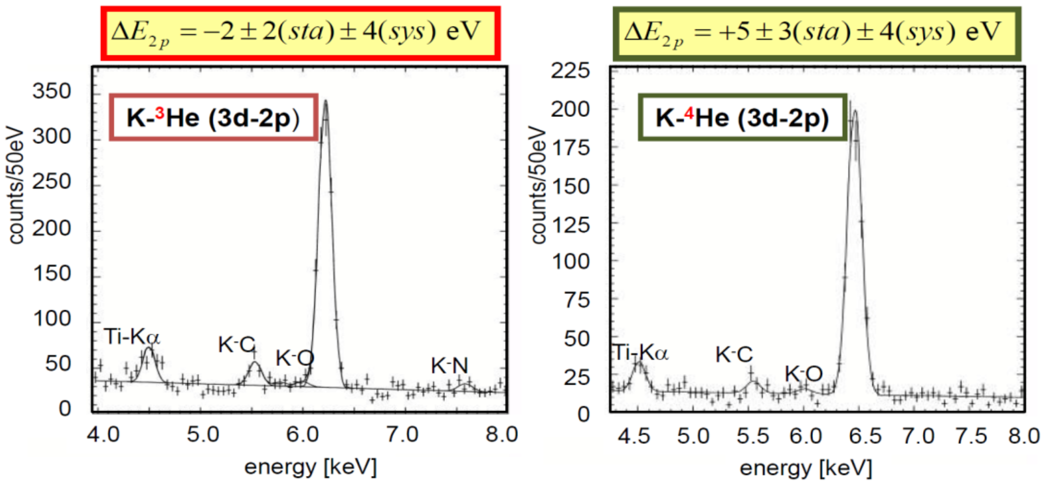

Figure 6: The positions of the K⁻He 3d→2p transitions are shown, X-ray energy spectra of K⁻³He (left), K⁻⁴He (right). Kaonic carbon 8→6, oxygen 7→6 and nitrogen 6→5 transitions are indicated.

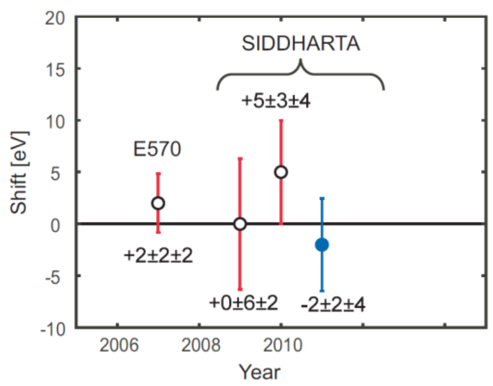

Figure 7: Results of the 2p transition X-ray measurement of kaonic helium.

The final results for the shift analysis are displayed in Figure 7, showing also the KEK E570 experiment [19]. A large shift of the order of 40 eV determined by the experiments performed in 70s and 80s was not obtained neither in kaonic ^{3}He nor kaonic ^{4}He. Both are consistent with 0 eV within the errors. The results agree with theoretical predictions determined from other kaonic atoms with Z ≥ 3 using optical model approaches [20], also the theoretical prediction by [21] cannot be excluded within our accuracy.

4.Conclusions

The new trigger-able SDD X-ray detector system, developed in the framework of the SIDDHARTA project, lead to an improved energy and time resolution over the past experiments. Therefore, it was possible to determine the strong-interaction energy-level shift and width of the kaonic-hydrogen atom 1s state with the best accuracy up to now, giving vital constraints on the theoretical description of the low-energy antikaon nucleon interaction.

5.Acknowledgements

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