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Probing Strong Interaction with Kaonic Atoms – from DAΦNE to J-PARC

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The study of the antikaon nucleon system at very low energies plays a key role to study strong interaction with strangeness, touching one of the fundamental problems in hadron physic today – the still unsolved question of how hadron masses are generated. Exotic atoms offer a unique possibility to determine s-wave kaon-nucleon scattering lengths at vanishing energy.
At the DAΦNE electron positron collider of Laboratori Nazionali di Frascati in the SIDDHARTA experiment kaonic atoms were formed with Z=1 (K^-p) and Z=2 (K^-He), which were measured with up to now unrivalled precision. This experiment is taking advantage of the low-energy charged kaons from ϕ-mesons decaying nearly at rest. Finally, using the experience gained with SIDDHARTA, a proposal to measure kaonic deuterium for the first time was submitted to J-PARC with the goal to determine the isospin dependent scattering lengths, which is only possible by combining the K^-p and the upcoming K^-d results.

KEYWORDS: low-energy QCD, kaonic atoms, K^-p scattering lengths, cryogenic X-ray detectors

1. Introduction

In light exotic hadronic atoms the Bohr radius is still much larger than the typical range of strong interaction formulated in QCD, and the average momentum of the bound hadron is very small. For light atoms, especially for hydrogen atoms, a detectable energy shift from the electromagnetic value of the ground state has been found, as well as an observable energy broadened ground state level, caused by nuclear absorption (see Fig.1). By measuring these observables, exotic atoms offer the unique possibility to determine s-wave kaon-nucleon scattering lengths at vanishing energy, alternatively to scattering experiments were an extrapolation to zero energy is necessary.

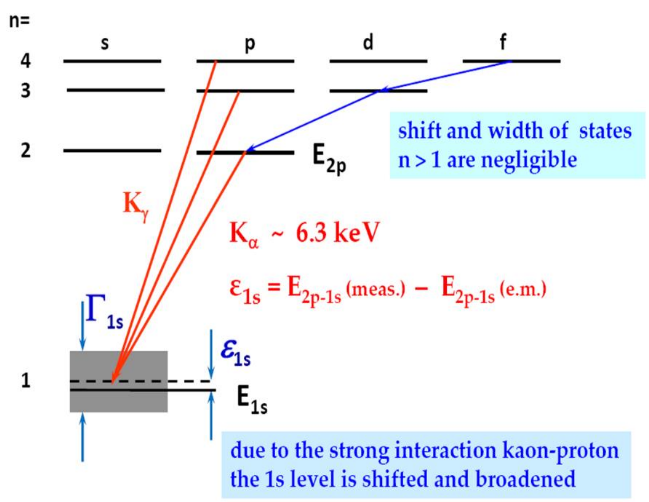

Fig. 1. After the atomic capture of the kaon a kaonic atom is formed in a highly excited state and a few kaons will cascade to ground state.

With SIDDHARTA at DAΦNE at the Laboratori Nazionali di Frascati (LNF) the strong interaction induced shift of the ground state of kaonic hydrogen atoms and the absorption width were measured with utmost accuracy up to now [1,2,3].

Measurements of the 2p shift and width of kaonic helium (^{4}He as well as ^{3}He) [4,5] completed the SIDDHARTA programme.

Because of the importance of the K^-d measurement an attempt was started to perform kaonic deuterium at J-PARC for the first time [6,7]. *"The necessity to perform measurements of the kaonic deuterium ground state observables is justified by the fact that, unlike the case of pionic atoms, the measurement of only the kaonic hydrogen spectrum does not allow – even in principle – to extract independently both s-wave antikaon-nucleon scattering lengths a_0 and a_1"*, quoting from U.-G. Meisser [8]. The kaonic deuterium X-ray measurement represents the most important experimental information missing in the field of the low-energy antikaon-nucleon interactions today.

2. The physics case

Chiral perturbation theory (ChPT) [9,10,11], with symmetries and symmetry breaking patterns of QCD included, is an appropriate framework to analyse the dynamics of hadrons at low energy, and to describe the observable effects in the spectrum of exotic hadronic atoms. For light atoms, especially for hydrogen atoms a detectable energy shift of the ground state is expected (with respect to the pure QED value) as well as an observable broadened ground state level (Fig. 1). By measuring these observables, the s-wave hadron–hadron scattering lengths at zero energy could be extracted. A Deser-type relation connects the observable shift and width to the real and imaginary part of the scattering length a_{K-p} with isospin breaking correction included [12] (μ_c is the reduced mass of the K^-p system, α is the fine-structure constant).

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

For the two-flavour case, with almost massless $m_{u,d}$ quarks and spontaneously broken $SU(2)_L$ x SU(2) symmetry, can be stated that ChPT describes very well the situation for π^-p-, $\pi^-\pi^-$- and also $K^-\pi^-$-atoms. Although, the low energy K^-N system is of special interest as a testing ground for chiral SU(3) symmetry (three-flavour QCD at low energy) due to the large mass of the strange quark where the kaon mass appears prominently in the symmetry breaking mass term. It has to be stated that ChPT is inapplicable in the sector with strangeness due to the presence of resonances, which is partly a consequence of the stronger explicit chiral symmetry breaking by the strange quark mass, implying a significantly stronger interactions of antikaons as compared to those of pions near their respective thresholds. The existence of the Λ(1405) resonance just below the K^-p threshold makes a perturbative ChPT treatment impossible. Therefore, non-perturbative coupled-channel techniques based on chiral SU(3) effective Lagrangians at next-to-leading order as input and in addition solving coupled-channels Lippmann-Schwinger equations to all orders, have been well established to deal with these problems [13,14]: the Λ(1405) resonance is generated dynamically as a K^-N bound state with isospin I = 0 and as a resonance in the πΣ channel.

The analysis of the K^- proton scattering data, extrapolated to zero energy, shows clearly that the s-wave K^- nucleon scattering length is repulsive (the real part is negative). X-ray measurements performed at KEK [15] and by the DEAR and SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by Timing Applications) experiments at DAΦNE [2,3] have confirmed these results, but are in contradiction to the older X-ray data (see Fig. 2) .

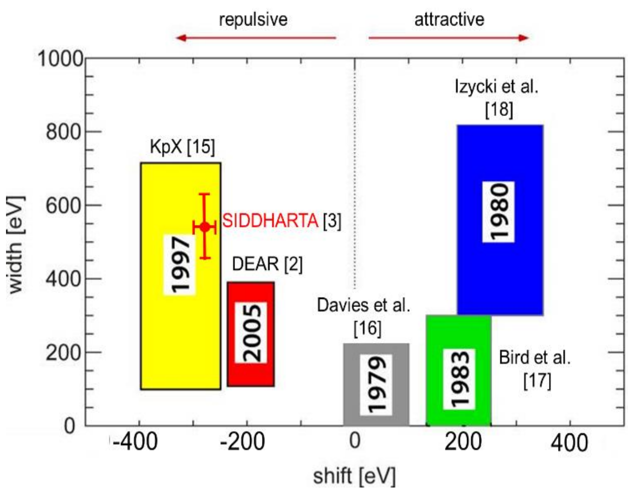

Fig. 2. Comparison of previous experimental results for the strong interaction 1s energy level shift and width of kaonic hydrogen.

It is, however, possible that the actual K^-p interaction is attractive, although it appears repulsive from the scattering data and from the energy shift measurements of the kaonic hydrogen. This effect is understood by analogy to proton–neutron scattering. The interaction between the proton and the neutron is attractive, but the scattering length in the deuteron channel (isospin I = 0, spin S = 1) is repulsive, due to the existence of the deuteron as a bound state. In nuclear matter, however, the deuteron disappears, largely due to Pauli blocking, and the true attractive nature of the proton–neutron interaction emerges. In the bound state picture of Λ(1405), analogously to the deuteron case, the scattering through the resonance gives rise to a repulsive contribution. Just as well as in this case, the "dissolving" of the bound state within the nucleus, allows the true nature of the K^-p interaction to emerge.

The K^-p X-ray data at threshold from DEAR [2] and KpX [15] and the new precision data from SIDDHARTA [3], together with K^-p scattering data [19] and decay ratios [20] set important constraints for such a theoretical work. The constraints set by the SIDDHARTA data is shown in Fig. 3 with the calculated real and imaginary parts of the K^-p amplitude (including Coulomb corrections) [21]:

$$Re\ a(K^-p) = (-0.65 \pm 0.10)fm \quad Im\ a(K^-p) = (0.81 \pm 0.15)fm \qquad (2)$$

Further extensions of such calculations based on chiral SU(3) effective field theory (ChEFT) have recently been reported in [22,23].

The SU(3) ChEFT coupled-channels approach also predicts K^-n amplitudes. While the weaker attraction in this I = 1 channel does not produce a quasibound state or resonance, the NLO calculations still suggest a sizeable K^-n scattering length [21]:

$$Re\ a(K^-n) = (-0.57 + 0.04 - 0.21)fm \quad Im\ a(K^-n) = (0.72 + 0.26 - 41)fm \qquad (3)$$

It is very important to provide empirical constraints for this quantity in order to achieve complete information for both isospin I = 0 and I = 1 channels of the antikaon nucleon system. Therefore, a first accurate measurement of K^-d, as proposed at J-PARC, is of great importance.

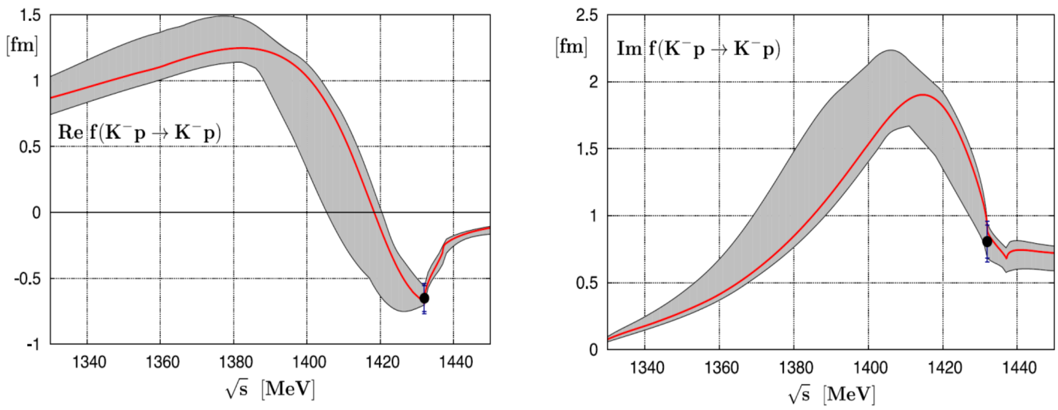

Fig. 3. Real and imaginary parts of the K^-p scattering amplitude from chiral SU(3) coupled-channels dynamics [21]. The threshold points indicating the real and imaginary parts of the corresponding scattering length are constrained by the SIDDHARTA kaonic hydrogen measurement.

3. The SIDDHARTA experimental setup

The SIDDHARTA setup consists of two main components, the light-weight cryogenic target cell and a specially developed large area, high resolution X-ray detector system made of Silicon Drift Detectors (SDDs). The kaons leaving the interaction point through the SIDDHARTA beam pipe are degraded in energy and enter the cryogenic gaseous hydrogen (helium) target placed above the beam pipe (see Fig. 4). Negative kaons are slowed down in the target gas and are finally capture in a highly excited state forming a kaonic atom. In these atoms the K^- will cascades down to the 1s ground state in the case of hydrogen emitting around 6 keV X-rays in the transition 2p-1s.

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. This design minimizes the X-ray absorption in the wall material. On the other hand it provides the necessary gas density under safe working conditions. A working pressure of 0.3 MPa was achieved, which leads to a hydrogen gas density of 2% of liquid hydrogen density, at a working temperature of 25 K.

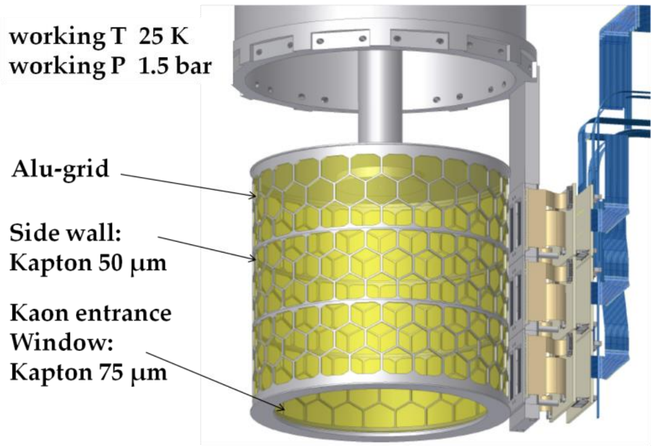

Fig. 4. Sketch of the lightweight cryogenic target cell, with one of the SDD sub-units attached to the cold-finger.

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 SDDs [24]. Using the X-ray signal from the SDDs in coincidence with the K^+K^- pair a triple coincidence could be set up. 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.

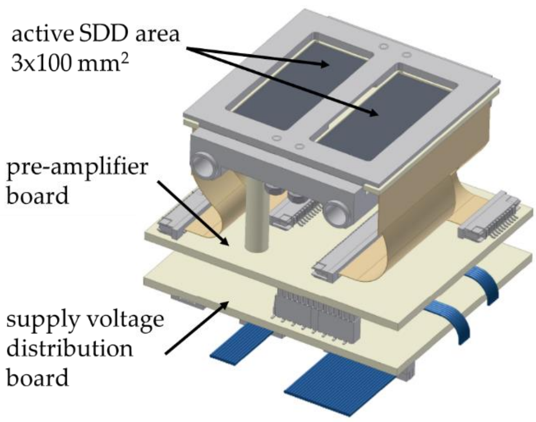

Fig. 5. Aluminium holder of the SDD-chip with pre-amplifier board and supply voltage board.

The SIDDHARTA SDDs were developed in a Joint Research Activity of the EU HadronPhysics project. The goal was to build SDD-chips with a total active area of 300 mm^2, consisting of three individual elements on one chip, two 300 mm^2 SDD-chips are mounted in an aluminium case (see Fig. 5), with three of these cases grouped to build up a sub-unit. Finally, a detector system with a total active area of 144 cm^2 was built. To achieve the required energy resolution (FWHM of 150 eV at 6keV) the SDDs are cooled to approx. 170 K.

4. Precision spectroscopy of light kaonic atoms at DAΦNE

DAΦNE operates at the centre-of-mass energy (m=1019.413 MeV) of the ϕ meson. The ϕ meson is produced in e^+e^- collisions almost at rest and decays with a branching ration of about 50%, back-to-back, to a K^+K^- pair with a kaon momentum of 127 MeV/c. During the SIDDHARTA beam time period an average ϕ-production rate in the order of R_ϕ=2.5x10^3 s^{-1} was achieved.

4.1 The experimental method

The K^+K^- pairs produced by ϕ decay were detected by a kaon detector, consisting of two scintillators installed above and below the beam pipe at the interaction point with two fast photomultipliers. Charged kaon pairs were identified by a time-of-flight technique. The slow kaon pairs are clearly separated from fast minimum ionizing particles (MIPs), due to excellent time resolution (<100 ps FWHM) and the stability of the clock pulses (380 MHz RF) delivered by DAΦNE. The kaonic atom X-rays were detected using the recently developed large area SDDs with an active area of 144 cm^2. X-ray signals in the SDDs were read out using a specially designed data acquisition system. In addition, time differences between the coincidence signals in the kaon detector and X-ray signals in the SDDs were recorded, whenever the coincidence signal occurred within a time window of 6 μs. The SDD data are categorized as one of two types, X-ray events uncorrelated with the kaon coincidence ("non-coincidence data"), which provides large statistics of calibration X-rays, the other type contains X-ray events correlated with the kaon coincidence ("coincidence data"), which provides kaonic atom X-ray energy spectra with a high background suppression.

4.2 Kaonic helium results

Until recently, there has been a discrepancy in the energy shift of kaonic helium. Three measurements of the energy shift of the kaonic ^{4}He 2p-state made in the 70's and 80's gave consistent results with an average value of the shift ΔE =−43 ± 8 eV.

On the other hand, the theoretical calculations based on the kaonic atom data with Z > 2 gave a shift of ΔE ~ 0 [28-32]. Most of the theoretical model could not explain the large shift, and this difference between experiment and theory was known as the "kaonic helium puzzle". The results of the KEK-PS E570 and the SIDDHARTA experiments are compatible with a shift of ΔE ~ 0 (see table 1).

Table I. $K^-{}^4$He Lα X-ray data, in red the data for $K^-{}^3$He

ΔE (eV)	References	
−41 ± 33	Wiegand et al.	[25]
−35 ± 12	Batty et al.	[26]
−50 ± 12	Baird et al.	[27]
+2 ± 2(stat) ±2(syst)	Okada et al.	[33]
0 ± 6(stat) ± 2(syst)	SIDDHARTA	[4]
+5 ± 3(stat) ± 4(syst)	SIDDHARTA	[34]
−2 ± 2(stat) ± 4(syst)	SIDDHARTA	[5]

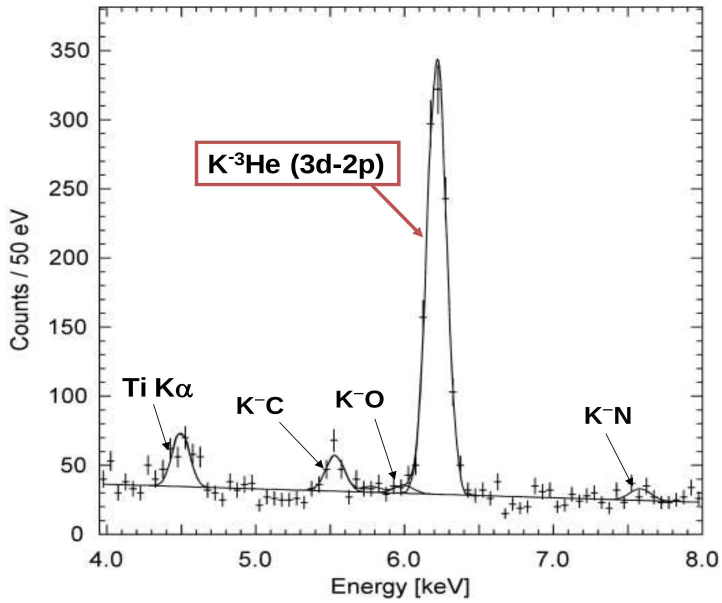

Fig. 6. First measurement of the kaonic ^{3}He L_α line.

Figure 6 shows the X-ray energy measured in SIDDHARTA. The peak seen at 6.2 keV is identified as the kaonic ^{3}He L_α line (3d→2p transition). Additional peaks are seen and can be identified: the Ti K_α fluorescence line at 4.5 keV, the kaonic carbon 6h→5g transition at 5.5 keV, the kaonic oxygen 7i→6h at 6.0keV, and the kaonic nitrogen 6h→5g at 7.6 keV, which are produced by kaons stopping in the target window made of Kapton.

4.3 Kaonic hydrogen

In order to sum up the energy spectra of each individual SDD, the energy calibration of each single SDD was performed by periodic measurements of fluorescence X-ray lines from titanium and copper foils, excited by an X-ray tube, with the e^+e^- beams in kaon production mode. For the summed spectrum of all SDDs the final refined in-situ calibration in energy and resolution (response shape) was obtained using titanium, copper and gold fluorescence lines excited by the uncorrelated background without trigger and in addition using the kaonic carbon lines from stops in the Kapton entrance window and wall of the target cell during trigger mode.

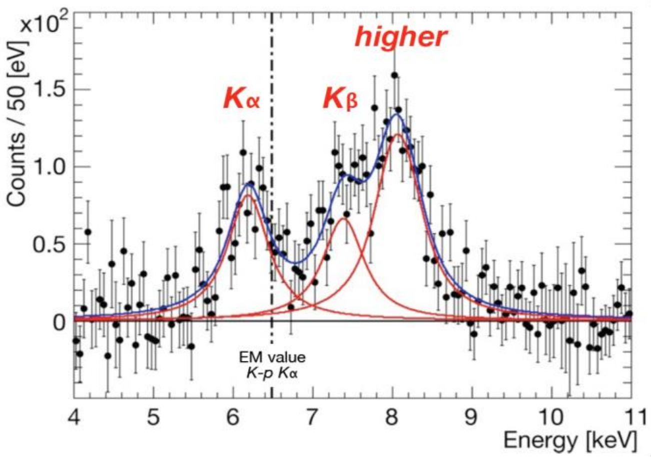

Fig. 7. Background subtracted X-ray energy spectrum for K^- triggered events of kaonic hydrogen.

We performed two independent analyses and the comparison of the shift and width values gives a direct measurement of the systematic error from the use of different procedures. The resulting shift values were consistent with each other within 1 eV, however the width differed by ∼ 40 eV. For shift and width we quote here the mean value of the two analyses and take into account the difference as one of the sources of the systematic error. Figure 7 shows the fit result with the background subtracted. The fit result indicated by the red lines shows well separated the K_α and K_β lines. The energy shift of the 1s state due to strong interaction from its pure electromagnetic value is clearly visible.

As a result, the 1s-level shift ε_{1s} and width Γ_{1s} of kaonic hydrogen were determined to be:

$$\begin{aligned} \varepsilon_{1s} &= -283 \pm 36_{\text{stat.}} \pm 6_{\text{sys.}}\ \text{eV} \\ \Gamma_{1s} &= -541 \pm 89_{\text{stat.}} \pm 22_{\text{sys.}}\ \text{eV} \end{aligned} \quad (4)$$

New theoretical calculation determining the K^-p scattering length using Chiral SU(3) coupled-channels dynamics are available now [21].

5. Kaonic deuterium at J-PARC

The proposed kaonic deuterium experiment will use the excellent features of the K1.8BR kaon beam line together with the K1.8BR spectrometer for tracking. In the centre of the spectrometer we plan to install the main parts for the K^-d experiment: the cryogenic deuterium target, which is surrounded by newly developed SDDs for high precision X-ray detection. The K1.8BR multi-purpose spectrometer has quite unique features for our needs, namely a large acceptance cylindrical spectrometer system (CDS), essential for efficient background reduction of the proposed kaonic deuterium X-ray experiment.

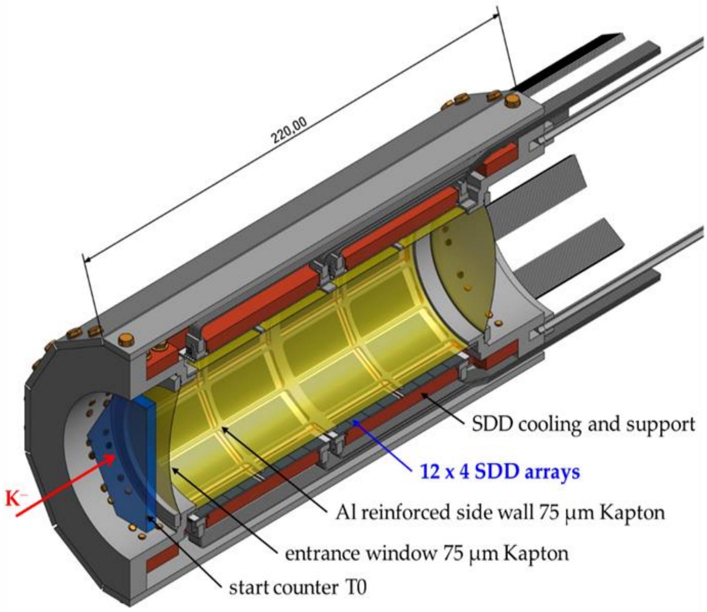

Fig. 8. Design consideration of the combined cryogenic target and detector part for the K^-d experiment at J-PARC.

The cryogenic deuterium target cell will be made of a 75μm Kapton body with a diameter of 65 mm and a length of 160 mm, with a reinforcement structure made out of aluminium. The working temperature of the target cell is around 30 K with a maximum pressure of 0.35 MPa, which allows a maximum gas density of 5% of the liquid deuterium density. 48 monolithic SDD arrays will be arranged around the target, with a total area of 246 cm^2 containing 384 readout channels (see Fig. 8).

We have simulated the kaonic deuterium X-ray spectrum ($3\cdot10^8$ K^- produced per day) using the new X-ray detector with an active area of 246 cm^2, with an assumed target gas density of 5% of LDD (see Fig. 10). The yield ratios of the K_α:K_β:K_{total} transitions were taken from the kaonic hydrogen data, but now for deuterium with an assumed K_α yield of

10^{-3} for the gaseous target. For the strong interaction induced shift and width, theoretical prediction were used: shift = 800 eV and width = 750 eV. The simulated spectrum for the transition energies of kaonic deuterium atoms is shown in figure 9, using the vertex cut method (successfully used for E570 at KEK) defining an active volume inside the target (5 mm away from the walls), and a charged particle veto for tracks passing through or nearby SDDs. For a gas density of 5%, the estimated signal to background ratio (integral) is1:4. Fitting a set of simulated data, we extracted the shift and width with a precision of 60 eV and 140 eV, respectively, which is comparable with the SIDDHARTA result of K^-p.

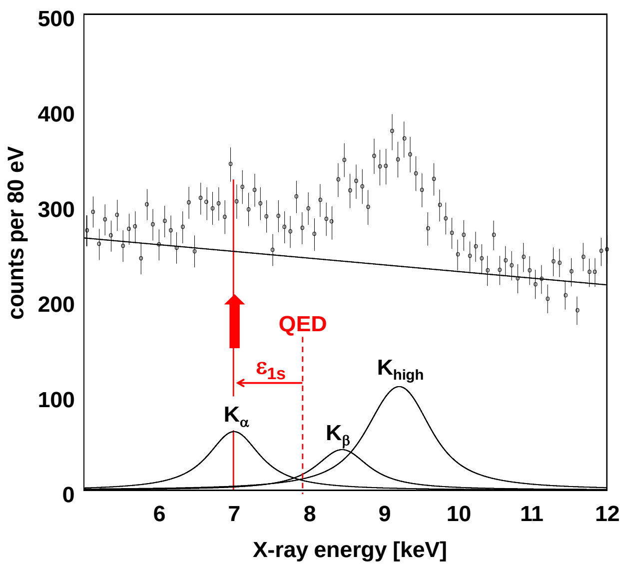

Fig. 9. Simulated kaonic deuterium x-ray spectrum, assuming $1.5 \cdot 10^{10}$ produced K^-.)

3. Conclusion

In conclusion, the SIDDHARTA experiment has performed the most precise measurement of the K-series X-rays of kaonic hydrogen atoms as well as a first measurement of the L-series X-rays of kaonic helium-3. This was made possible by the use of new triggerable SDD X-ray detectors, developed in the framework of the SIDDHARTA project, which lead to a much improved X-ray detection compared with former experiments and much lower background in comparison with the DEAR experiment.

Our determination of the shift and width does provides new constraints on theories, having reached a quality which supports refined calculations of the low-energy antikaon-nucleon interaction. For further studies it is essential to measure the kaonic-deuterium K-series X-rays to disentangle the isoscalar and isovector scattering lengths.

Acknowledgment

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