Kaonic hydrogen X rays - experiments at DAFNE

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Abstract: At the DAΦNE electron-positron collider of Laboratori Nazionali di Frascati we study kaonic atoms, taking advantage of the low-energy kaons produced in the Φ-meson decay. The low-energy kaon-nucleon interaction in kaonic hydrogen and kaonic deuterium can be investigated under favorable conditions.

The DEAR (DAΦNE Exotic Atom Research) experiment at LNF delivered the most precise data on kaonic hydrogen up to now. DEAR and its follow-up experiment SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by Timing Application) are using X-ray spectroscopy of kaonic hydrogen and kaonic deuterium atoms to measure the strong interaction induced shift and width of the ground state. From these quantities the isospin-dependent antikaon-nucleon scattering lengths can be determined, quantities useful to test the understanding of chiral symmetry breaking in the strangeness sector.

Within the SIDDHARTA project new X-ray detectors are being developed. We will use an array of large area silicon drift detectors (SDDs) having excellent energy resolution but also providing timing capability which will result in a huge suppression of background and so overcome the precision limits of the former experiments.

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1. The scientific case

The hadron masses being much higher than the mass of their quark content raise one of the fundamental questions in hadron physics today. 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 massless quarks in strong interaction physics [1]. It results in a ground state - the vacuum state - with a finite expectation value for quark antiquark pairs, the chiral quark condensate [2]. The hadrons are considered to be quasi particle excitations of this chiral condensate.

Sensitive tests on the understanding of the chiral symmetry breaking scenario are provided by studies of pionic and kaonic hydrogen atoms. In both cases the strong interaction manifests in the shift and width of the atomic ground state (1s). However, there are substantial differences: Besides the fact, that in the kaonic case we deal with the strangeness sector, the strong interaction effect amounts to a very small shift/width in pionic hydrogen of 7 and 1 eV respectively - to be compared with 200 and 240 eV in kaonic hydrogen - and in the kaonic case resonances like the elusive $\Lambda(1405)$ are present.

Due to the tiny strong interaction effect the study of pionic hydrogen [3] calls for an X-ray spectrometer system with ultimate precision - provided by a crystal spectrometer which is feasible due to the huge pion beam intensity provided at PSI - whereas kaonic hydrogen can be studied with X-ray detectors like CCDs or SDDs directly.

In principle the isospin dependent pion-nucleon scattering lengths can be extracted from the measurement of the shift and width of pionic hydrogen alone using Deser-type formulae. In the kaonic hydrogen case however the corresponding scattering length can only be determined by measuring the shift and width of kaonic hydrogen as well as kaonic deuterium.

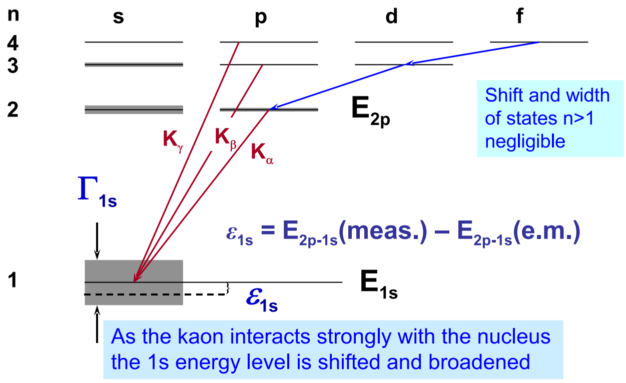

Fig. 1. Schematic view of the energy levels of kaonic hydrogen showing the shift and width due to strong interaction

A kaonic atom is formed when a negative kaon enters a medium, looses its kinetic energy through ionization and excitation of the atoms and molecules and eventually is captured, replacing the electron, in an excited orbit ($n \simeq 25$). Via different cascade processes (Auger transitions, Coulomb deexcitation, scattering) the kaonic atom deexcites to lower states. When a kaon reaches a low-n state with small angular momentum, strong interaction with the nucleus causes its absorption. The strong interaction is the reason for a shift in the energies of the low-lying levels from the purely electromagnetic values and the finite lifetime of the state corresponds to an increase in the observed level width. Experimental results for kaonic deuterium are not available, although the case (as the kaonic hydrogen case) is of high scientific interest [6] [7] [8] [9]. Measuring the shift and width allows to study the K^-p interaction at threshold using Deser-type relations [10].

In a previous experiment [11] at KEK the strong interaction shift of the $1s$ state in kaonic hydrogen was found to be repulsive in agreement with kaon nucleus scattering data and in disagreement with earlier kaonic hydrogen experiments. The origin of this repulsive strong interaction at threshold can be traced back to the presence of the $\Lambda(1405)$ resonance which leads on one hand to a repulsive K^-p scattering length and on the other to the possible existence of strongly bound kaonic states in light nuclei [12].

For quantitative tests of recent theoretical work on the topic, additional data with higher precision and finally a kaonic deuterium measurement are required. With DEAR we succeeded to perform an improved measurement of kaonic hydrogen [4]. (See fig.2,3). We obtained significantly higher precision and smaller shift and width values than the KpX experiment [11], still for the given precision the results are compatible.

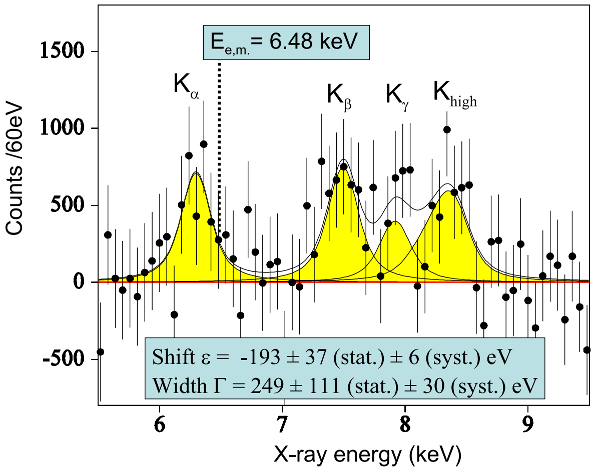

Fig. 2. Background subtracted X-ray energy spectrum of kaonic hydrogen (DEAR experiment).

In DEAR we used a light weight cryogenic gas target operated with hydrogen at a temperature of T=25K and a pressure of P=2bar [1] and as X ray detectors 16 CCDs (Marconi Applied Technologies CCD55, depletion depth 40 micron) with a total sensitive area of 116 cm^2. Each chip has about 1 millon pixels, so the readout with the necessary excellent energy resolution (155eV FWHM @ 6.4keV) is slow and prohibits tagging. The advantages of CCDs are large area, pixel cluster analysis capability for background reduction, excellent energy resolution and robustness in a radiation environment.

The precision obtained in DEAR was clearly limited by the signal to background ratio of about 1:100, so for improved experiments, especially for kaonic deuterium where the signal is expected to be 10 times smaller as compared to kaonic hydrogen, an other experimental technique will to followed: the experiment on kaonic deuterium is currently under development within the SIDDHARTA project.

We will also do measurements using kaonic He-3 and He-4, which will contribute to the ongoing search for kaon-nucleon clusters.

Finally we want to point out that the scattering lengths are related to the so called meson-nucleon sigma terms [13] as shown by 'low energy theorems'. These terms are important quantities in non-perturbative Quantum Chromo Dynamics (QCD) since they provide a measure of the chiral symmetry

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[1] results in a density of 2.1g/l, 0.03 of liquid hydrogen density

Fig. 3. DEAR apparatus installed at DAΦNE interaction point 2.

breaking.

2. SIDDHARTA

The kaonic atom experiments require high resolution X-ray spectroscopy in the radiation environment of an accelerator, which is a challenge to experimental techniques. In the SIDDHARTA project (Silicon Drift Detectors for Hadronic Atom Research by Timing Application) a triggered soft X-ray detection system is being developed. In fig. 4 the principle of the system is sketched.

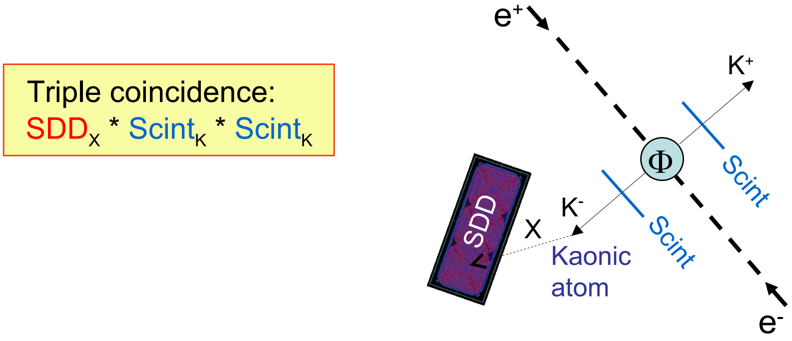

Fig. 4. Scheme of the triggered detection system for kaonic X-rays.

Since the soft X-ray background at DAΦNE originates almost entirely from electromagnetic showers from lost beam particles as was seen in DEAR, by demanding a coincidence of the X-ray with the back-to-back emitted charged kaons we will get much cleaner spectra. Practically only charged kaon correlated background will remain.

Silicon Drift Detectors (SDDs) are based on the principle of sideward depletion introduced by Gatti and Rehak [14] in 1984. In an advanced SDD design optimized for X-ray spectroscopy (see fig. 5), the concentric ring-shaped n^+ strip system for the generation of the drift field as well as the collecting anode in their center are placed on one side of the structure, while the opposite surface is a non-structured p^+ junction acting as the radiation entrance window. There is no field-free region, the whole volume is sensitive to the absorption of ionizing radiation. Each electron generated in this volume has to fall down to the point of lowest potential energy, which is the anode in the center of the front side. The small value of the anode capacitance (which is almost independent of the detector area) results in a large amplitude and a short rise time of the output signal. Compared to conventional photodiodes the SDDs can be operated at higher counting rates and yield a much better energy resolution. They can be operated even at room temperature or with moderate cooling.

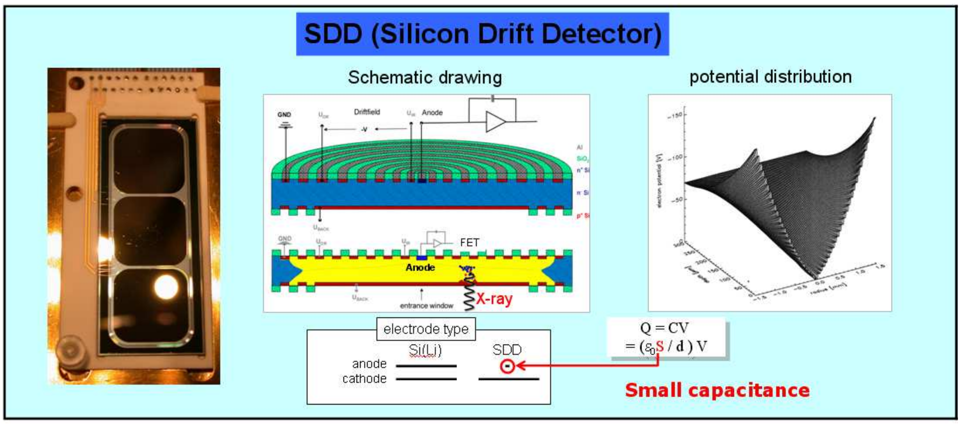

Fig. 5. View of a 3 x 1 cm^2 module of the Silicon Drift Detectors (left) and working principle.

The SDD chips developed by the company PNsensor and the MPI for extraterrestrial physics within the project have a nearly quadratic structure (see fig. 5) with an active area of 1 cm^2 and a thickness of 450 μm. Three of these structures are integrated on one chip, 2 chips make up a SDD detector element. The production has started, and first modules were assembled and tested with the electronics to be used in the real experiment. The devices show an excellent energy resolution (140 eV FWHM at 5.9 keV) due to the low leakage current obtained by the refined processing technology (see fig. 6). The timing resolution is better than 500 ns FWHM.

The kaonic atom experimental program using these SDDs will be starting at LNFrascati in 2007.

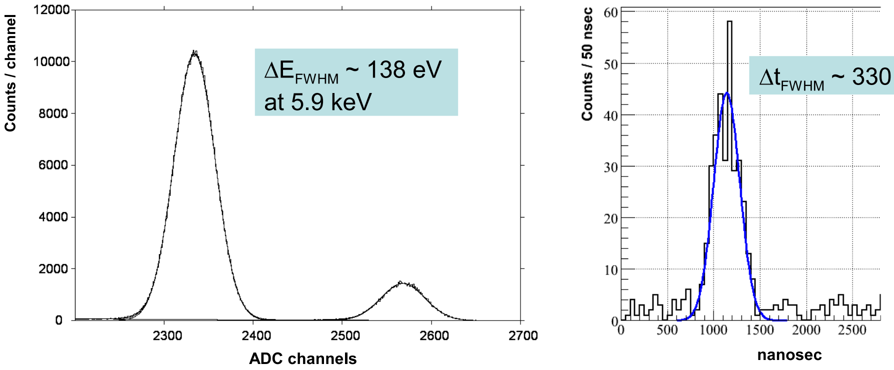

Fig. 6. Energy resolution of the SIDDHARTA chip measured with an Fe55 source (left), timing resolution of the 1cm^2 SDD chip used at KEK experiment E570 [15] (right) .

For kaonic deuterium with an assumed yield of 0.002 for the K_α transition and a width of 630 eV

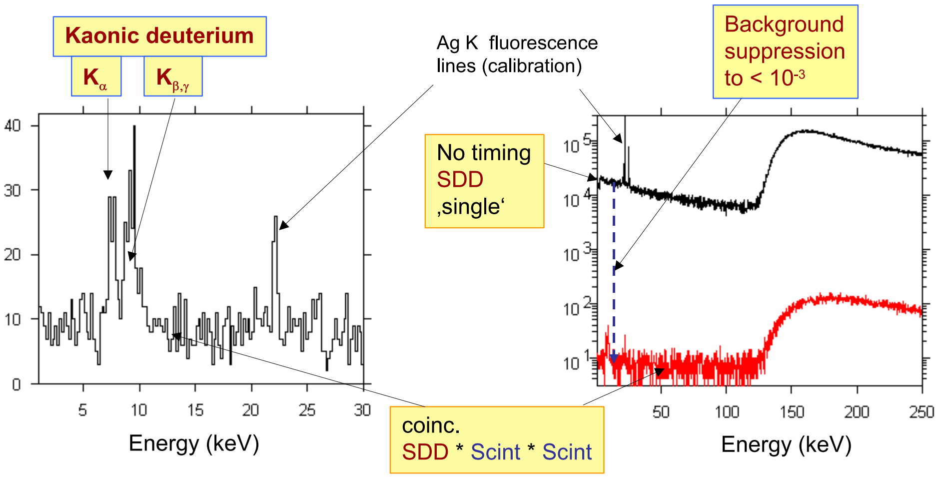

Fig. 7. Monte Carlo simulation of the kaonic deuterium experiment, assuming background intensities as measured in DEAR. Note the good background suppression resulting in a signal/background ratio of about 1:1.

the Monte Carlo simulations let us expect a signal to background ratio of about 1:1 (see fig.7) using a coincidence width of 1 μs. For 30 days of data taking at DAΦNE (current luminosity) we expect 3000 events in the K_α peak, which would result in a precision (standard deviation) of about 18 eV for the shift and 45 eV for the width.

3. Conclusions

DAΦNE has unique features as a kaon source for kaonic atom research: intrinsically clean kaons of low momentum are produced, a situation not available with fixed target machines. The kaonic atom experimental program at DAFNE which started by delivering the most precise result for kaonic hydrogen up to now (DEAR) will be followed with a new technique, SDDs as triggered X-ray detectors (SIDDARTA), which will allow a new range of precision in kaonic hydrogen and a first time measurement in kaonic deuterium. The upcoming results will open new possibilities in the study of the antikaon-nucleon interaction at low energies, in particular chiral symmetry breaking in the strangeness sector.

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