Exotic Atom Research Using Large Area Silicon Drift Detectors

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New large area silicon drift detectors (SDDs) will be used at LN Frascati for spectroscopy of X-ray transitions in kaonic atoms like kaonic hydrogen and kaonic helium. These detectors provide excellent energy resolution for low energy X-rays but also timing capability which is important to efficiently suppress background by time correlations. Precise data on the strong interaction in these hadronic atoms can be obtained leading to new insight into the field of low-energy kaon-nucleon interaction. The performance of these detectors and first experiments in the environment of the accelerator based research will be presented. An outlook to future experiments with SDD detectors will be given.

1. INTRODUCTION

The strong interaction in kaonic hydrogen atoms between the orbiting negative kaon and the proton can be studied with high precision using X-ray spectroscopy. The 1s ground state level in kaonic hydrogen is shifted in energy and broadened since nuclear absorption leads to a shortened life time. By measuring the strong interaction shift ϵ_{1s} and the width Γ_{1s} the isospin dependent scattering lengths can be extracted using the Deser-Trueman formula [1]. It is obvious that high resolution X-ray detectors are crucial for this research. Whereas in former experiments Si(Li) detectors were used the presently most precise values for ϵ_{1s} and Γ_{1s} were obtained in the DEAR experiment at LNF using CCDs (charge coupled devices) as X-ray detectors [2–5]. In this context it has to be mentioned the new method [6] providing the refined analysis of the CCD data. The main drawback of CCDs - the limited suppression of soft X-ray background due to the lack of timing capability - can be overcome with SDDs (silicon drift detectors). Within the SIDDHARTA[1][7] project novel large area SDDs are in development now.

2. X-RAY DETECTORS FOR EXOTIC ATOM RESEARCH

The use of modern advanced X-ray detectors like CCDs resulted in major results in exotic atom research. The next step in semiconductor X-ray detector technology is the development of SDDs which provide an energy resolution comparable with CCDs, large area (1 cm^2), high intrinsic efficiency, low noise and - most important - timing capability. The latter feature of SDDs allows for the suppression of background events by using the time correlations in the next experiments at DAΦNE.

[1]Silicon Drift Detectors for Hadronic Atom Research by Timing Application

3. X-RAY STUDIES OF KAONIC ATOMS

In order to investigate X-ray transitions in kaonic atoms the X-ray detection has to provide high efficiency and excellent energy resolution in the soft energy range, e.g. the K X-ray transitions of kaonic hydrogen or kaonic deuterium are in the range of 6 to 10 keV. All the experiments done until recently used Si(Li) detectors. A major step forward was the use of CCDs in the DEAR project on kaonic hydrogen. For a comparison of different X-ray detectors see table I. However, the drawback of CCDs - the lack of timing information - will be overcome by the use of SDDs.

3.1. Kaonic hydrogen: From CCD to SDDs

CCDs are high efficient X-ray detectors with very good energy resolution. Regarding background suppression only the selection of single and double pixel events can be used for discriminating background events. In spite of these background reduction in the past DEAR experiments the precision of the determination was limited by the signal-to-background ratio (in the order of 1:70 in the kaonic hydrogen measurement).

A new era of high precision experiments in the field of exotic atoms is opened by the application of SDDs which are based on the principle of sideward depletion pioneered by Gatti and Rehak [8] in 1984. On one side of a SDD the ring-shaped system of n$^+$ strips providing the drift field and the anode in the center are placed. The other side is a non-structured p$^+$ junction serving as radiation entrance area. Since there is no field-free region in the device the whole volume is sensitive to the ionizing radiation. The electrons generated in the SDD drift to the anode in the center of the front side. This anode is characterized by the small value of the capacitance which results in a large amplitude and a short rise time. SDDs incorporate all necessary features to be the X-ray detector of choice for exotic atom studies.

Table I Comparison of properties of X-ray detectors used for exotic atom research: lithium drifted silicon Si(Li) detector, CCD-55 used in kaonic atom research and large area SDD (this work).

Detector	**Si(Li)**	**CCD**	**SDD**
Effective area [mm^2]	300	724	100
Thickness of depletion [mm]	4	0.03	0.26
Energy resolution [eV] at 6 keV	$\sim$300	$\sim$150	$\sim$160
Time resolution [ns]	$\sim$280	–	$\sim$330

Features of SDDs:

- timing capability with sufficient time resolution ($< 1\mu$s) to suppress the asynchronous background efficiently,
- high efficiency close to 1 in a wide range of X-ray energies up to about 15 keV due to the sensitive layer thickness ($\sim$ 450 μm),
- good energy resolution, achievable with cooling ($\sim$ 120K),
- low noise due to the small anode with low capacitance,
- high detection rate capability,
- low internal electromagnetic background compared with thicker (crystal) detectors,
- good energy separation between minimum ionizing particles and photons,
- flexibility for arrangements in large X-ray detector arrays due to the compact design.

3.2. Development of SDD detectors for SIDDHARTA

The development of large area SDDs for SIDDHARTA is conducted in a Joint Research Activity (JRA10) within I3-HadronPhysics - a project in the 6th framework program of the European Community. The chips are produced by the Halbleiterlabor in Munich. Special care has to be devoted to the composition of ceramic material on which the SDDs are glued. Using proton induced X-ray emission the ceramic material with the lowest content of elements with fluorescence lines in the region of interest is chosen.
A dedicated read-out electronics for the SDD detector array is in development.

At the DAΦNE facility the electron-positron collision energy is set to the Φ resonance and subsequently kaons are produced by Φ decay. Due to their timing capability SDDs allow to use the time correlation between the incoming K^- from the Φ-meson decay (branching ratio for the main decay channel $\Phi \rightarrow K^- + K^+$ is about 50 percent) and the X-ray. The mono-energetic kaons are emitted back-to-back and provide a perfect trigger (triple coincidence K^+ - K^- - X-ray). The kaons are to be detected by fast scintillation counters surrounding the beam pipe. The SIDDHARTA setup is in development at our institute in Vienna [9] (see fig.3). Using an SDD array an utmost precision of the strong interaction induced shift and width can be achieved. Furthermore, the first measurement of kaonic deuterium will be performed with this setup. Kaonic hydrogen together with precision measurements of kaonic helium X-rays will allow to study the sub-threshold $\Lambda(1405)$ resonance, which might lead to strongly bound kaonic states in light nuclei [10].

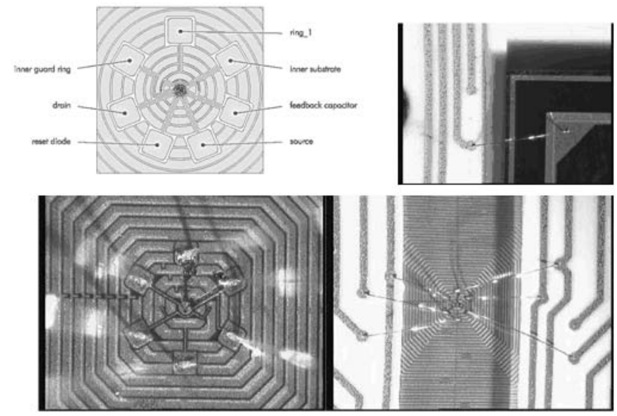

Figure 1: Structure of the anode region of SIDDHARTA SDDs. The photos are taken for quality assurance of the bonding process.

According to Monte-Carlo simulations [11, 12] a signal-to-background ratio for kaonic hydrogen in the order of 10:1 can be achieved. For deuterium the calculated S/N ratio will be 1:1 assuming the theoretical estimate for the K_α X-ray yield ($Y_{K_\alpha} \sim 0.2$ percent) which is about an order of magnitude lower than in the kaonic hydrogen case. For the strong interaction induced shift ϵ_{1s} and width Γ_{1s} of kaonic hydrogen the final results of the DEAR experiment (ε_{1s}=193 eV, Γ_{1s}=249 eV) and for kaonic deuterium the theoretical values (ε_{1s}=325 eV, Γ_{1s}=630 eV) [13] were used. The simulated energy spectra for kaonic hydrogen and kaonic deuterium respectively are given in fig.4. The envisaged precision in the measurement of the strong interaction shift in kaonic hydrogen is at the level of eV corresponding to a precision at the percent level.

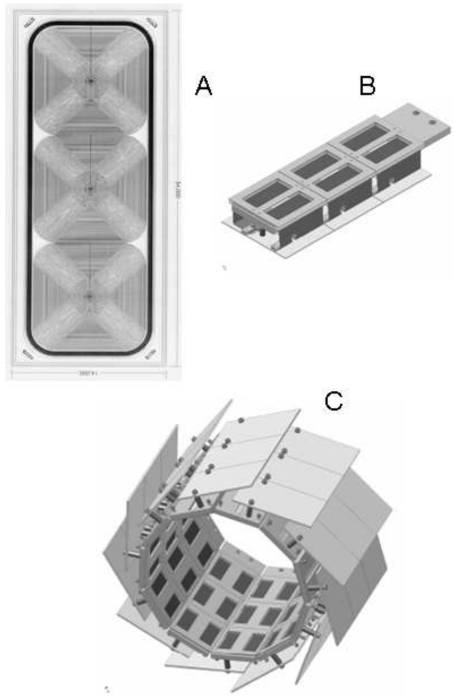

Figure 2: (A) SDD chip consisting of 3 SDDs each with 1cm^2 active area, (B) module of 2x3 SDD chips mounted and (C) setup of the full SDD array (200 SDDs in total) which will surround the light-weight gas target cell. On the outside the pre-amplifier and voltage supply boards are arranged.

3.3. Kaonic helium

In 2005 a first experiment with large area SDDs was already conducted at KEK - the experiment E570. It was the first application of SDDs in the field of exotic atom research. The goal was the precise measurement of the $3d \rightarrow 2p$ transition in kaonic ^{4}He in order to clarify the puzzling disagreement between theory and former experiments [14] giving a large shift ($\sim$ 40eV) and width ($\sim$ 50 eV) of the 2p state. A possible explanation of the large hadronic shift is given by considering the existence of deeply bound kaonic states [15].
In this experiment we used successfully a setup of 8 SDDs each with 100mm^2 active area made by the KETEK company. For the time resolution of these large SDDs a value of 330 ns was extracted. Using in-beam energy calibration provided by fluorescence X-ray lines from Ni and Ti foils X-ray spectrum of kaonic helium was measured with a precision at the eV level showing the excellent performance of this detector type for exotic atom research.

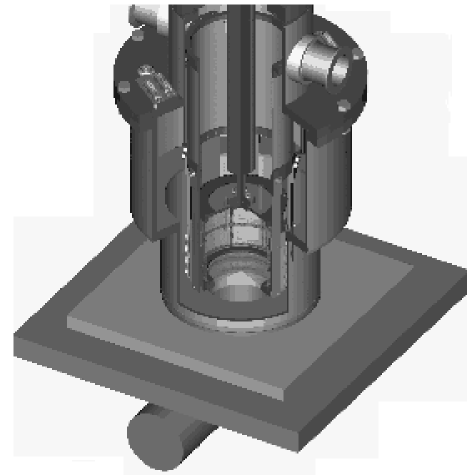

Figure 3: Schematic view on the SIDDHARTA setup. The cryogenic target system with the SDD array is contained in an insulation vacuum. The setup is mounted at the electron-positron interaction region on a table above the DAΦNE beam pipe.

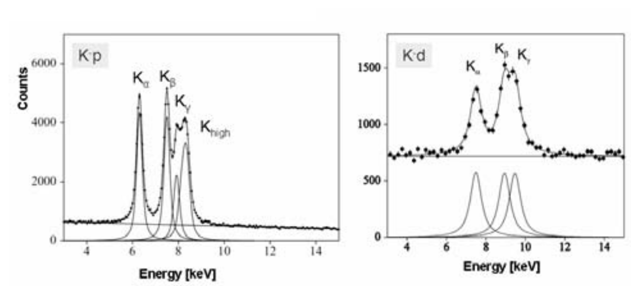

Figure 4: Monte Carlo simulated X-ray spectra of K-transitions in kaonic hydrogen and kaonic deuterium measured with SDDs and applying the time correlation between X-ray and kaon. A data taking time of 30 days was assumed.

Acknowledgments

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