# Performance of CCD X-ray detectors in exotic atom experiments

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**Abstract**

Applications of CCD X-ray detectors in high background environments at the DAΦNE electron-positron collider (LNF, Italy), and the $\pi$E5 pion beam line (PSI, Switzerland) are presented. The CCD X-ray detectors were installed at the interaction point of the DAΦNE electron-positron collider for the first time. The kaonic nitrogen and hydrogen experiments were performed using 16 CCDs at LNF. The pionic hydrogen experiment was performed using an array of 6 CCDs together with a crystal spectrometer at PSI. These studies established the feasibilities of CCD applications in exotic atom research.

*Key words:* CCD, X-ray detector, kaonic atom experiment, pionic atom experiment, kaonic nitrogen yields, pionic hydrogen shift
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## 1. Introduction

Applications of charge-coupled device (CCD) as X-ray detectors have spread from medical use to astrophysics, and atomic, nuclear, and particle physics. Although CCDs do not have timing information, they have unique advantages of excellent background rejection capabilities, good detection efficiency, high energy resolution, and intrinsic position resolution.

Information about the position and energy of an incident particle is stored as CCD data. Because of different ionizing power, an X-ray deposits its total energy into a few pixels, while a charged particle or a high energy gamma ray deposits its energy in several adjacent pixels as a minimum ionizing particle (MIP). Thus, the number of pixels in which a particle deposits (a hit event) identifies its particle type. The energy of an X-ray event is also determined.

The physics of exotic atoms can bridge the gap between nuclear physics and atomic physics, because of the size and energy scale of exotic atoms. Studies of pionic and kaonic atom X-ray measurements are important to understand low-energy QCD effects as well as to obtain very precise determination of the charged pion and kaon mass.

Here, the performance of CCDs in the kaonic

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atom experiment at LNF [1] (Italy) [1] and the pionic atom experiment at PSI [2] (Switzerland) [2] are described.

## 2. CCD application of the kaonic atom experiment

To measure the shift and width of the $1s$ state of kaonic hydrogen and deuterium with an accuracy of a few %, a kaonic atom experiment is performed by the DEAR (DAΦNE Exotic Atom Research) collaboration, using the DAΦNE $\phi$-factory at LNF [1]. The successful measurements of kaonic nitrogen and hydrogen were performed in 2002. Experimental data of sequential X-ray line yields at low density are required to make a reliable theoretical cascade model. Here, the first measurement of three sequential X-ray lines from kaonic nitrogen in a gaseous target is reported [3].

The main experimental characteristics of DEAR are as follows. (i) The use of a “kaon beam” generated in an electron-positron collider (DAΦNE). DAΦNE is optimized for producing $\phi$ particles from the electron-positron annihilations at the $\phi$ resonance (energy 1020 MeV). About 50% of the $\phi$ particles decay into $K^+K^-$ pairs, thereby generating the so-called “kaon beam”. This kaon beam is pure (not contaminated with other hadrons), and has low energy (about 16 MeV) and low energy spread (less than 0.6%). (ii) The use of a specially designed target containing pressurized cryogenic gas. The specific target conditions are optimized to increase efficiencies for kaons to stop in the target and to reduce X-ray absorption in the target. (iii) The use of CCDs as X-ray detectors taking advantage of their high capability of charged-particle background rejection. Marconi Applied Technologies CCD55-30 chips were selected. Each CCD has 1152 columns × 1242 rows of pixels, and the size of each pixel is 22.5×22.5 microns (the total effective area is 7.24 cm$^2$). The depletion depth is about 30 microns.

Fig. 1 shows the experimental setup. A beam pipe made of CFRP surrounds an interaction point at which $\phi$ particles are produced almost at rest. $K^-$s from decay of $\phi$s stop in the target cell made of low-$Z$ materials. As a target, nitrogen gas at 1.5 bar and 120 K ($\sim 3.4\ \rho_{NTP}$) is selected. Thin Ti and Zr foils are installed for the energy calibration. X-rays from kaonic nitrogen are detected by 16 CCDs, which surround the target cell. Two scintillators are mounted on both sides of the beam pipe at the interaction point to detect $K^+K^-$ pairs in coincidence [4]. The X-rays are significantly attenuated due to absorption by other nitrogen atoms. Therefore, to obtain the yield of a transition line, the absorption rates are evaluated using Monte Carlo simulations.

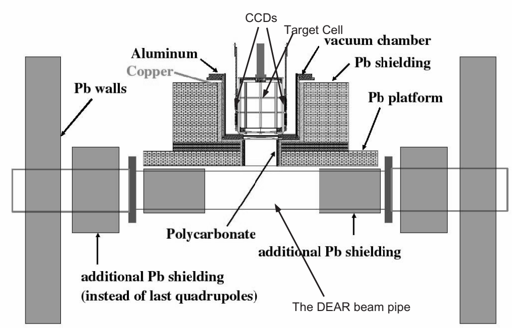


Fig. 1. Schematic view of the DEAR experimental setup.

Fig. 2 shows the relationship between the cluster sizes and their ADC values, where the horizontal axis gives the size of a hit event and the vertical axis the sum of the ADC channels in the event. The brightness corresponds to the number of counts. In the center of the figure, there is a large correlation, which appears as a blob. This is caused by MIPs that penetrated into the CCD depletion layer and deposited their energy. As seen, the majority of the MIPs events are well separated from X-ray events. To obtain an energy spectrum with a good signal-to-background ratio, a hit event having 1 or 2 pixels is selected as an X-ray event.

Exploiting the above characteristics and careful analysis, three kaonic nitrogen X-ray lines were observed. The energy spectrum of this experiment is plotted in Fig. 3. The obtained X-ray events were $(3.31 \pm 0.69) \cdot 10^3$, $(5.28 \pm 0.38) \cdot 10^3$, and

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[2] The Paul Scherrer Institute

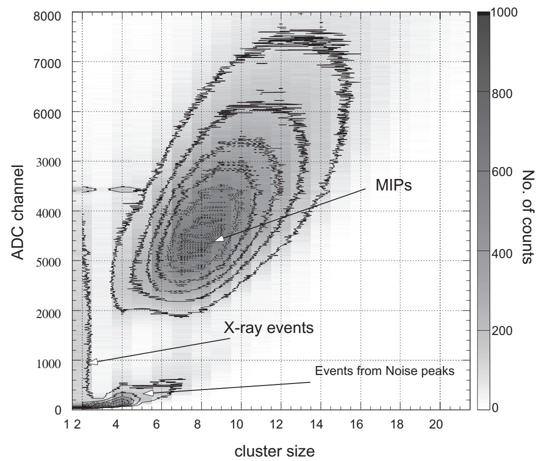


Fig. 2. The relationship between the cluster sizes and the ADC values. The brightness corresponds to the number of counts. A large correlation appearing as a blob is due to MIPs. Strong rejection of high energy particles is clearly seen.

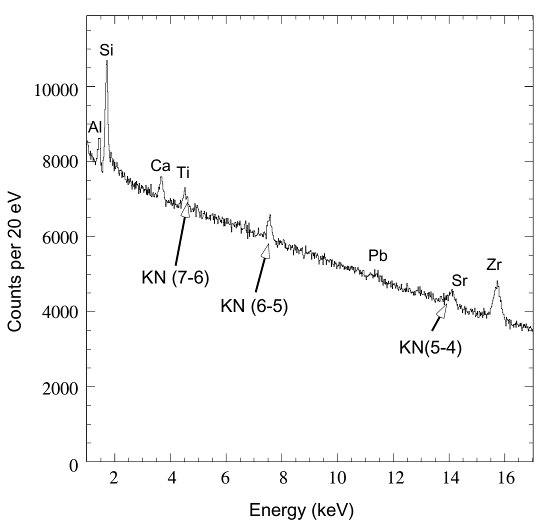


Fig. 3. Energy spectrum of kaonic nitrogen atoms in a gaseous target. Kaonic X-ray lines are indicated.

$(1.21 \pm 0.32) \cdot 10^3$ for the $7 \to 6$, $6 \to 5$ and $5 \to 4$ transitions. Estimating the efficiency for kaons to stop in the target and for X-ray detection by the Monte Carlo simulations, the following yields $Y$ were obtained: $Y = 41.5 \pm 7.4$ (stat) $\pm 4.1$ (sys) %, $Y = 55.0 \pm 3.9$ (stat) $\pm 5.5$ (sys) %, and $Y = 66.4 \pm 15.2$ (stat) $\pm 5.7$ (sys) % for the $7 \to 6$, $6 \to 5$ and $5 \to 4$ transitions, respectively. Here (stat) is the statistical error and (sys) is the systematic error. Using these experimental yields for cascade calculations, the K-shell electron population was found to be $1 \sim 3\%$ [3].

## 3. CCD application for the pionic atom experiment

To measure the shift and width of the $1s$ state of pionic hydrogen and deuterium with an accuracy of below 1%, a pionic atom experiment is performed by the piH collaboration, using the $\pi$E5 beam line at PSI. The first goal of this experiment is a measurement of pionic hydrogen K lines ($2p \to 1s$, $3p \to 1s$, and $4p \to 1s$), to obtain the density independence of the shift, and the Doppler width caused by Coulomb deexcitation. Here, the measurement of the pionic hydrogen X-ray lines is reported [5].

The main experimental characteristics of the pionic hydrogen experiment are as follows. (i) The use of a cyclotron trap (cyclotron trap II) to increase the efficiency for pions to stop in a target. (ii) The use of a reflection-type crystal spectrometer made of spherically bent silicon or quartz crystal. (iii) The use of CCDs taking advantage of their energy and position resolutions. EEV (Marconi Applied Technologies) CCD22 chips were selected. Each CCD has 600 columns $\times$ 600 rows of pixels, and the size of each pixel is $40 \times 40$ microns (the total effective area is 5.76 $\mathrm{cm}^2$). The depletion depth is about 30–40 microns. Using the crystal spectrometer along with the CCDs, an excellent energy resolution ($\Delta$ E = $\sim$ 100 meV) as well as large background suppression can be achieved.

Fig. 4 shows the experimental setup. The densities of gaseous targets can be changed by cooling. The targets can be cooled down to 20 K where hydrogen gas is liquefied. The cyclotron trap is used for pions to efficiently stop in a gaseous target. X-rays from pionic atoms are reflected by the crystal spectrometer, and they are detected by an array of 6 CCDs.

Fig. 5 shows the energy spectrum of the pionic hydrogen $3p \to 1s$ transition as well as the pionic oxygen $6h \to 5g$ transition. The energy cali-

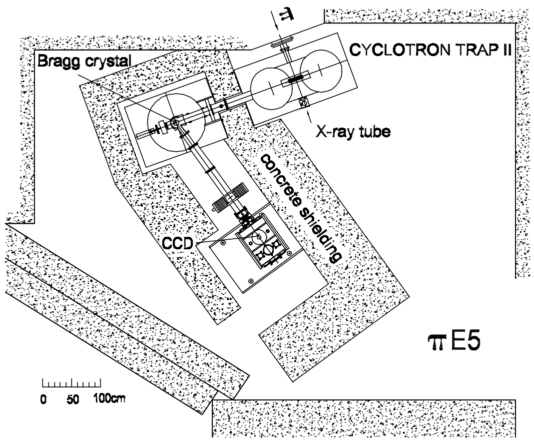


Fig. 4. Schematic view of the PSI experimental setup.

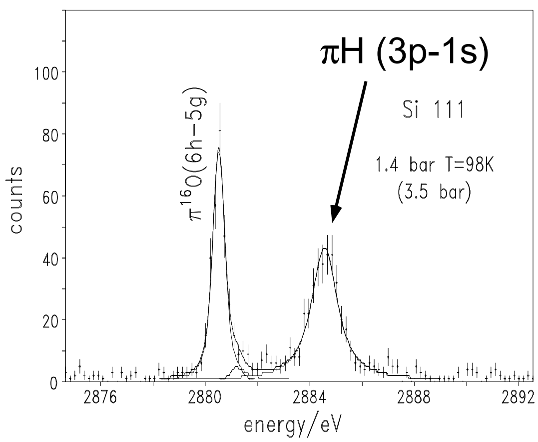


Fig. 5. Energy spectrum of the pionic hydrogen $3p \to 1s$ transition.

bration is performed by the $\pi$O$(6h \to 5g)$ transition, because this transition is not affected by the $\pi N$ strong interaction and screening effects from remaining electrons are also negligible [6]. At low densities, the $\pi$O$(6h \to 5g)$ and the $\pi$H$(3p \to 1s)$ lines are measured simultaneously using a mixture of hydrogen and oxygen gas ($H_2$:$O_2$ = 98%:2%). At higher densities, pionic hydrogen and oxygen are measured alternatively.

As a result, three pionic hydrogen $2p \to 1s$, $3p \to 1s$, and $4p \to 1s$ lines were successfully observed at several densities. No density dependence is observed for the energy of the $\pi$H$(3p \to 1s)$ transition in the target densities ranging from 3.5 bar to liquid. The shift in the pionic hydrogen $3p \to 1s$ transition was obtained as follows:

$$\epsilon_{1s} = 7.120 \pm 0.008 \text{ (stat)}^{+0.009}_{-0.008} \text{ (sys) eV},$$

where (stat) is the statistical error and (sys) is the systematic error [5].

## 4. Summary and Outlook

The kaonic nitrogen X-ray measurement at LNF was successfully completed. This measurement established the feasibility of new kaonic atom experiments at DAΦNE using CCD X-ray detectors. The first stage of the pionic hydrogen measurement at PSI was successfully completed. Using the capability of the position resolution of the CCDs along with the crystal spectrometer, the energy resolution ($\Delta E/E$) was obtained to be in order of $10^{-4}$. Recent results can be found in [7].

Taking the advantages of the two experiments (i.e. the DAΦNE collider, a crystal spectrometer, a cyclotron trap, and CCDs), a new method to obtain a precise value of the mass of the charged kaon is proposed [8]. In addition, we are now developing a large area ($\sim$ 1 cm$^2$) of Silicon Drift Detectors (SDDs).

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