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New analysis method for CCD X-ray data

T. Ishiwatari[a], G. Beer[b], A.M. Bragadireanu[c,d], M. Cargnelli[a], C. Curceanu (Petrascu)[c,d], J.-P. Egger[e], H. Fuhrmann[a], C. Guaraldo[c,*], M. Iliescu[c,d], K. Itahashi[f], M. Iwasaki[f], P. Kienle[a], B. Lauss[g], V. Lucherini[c], L. Ludhova[h], J. Marton[a], F. Mulhauser[h], T. Ponta[d], L.A. Schaller[h], D.L. Sirghi[c,d], F. Sirghi[c], P. Strasser[f], J. Zmeskal[a]

[a]Stefan Meyer Institut für subatomare Physik, Boltzmanngasse 3, A-1090 Vienna, Austria
[b]Department of Physics and Astronomy, University of Victoria, P. O. Box 3055 Victoria B. C. V8W 3P6, Canada
[c]INFN, Laboratori Nazionali di Frascati, C. P. 13, Via E. Fermi 40, I-00044 Frascati, Italy
[d]Institute of Physics and Nuclear Engineering Horia Hulubei, IFIN-HH, Particle Physics Department, P.O. Box MG-6, R-76900 Magurele, Bucharest, Romania
[e]Institute de Physique, Université de Neuchâtel,1 rue A.-L. Breguet, CH-2000 Neuchâtel, Switzerland
[f]RIKEN Wako Institute, RIKEN (The Institute of Physical and Chemical Research), Wako-shi, Saitama, 351-0198, Japan
[g]Department of Physics, LeConte Hall 366, University of California, Berkeley, CA 94720, USA
[h]Physics Department, University of Fribourg, CH-1700 Fribourg, Switzerland

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Abstract

The analysis method developed for kaonic nitrogen X-ray data obtained at the DAΦNE electron–positron collider of Frascati National Laboratories using Charge-Coupled Devices (CCDs) in the DEAR experimental setup is described. Background events could be highly rejected by this analysis procedure. Three sequential X-ray lines from kaonic nitrogen transitions, showing good energy resolution, could be clearly identified, and the yields measured for the first time.

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Keywords: Pixel detectors; CCD data analysis procedure; Kaonic nitrogen energy spectra

1. Introduction

The DEAR (DAΦNE Exotic Atom Research) experiment at the DAΦNE ϕ-factory of Frascati National Laboratories is based on the detection of kaonic atom X-rays. Low absolute line yields and high background radiation in the electron–positron collider environment pose a serious experimental challenge. A new analysis method had to be developed for extracting accurate X-ray information from the CCD detectors, because the previously employed analysis techniques [1,2] were not sophisticated enough to be successfully employed for the DEAR data evaluation.

The main goal of the DEAR scientific program is to determine isospin-dependent $\overline{K}N$ scattering lengths by measuring the shift and the width, due to the strong interaction, of the $1s$ state in kaonic hydrogen and kaonic deuterium [3].

In the first stage of the DEAR program, the measurement of kaonic nitrogen was performed [4] with the aim to study machine background and setup performance, since the yields of kaonic nitrogen transitions are much higher than those of kaonic hydrogen. The possibility of precisely determining the charged kaon mass by studying the kaonic nitrogen atom was also explored in the preliminary measurement [5]. Three sequential X-ray lines of the kaonic nitrogen spectrum at 4.6, 7.6, and 14.0 keV

*Corresponding author. Tel.: +39 06 9403 2318; fax: +39 06 9403 2559.
E-mail address: carlo.guaraldo@lnf.infn.it (C. Guaraldo).

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(corresponding to the $7 \to 6$, $6 \to 5$, and $5 \to 4$ transitions) were clearly identified and their yields measured for the first time [4].

In this paper, we give a detailed description of the analysis method applied to the CCD X-ray data. Section 2 describes the CCD analysis procedure, recalling briefly the characteristics of this detector and the features of X-ray events. In Section 3, the energy spectra obtained from the analysis are shown. In Section 4, the technique to determine the kaonic nitrogen transition yields is described. Conclusions are drawn in Section 5.

2. CCD analysis procedure

2.1. CCD X-ray detectors

The DEAR experimental setup is described in Ref. [4]. Charge-Coupled Devices (CCDs), which are sensitive to low-energy (below 20 keV) X-rays, were used as detectors. CCDs have a large number (1152×1242) of small-size pixels ($22.5 \times 22.5\,\mu m^2$). CCDs have unique capabilities of background rejection, high energy resolution, good detection efficiency, and intrinsic position resolution.

Identification of X-ray events and determination of their energies are achieved by taking advantage of the specific CCD features [1]. On one hand, photoelectrons produced by a low-energy X-ray are completely confined within the depletion layer in a few pixels (usually $\leqslant 2$). Thus their full energy can be measured. On the other hand, minimum ionizing particles (MIPs), which are the largest background for DEAR, and X-rays above 20 keV penetrate the depletion layer and create electron-hole pairs in the field-free region, where they spread over many pixels. Thus, only the energy deposit in or near the depletion layer, a fraction of the total energy, can be collected and read out.

A CCD image with events attributed to X-rays and background events from MIPs or γ-rays is shown in Fig. 1. Clusters consisting of one or two pixels are recognized as X-ray events, those with more hit pixels constitute the background. X-ray energy spectra are constructed via selection using this X-ray definition which will be corroborated in Chapter 3.1.

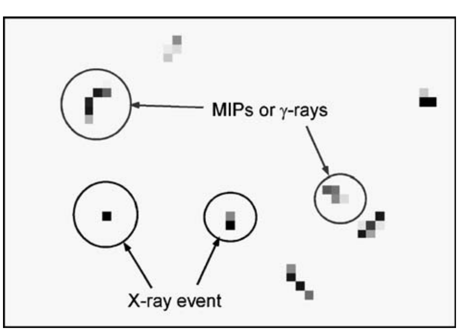

Fig. 1. CCD image. The grey scale is proportional to energy. MIPs or γ-rays create large-size events. Low-energy X-rays mainly create small-size events (one or two pixel hits).

2.2. Event definition via noise threshold determination

Even if a pixel was not hit during the exposure time, a charge content due to dark current from CCD readout is stored in such pixels. It can be seen as a Gaussian noise peak in the very-low-energy region of the energy spectrum. The peak location defines the offset, which is subtracted from each energy spectrum.

An event is then defined on the basis of the hit pixels whose signal is larger than a noise threshold, the remaining pixels being noise pixels. A cluster of hit pixels surrounded by only noise pixels is counted as one event, the energy of which is the sum of the hit pixels energies and whose size is defined by the number of hit pixels. Single-pixel events are size 1 events, double-pixel events are size 2 events, etc. In Fig. 2, several types of events are shown. For size $\geqslant 2$ events, events with energy higher than the upper limit of the ADC channels (4096 in a 12-bit ADC) are possible as the pixel contents get summed up.

The determination of the noise threshold is an essential requirement in the analysis procedure, since it determines event size, hence X-ray detection efficiency, energy resolution, and capability of background rejection. Several methods of noise threshold determination have been reported: see Refs. [2,6].

If an X-ray creates a double-pixel event, in which one of the two pixels has a larger fraction of signal and the other is registered as a noise pixel, this double-pixel event is wrongly selected as a single-pixel event, thereby resulting in a low-energy tail on an X-ray peak.

To minimize such misidentification of the event size, the noise threshold must be set to a small value, close to the readout noise fluctuations. If, however, this value is too small, a noise pixel might be selected as a hit pixel. Assuming that noise in the eight noise pixels surrounding a single-pixel event has a Gaussian distribution with mean value equal to 0 and standard deviation σ, the chance for this event to be selected as a single-pixel event is given by

$$p(E_{\rm th}) = \left(\frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{E_{\rm th}} {\rm e}^{-E^2/2\sigma^2}\, {\rm d}E \right)^8 \qquad (1)$$

where $E_{\rm th}$ is a threshold value. Fig. 3 shows $p(E_{\rm th})$ plotted as a function of $E_{\rm th}/\sigma$. When $E_{\rm th}/\sigma$ is over 3, the

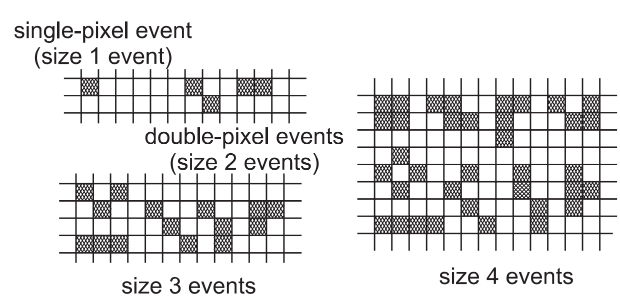

Fig. 2. Definition of events. One event is defined as a group (cluster) of connected hit pixels that are surrounded only by noise pixels. Events are named according to the number of pixels in a cluster.