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Study of electron tracks in Timepix3 detector at kinetic energies of 1 and 1.5 MeV

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Abstract: We report on measurements of 1 and 1.5 MeV monoenergetic electrons with a Timepix3-based detector using a 0.5 mm thick silicon sensor. A ^{90}Sr β-emitting radioisotope was used as the source of electrons, and a monochromator equipped with an adjustable magnetic field was employed to only pass electrons of desired energy into the detector. We provide experimental results of deposited-energy spectrum in the sensor and linearity of detected tracks. Alongside with the experiment, the whole system has been modelled in software and a Monte Carlo Geant4/Allpix^2 simulation of the experiment has been carried out. Generally, we find a good agreement between the two.

Keywords: Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); Particle tracking detectors (Solid-state detectors); Pixelated detectors and associated VLSI electronics

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1 Introduction

Motivated by a wish to remeasure the so-called ATOMKI anomaly reported in 2016 [1], we are building a detector suitable for measuring energies and directions of electrons and positrons, of typical energy about 9 MeV, emerging from a nuclear reaction taking place in a target hit by accelerated protons. The innermost part of the detector will consist of a ring of six Timepix3-based (TPX3) [2] silicon pixel detectors. Since there is no suitable source of electrons (positrons) of the given energies available to us, we, to an extent, rely on simulations to predict the detector behaviour. Nonetheless, even the simulation framework itself needs to be tested, preferrably against experimentally verifiable data. We therefore conducted several measurements with simplified setups utilizing accessible electron sources, though, of lower energies. On one hand we believe that many conclusions drawn from such experiments will apply to the final (ATOMKI-like) experiment, too. On the other, the results may potentially be interesting on their own right. Thus, in this work we describe measurements with a single TPX3 detector of monoenergetic semi-relativistic electrons with kinetic energy of 1 and 1.5 MeV, obtained from a ^{90}Sr radioactive source by means of selection by an adjustable magnetic monochromator. The experiments are complemented by thorough simulations and the results are mutually compared.

The TPX3 is a read-out chip for both semiconductor and gas-filled detectors. Developed within the Medipix collaboration [2], the chip is a square matrix of 256×256 pixels, each of $55\ \mu\text{m} \times 55\ \mu\text{m}$ size, hence with a total active area of $14 \times 14\ \text{mm}^2$. The chip is typically bump-bonded to a suitable sensor and collects the charge left behind ionizing radiation. In the so-called data-driven mode, which we employed, the information about an activated pixel is made available without delay and independently of other pixels. Each pixel measures both the time-of-arrival (ToA) and the time-over-threshold (ToT) of the detected signal, with a precision of 1.6 ns. ToT reflects the energy deposited in the pixel.

This work used a TPX3 detector equipped with a 0.5-mm-thick silicon sensor. The detector was read by the so-called Katherine readout [3] and the acquired data were transferred through ethernet to a personal computer for further analysis.

It has been shown [4, 5] that electrons (and positrons) of the mentioned energies (i.e., of the order of 1 MeV) are frequently multiply scattered within the detector sensor, leading to wiggly tracks which hinders determination of the particle incoming direction. On the other hand, it is these processes that allow full-energy deposition in a sensor with thickness smaller than would correspond to electron range calculated solely from the sensor-material linear stopping power. It is the aim of this paper to provide quantitative evidence of such effects, i.e., show experimental results of measured electron energy and linearity of tracks. At the same time we want to document that our Monte Carlo simulations of the experiment lead to its faithful representation, the importance of which lies in certain justification of using the developed simulation framework also later for our further experiments. Last, while setting up the simulation we built a detailed model of the monochromator, which may turn useful for other researchers using the device.

2 Experimental setup — Electrons from ^{90}Sr source

A monoenergetic electron beam is obtained from a ^{90}Sr β source[1] supplemented with a tuneable magnetic monochromator. Figure 1 shows a CAD drawing of the setup. Electrons emitted from ^{90}Sr enter a region with magnetic field provided by an iron-core electromagnet. The current through its coils is adjustable and only electrons of certain energy make it through the depicted apertures to the outside world. The chamber of the monochromator is kept at 10-mbar pressure, and the electrons exit the monochromator through a 12-µm-thick mylar window. The setup produces electrons in useful amounts from 0.4 and 1.8 MeV with the intensity peaking at 1 MeV and dropping to half at 0.5 and 1.5 MeV. Beam energy resolution varies from approximately 10% at 150 keV to 3% at 1.5 MeV. Reference [6] provides further technical details.

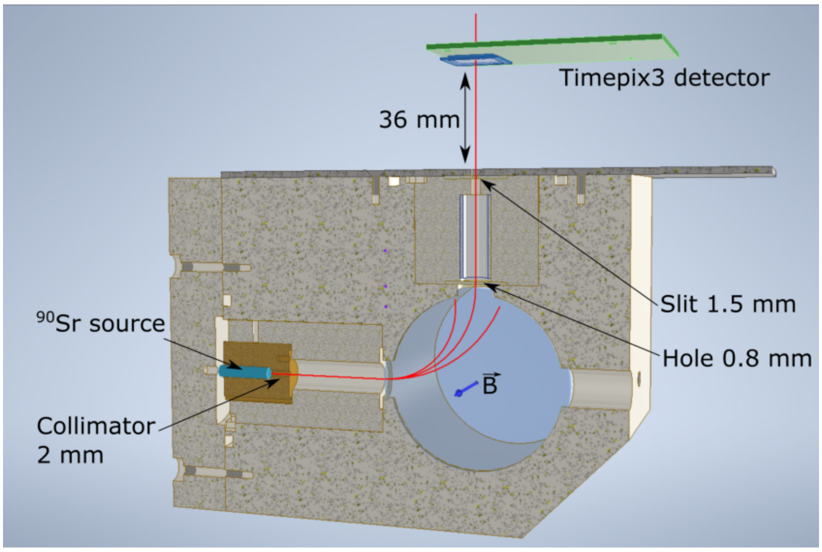

Figure 1. Schematics of the experimental setup; the electromagnet parts have been left out for clarity.

The calibration of the electron source (i.e., the relation between outgoing particle energy and electromagnet current) was checked with a 1-mm-thick silicon-diode detector that had been pre-calibrated using the 481.7- and 976-keV conversion electrons emitted from a ^{207}Bi source [7].

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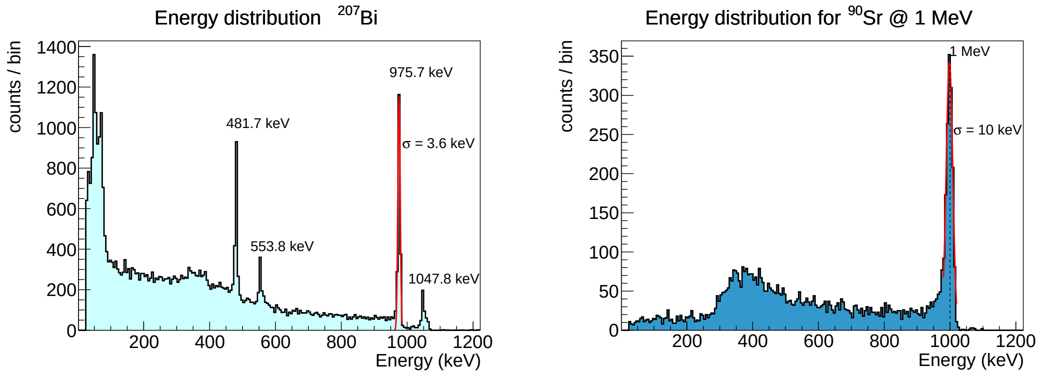
[1] Unstable ^{90}Sr decays to ^{90}Y via β^- decay, with a Q_β of 0.55 MeV. Subsequently, ^{90}Y decays to stable ^{90}Zr via β^- decay, with a Q_β value of 2.28 MeV.

Figure 2(a) shows the ^{207}Bi electron-energy spectrum measured with the diode, figure 2(b) then depicts the electron-energy spectrum, measured with the same detector, from the calibrated ^{90}Sr source set to output 1-MeV particles. (1-MeV electrons generally pass through the 1-mm silicon diode. If viewed as 'heavy' particles, they would most probably deposit about 350 keV in the sensor, which is reflected in the broad Landau-like peak in figure 2(b); since they are not heavy and therefore scatter frequently, some electrons still loose all their energy in the sensor.)

Since the real energy of 976-keV electrons is well-defined, the respective peak width in figure 2(a) corresponds to the detector resolution; the Gaussian fit yields the sigma of about 4 keV. From this and from the measured 10-keV Gaussian sigma-width of the 1-MeV peak in figure 2(b) one can estimate the true energy spread of the electrons leaving the ^{90}Sr-based source to be of about 9 keV sigma, i.e., about 20 keV FWHM (2% at 1 MeV), in accordance with [6].



(a) (b)

Figure 2. Electron-energy distribution measured by a 1-mm-thick silicon diode for electrons originating from two different sources: (a) ^{207}Bi, (b) ^{90}Sr source with monochromator set to emit 1-MeV particles.

In experiments described in this work a TPX3 detector was placed at a fixed distance of 36 mm from the monochromator exit window, and electrons with energies of 1 MeV and 1.5 MeV were used.

3 Simulations

A 3D model of the complete experimental setup, including the parts of the monochromator and the TPX3 detector, has been built using CAD software and described in the geometry description markup language (GDML). The GDML description, besides the geometry, also specifies the material of each part of the setup.

Geant4 [8], a Monte Carlo-based toolkit, takes the GDML model and simulates propagation of electrons emitted from the ^{90}Sr source through the monochromator and into and within the TPX3 sensor. It takes care of any secondary particles involved, namely, it reports about creation of electron-hole pairs in the TPX3 sensor brought about by the passage of the primary electron.[2] For simplicity, the ^{90}Sr source is modelled to emit electrons isotropically, the cavities of the monochromator are represented by vacuum, and the magnetic field in the monochromator chamber is taken to be homogeneous. The strength of the magnetic field is adjusted to have electrons of wanted energy hit the detector.

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[2] Geant4's `QGSP_BERT_EMZ` physics list has been used.

The information about created electron-hole pairs in the sensor, as provided by Geant4, is taken over by the Allpix^2 [9, 10] program, which simulates the evolution of the charges within the sensor, their collection, and the generation and digitization of the signal eventually provided by the TPX3 detector. Thus, Allpix^2 output parallels that of a real experiment, reporting when (ToA) and what pixels were activated, as well as the energy deposited in the individual pixels (ToT). The Allpix^2 program is intimately aware of the TPX3 detector internals. Furthermore it takes a set of parameters specifying current operating conditions, such as those listed in table 1; the values there correspond to the real conditions of our detector during the data taking.

The geometry of the electron monochromator used in our simulations is based on existing documentation. However, it is known that the monochromator construction did not adhere exactly to the documented specifications. Since the device is sealed, it was not possible to verify the exact dimensions and shapes of the slits and collimators. The final model is therefore also partially based on results from a series of attempts to reproduce the experimental data.

Table 1. Operating parameters used in the Allpix^2 simulation for the TPX3 detector.

Bias voltage	210 V
Depletion voltage	100 V
Temperature	352 K
Electronic noise	100 e^-
Threshold	$(1248 \pm 35)\, e^-$
Integration time	100 ns

4 Results

4.1 Energy distribution

Figure 3 shows the experimental and simulated distribution of energy deposited by 1 MeV electrons in the sensor; the number of simulated and experimental events were the same. The experimental data are well reproduced. Since the majority of electrons pass through the sensor, the Landau-like curve is to be expected and is indeed obtained, with the most probable energy loss of 150 keV in accord with the sensor thickness. The smaller peak at 1 MeV is a full-energy peak brought about by electrons scattered enough times in the sensor to leave all their kinetic energy there, cf. section 4.3 and figure 5 below.

4.2 Spatial distribution

The spatial distributions of activated pixels (hits) along the x and y axes are depicted in figure 4(a) and 4(b), respectively. The simulation accurately reproduces the distribution along the x axis (along which the electron movement is not affected by the magnetic field), and slightly less so along the y axis, namely in the tails of the distribution. To rule out detector-related effects as the cause of the discrepancy we compared the above distributions, counting all activated pixels, with analogous spatial distributions of the first hit of each detected track (entry point to the detector; pixel with maximum ToA). The resulting distributions were essentially identical to those in figure 4, hence the discrepancy is not caused by what happens in the detector. It may, however, be related to the differences between the actual experimental setup and its simulated model, as discussed in section 3.

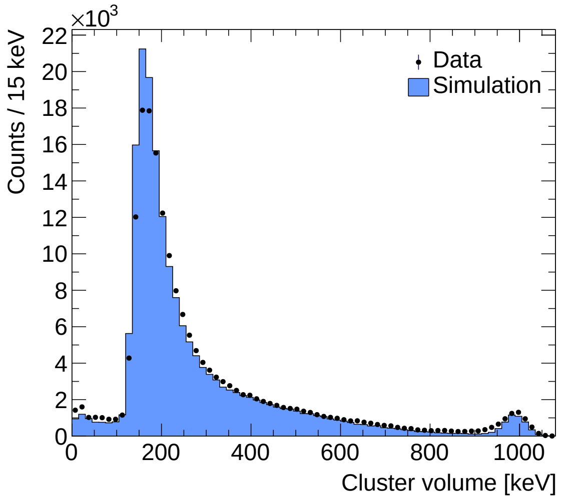
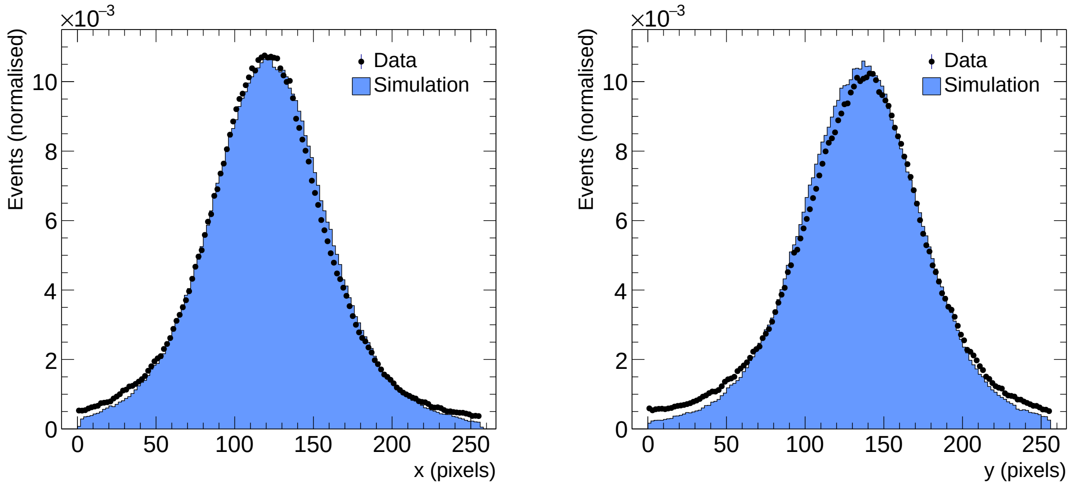


Figure 3. Comparison of deposited-energy distributions for 1-MeV electrons in experiment and simulation. [Cluster volume is the sum of energies deposited in contiguous activated pixels (a cluster); an event can sometimes consist of several clusters (then they are counted separately), both in experiment and simulation, due to, e.g, insufficient energy deposition in some pixels, or also backscattering of particles from construction materials.]



(a)

(b)

Figure 4. The spatial distribution of activated TPX3 pixels in experiment and simulation along (a) the x-axis and (b) the y-axis.

4.3 Track linearity

The track linearity is defined as the fraction of activated pixels intersected by a straight line drawn between a track's start and end points. I.e., it is one for straight tracks and generally decreases when scattering (change in direction) occurs along the track; linear tracks are more probable for particles of higher energies.

Figure 5(a) displays the (experimental) correlation of track linearity with the energy deposited by 1-MeV electrons in the sensor. As mentioned in section 4.1, 1-MeV electrons have the range well exceeding the sensor thickness. Hence the energy deposited by electrons that do not undergo

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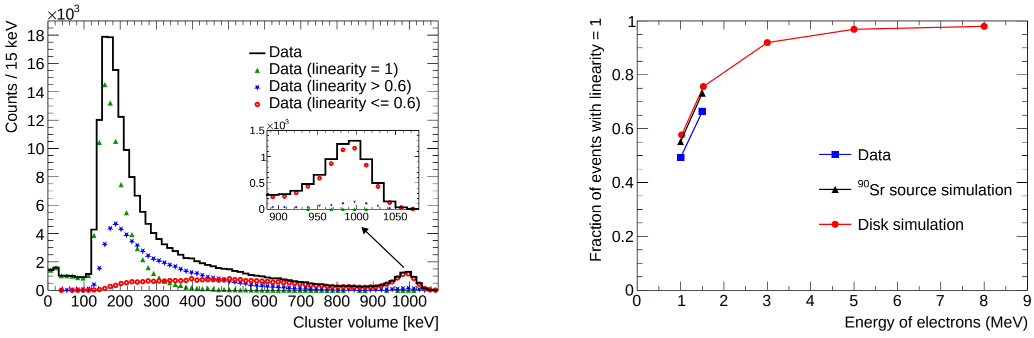
substantial scattering — their tracks have high linearity — should follow the Landau curve. On the other hand, electrons with tracks of low linearity should contribute to the full-energy peak. The figure classifies (somewhat arbitrarily) the tracks into three groups according to their linearity, and confirms the argument.



(a) (b)

Figure 5. (a) Experimental deposited-energy spectrum for 1-MeV electrons with tracks categorized into three groups based on their linearity. (b) The fraction of perfectly linear tracks (linearity equal to 1) for different electron energies.

Besides electrons of 1 MeV also 1.5-MeV ones were measured. Blue points (squares) in figure 5(b) then substantiate the intuitive picture that linearity of tracks grows with energy. For these two energies whole-setup-simulations were carried out, resulting in the black points (triangles) of the figure, in 10% agreement with the data. Due to limitations of the electron source, no experimental data is available for higher energies, and only simulation results, here for energies up to 8 MeV, can be shown. Furthermore, since simulation of the whole setup is computationally rather intensive, what is displayed as the figure's red points (circles) are results of our older simplified simulations, in which the whole electron-source setup was replaced with a point source emitting electrons of a given energy towards the detector, with a Gaussian-like distribution of directions deflecting from the shortest line from the source to the detector centre. To reproduce the experimental findings for 1 and 1.5-MeV electrons, the point source was placed 23 mm in front of the detector and the sigma of the polar-angle distribution was set to 4.5°. (We note that although in the experiment there is 36 mm of air between the particle source and the detector, leading to non-negligible multiple scattering, we had vacuum there in this simplified simulation, and the effect of the scattering was, effectively, incorporated into the sigma and the shorter distance to the detector.)

From figure 5(b) it follows that, in a 0.5-mm-thick silicon sensor, above 95% of electrons with energy above 5 MeV have their track linearity equal to 1.

5 Conclusion

Semi-relativistic 0.5 and 1.5 MeV electrons were measured with a Timepix3 detector using a 0.5-mm Si sensor. The measurement was compared with a full-setup simulation, which modelled both the inner parts of the monochromator that selected electrons of a given energy and the processes of the detection proper inside the sensor. The agreement between the simulation and experiment, concerning the deposited-energy spectra, spatial profiles of the electron beam, and tracks linearity is satisfactory in general. The work brought some understanding of how linearity of tracks in the used Si sensor evolves with energy. In particular, one can expect that already at 3 MeV over 90% of electrons (positrons) leave tracks of linearity (of our definition) equal to one.

The results indicate that the developed simulation framework is trustworthy and can be used for our forthcoming studies engaging higher-energy electrons and positrons related to the ATOMKI-anomaly.

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