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A Geant4-based model for the TRISTAN detector

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Abstract. The TRISTAN project is the upgrade of the KATRIN experiment designed for the search of sterile neutrinos by replacing the current KATRIN detector with a multipixel SDD (Silicon Drift Detector) matrix. We have characterized SDDs response to electrons using a SEM (Scanning Electron Microscope) as an electron source and a Geant4-based simulation whose output is processed with an empirical function to reproduce data. We have crosschecked this model by reconstructing backscattering measurements obtained using a radioactive electron source.

1. The TRISTAN project within the KATRIN experiment

Tritium β decay offers the possibility to search for sterile neutrinos, particles predicted by many Beyond Standard Model theories, that, interacting only with gravity, would represent a viable Dark Matter candidate. A sterile neutrino would manifest itself as a kink-like distortion in the β spectrum. In order to search for this signature, a high statistics and high resolution differential spectrum is needed. TRISTAN will search for sterile neutrinos exploiting the KATRIN apparatus (with 1% of the nominal Tritium column density) combined with a new multipixel detector based on SDD technology [1] [2]. SDDs high resolution (300 eV @ 20 keV) and capability to sustain high count rates (up to 10^5 counts/s) fulfil the requirements for a sterile neutrino search. Electron spectroscopy is a relatively novel SDD application, it is therefore necessary to characterize SDDs response to electrons.

2. SDDs response function

An excellent source of monochromatic and collimated electrons is the Scanning Electron Microscope (SEM). We have taken data by illuminating a single pixel SDD with SEM electrons at different energies (10, 20 keV) and incidence angles (from 0° to 60°) [3]. Spectra acquired at different energies and angles are shown respectively in figures 1 and 2.

In order to reconstruct these data a Geant4 simulation is used as starting point. It takes into account electron interactions with Silicon. The goal is to study the response function due to surface effects, the SDD is therefore simulated with an entrance window made by 30 layers, each

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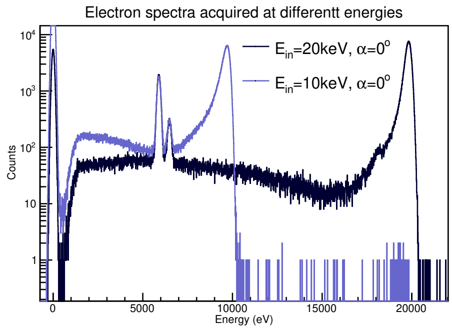


Figure 1. Electron spectra at different energies with ^{55}Fe X-rays acquired by an SDD.

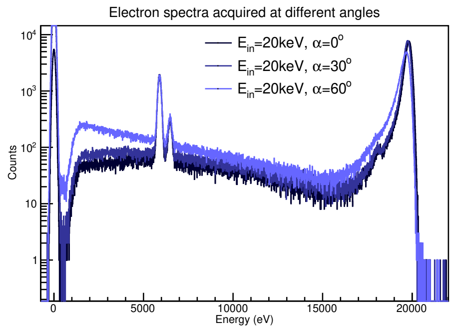
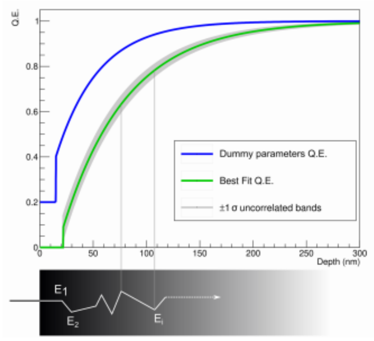


Figure 2. Electron spectra at different angles with ^{55}Fe X-rays acquired by an SDD.

one $10nm$ thick, and a bulk. For each event the output of the simulation are the 31 energies deposited in these regions. Non-idealities are introduced by applying a Quantum Efficiency (QE) that assigns a weight to the 30 energies released in the layers. The sum of these 30 weighted energies and the energy released in the bulk represents the energy recorded by the SDD. The resolution is then added by a convolution of the obtained spectrum with a Gaussian (the precise value of the resolution is obtained extrapolating the baseline and ^{55}Fe peaks resolution to all energies). We have modeled the QE with a dead layer followed by a region with an exponential depth-dependence. QE curve and its analytical formula are shown in figure 3.



$$QE(z; DL, p1, \lambda) = \begin{cases} 0, & z < DL \\ 1 + (p_1 - 1)e^{-\frac{z-DL}{\lambda}}, & z > DL \end{cases}$$

Figure 3. QE curve.

QE is parameterized with three parameters: the dead layer thickness (DL), the efficiency after the dead layer (p_1) and the coefficient of the exponential (λ). By varying these parameters different spectra are built. They are then compared one by one to the experimental data. The estimation of the best parameters is done by minimizing the following χ^2:

$$\chi^2(DL, p_1, \lambda) = \sum_{i=bMin}^{bMax} \frac{(N_i^{data} - f_{norm} N_i^{MC}(DL, p_1, \lambda))^2}{\sigma^2}$$

where bMin and bMax are the bins on which χ^2 is computed, f_{norm} is a normalization factor, N_i^{data} and N_i^{MC} are data and simulation bin contents and σ is the Poisson uncertainty [4]. We introduce an additional free parameter (V) multiplying the deposited energy, to account for possible miscalibrations. Results for some energy-angle combinations are reported in figures 4-7.

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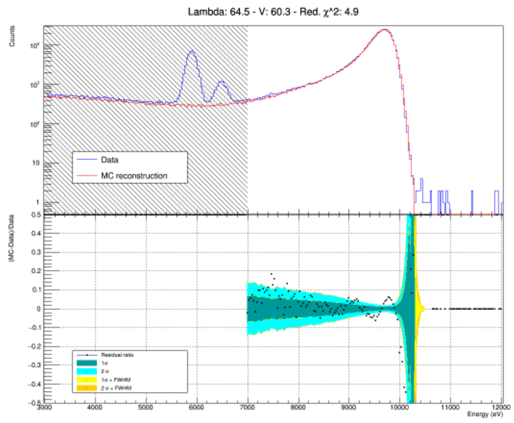

Figure 4. Best reconstruction for an energy of 10 keV and an angle of 0°.

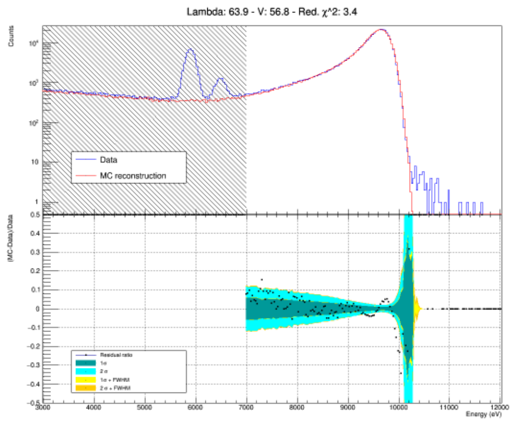

Figure 5. Best reconstruction for an energy of 10 keV and an angle of 30°.

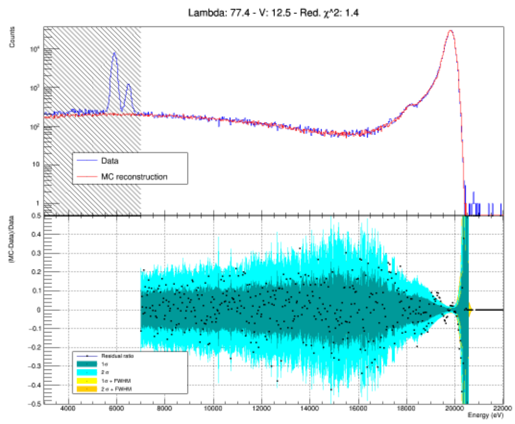

Figure 6. Best reconstruction for an energy of 20 keV and an angle of 0°.

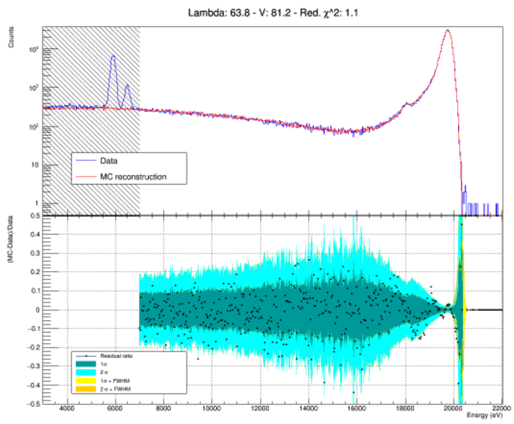

Figure 7. Best reconstruction for an energy of 20 keV and an angle of 30°.

All the features of the spectra are well reconstructed: the main peak, the Silicon escape peak and the continuous due to backscattering.

3. Backscattering measurements

We applied the SDD model obtained with the analysis of SEM data to the study of backscattering on SDDs by expoiting time coincidences between two detectors. The electron source is ^{109}Cd, which emits mainly two electrons at 62 and 84 keV. This source is facing a single pixel detector (Detector 0, rotated by 45°) while a 12-pixel SDD matrix (Detector 1) is placed horizontally below (see figure 8). A copper shield avoids the direct line of sight between source and Detector 1. Our DAQ allows us to search for coincidences between Detector 0 and any one among the twelve Detector 1 SDDs. In case of coincidence, the energies deposited in the two SDDs are represented as a point in the scatter plot (see figure 9).

Starting from the scatter plot, the backscattering spectrum (energy deposited in Detector 1) and the sum spectrum (sum between energies deposited in Detector 0 and 1) are built. We have then simulated the whole geometry (source, SDDs and shield) in Geant4, with both the detectors having an entrance window made by 30 layers. The simulation output is processed with the best QE found from SEM data. The result of this reconstruction is shown in figures

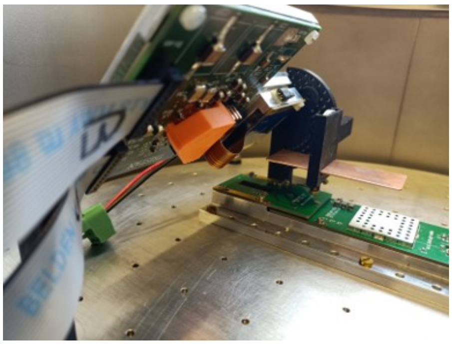

Figure 8. Experimental setup for backscattering measurements.

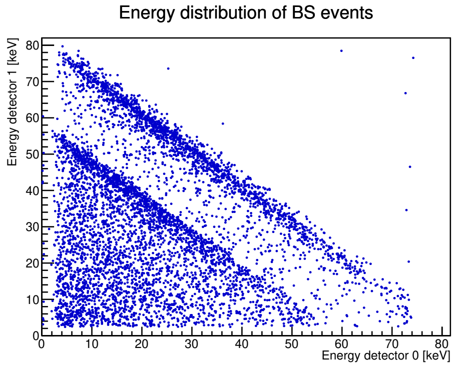

Figure 9. Scatter plot obtained from backscattering measurements.

10 and 11.

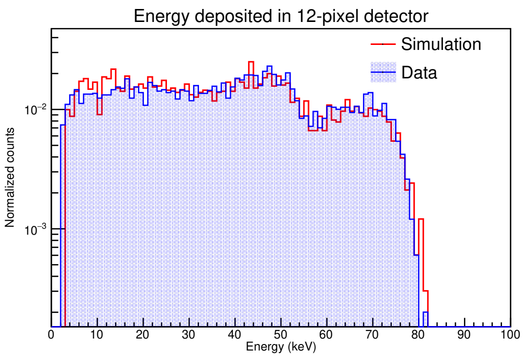

Figure 10. Reconstruction of the backscattering spectrum.

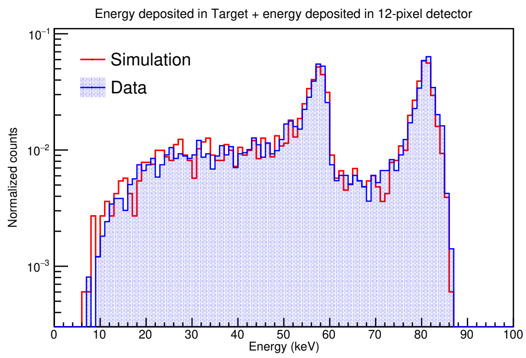

Figure 11. Reconstruction of the sum spectrum.

Even in this case all the main features of the spectra (the two structures in the backscattering spectrum and the peaks in the sum spectrum) are well reconstructed.

4. Conclusions

We have developed a Geant4 simulation for the interaction of low energy electrons with Silicon, introducing SDDs entrance window related effects through an empirical function. Using this model, a good agreement with both SEM and backscattering measurements is found. Such a model is mandatory in order to correctly reconstruct the Tritium spectrum measured in TRISTAN.

5. References

[1] Mertens S et al., *Sensitivity of next-generation tritium beta-decay experiments for keV-scale sterile neutrinos*, J. Cosmol. Astropart. P. 2015 (2015) 020
[2] Mertens S et al., *A novel detector system for KATRIN to search for keV-scale sterile neutrinos*, Journal of Physics G: Nuclear and Particle Physics 46.6 (May 2019), p. 065203
[3] Gugiatti M et al., *Characterization of a silicon drift detector for high-resolution electron spectroscopy*, Nuclear Instruments and Methods in Physics Research 979 (2020)
[4] Biassoni M et al., *Electron spectrometry with Silicon drift detectors: a GEANT4 based method for detector response reconstruction.* Eur. Phys. J. Plus 136, 125 (2021)