

ASPECT-BET: A novel SDD-based detector for electron spectroscopy

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Summary. — Silicon Drift Detectors (SDDs) are widely used in low energy X-ray spectroscopy. However, their application in electron spectroscopy is rather recent due to the complexity of modelling the low energy interactions in silicon, which are crucial for an accurate reconstruction of the measured spectra. The ASPECT-BET Collaboration has dedicated its efforts to the development of a novel SDD-based spectrometer, with a custom design optimised for the measurement of electrons with energies in the order of hundreds of keV. This dedicated setup has been selected to ensure a wide dynamic range to accurately measure several forbidden β spectra. The novel ASPECT-BET setup implements a couple of 1 mm thick SDDs (FWHM \approx 200 eV at 5.9 keV when cooled at -3 °C) with a custom readout electronics. GEANT4 simulations are used extensively to model the geometry and the spectrometer response. The spectroscopic capabilities of the setup have been tested with both X-ray and monochromatic electron sources and with a measurement of the allowed β spectrum of ^{14}C . Currently the collaboration is focused on the first SDD-based measurement of the β spectrum associated with the ^{99}Tc forbidden transition ($Q = 297$ keV).

1. – Science case

In recent decades, there has been a growing interest within the scientific community in the field of β spectroscopy of forbidden nuclear decays, especially due to the potential of validating nuclear models through high-precision measurements of the electron spectra [1]. Despite the considerable interest, experimental datasets on forbidden β transitions in the literature are limited to a few isotopes and are often subject to significant uncertainties, mainly due to the numerous experimental challenges associated

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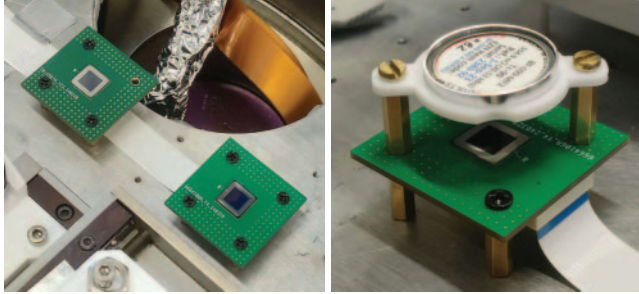


Fig. 1. – SDDs inside the vacuum chamber and setup with 3D-printed source holder.

with the complex interaction of low-energy electrons with matter. In particular, the spectral shape measured for electrons with $E < 1$ MeV is significantly distorted due to several effects, such as energy loss in passive volumes, electron backscattering on the detector surface and the escape of secondary particles from the active volume. In recent years, however, the advent of new technologies and experimental techniques has made it possible to achieve unprecedented levels of precision in β spectroscopy. A notable example is TRISTAN [2], the upgrade of the KATRIN experiment, which aims to perform a high-resolution measurement of the β spectrum of tritium using an array of silicon drift detectors (SDDs) [3]. Although typically employed in the field of X-ray spectroscopy, SDDs possess a number of optimal properties that make them a valuable option for β spectroscopy, such as excellent energy resolution with moderate cooling and a thin dead layer $\mathcal{O}(10$ nm). The ASPECT-BET Collaboration was established with the aim of developing a β spectrometer based on SDD technology, aiming to create a versatile detector optimised for high-precision measurements of forbidden transition spectra without the need for cryogenic temperatures. A first proof of concept was carried out by performing a measurement of the allowed spectrum of ^{14}C [4] using an array of SDDs identical to those used for TRISTAN, which, however, are limited by design to electron energies of approximately 160 keV. In order to enable the measurement of β spectra with higher Q -values, the collaboration focused on the development of a new experimental setup based on a pair of novel SDDs and on the associated readout electronics.

2. – ASPECT-BET novel SDDs: setup and performances

The novel SDDs, fabricated by FBK, implement a non-standard design optimised for electron spectroscopy, characterised by a thickness of about 1 mm and an active area of 64 mm². The SDDs are mounted on two independent PCBs, allowing multiple spectrometer configurations for dedicated coincidence measurements (fig. 1). The large surface area of these SDDs is associated with a significant leakage current, thus requiring moderate cooling a few degrees below 0 °C to guarantee optimal detector performances. Each SDD is readout by a low-noise integrated charge-sensitive preamplifier (CUBE) developed by Politecnico di Milano. An external two-channel board provides power supply, reset management, filtering, amplification and differentiation, allowing flexible signal acquisition with several Digital Pulse Processing units. The digitised signals are acquired at waveform level and processed offline through the application of a trapezoidal filter. To prevent electron energy loss in air the SDDs are operated in a vacuum chamber. The detector PCBs are in thermal contact with the floor of the chamber, thereby enabling efficient detector cooling through the use of an industrial chiller capable to reach -10 °C. In this work we

report the results obtained with one of the two detectors, namely SDD1. The detector was operated in vacuum at approximately 10^{-5} mbar and at a temperature of about -3 °C, read by a sensor on the SDD’s PCB. The characterisation of the detector was carried out by a stepwise approach, starting with a spectroscopic measurement of the characteristic X-rays emitted by a ^{55}Fe source. By estimating the width of the Gaussian peaks, a value of the *FWHM* of approximately 200 eV at 5.9 keV was obtained, thus demonstrating the optimal energy resolution of the detector. The X-ray campaign was followed by a measurement of the radioactive emission of ^{109}Cd . This was done to characterise the detector response to monoenergetic electrons (*e.g.*, 62.5 keV, 84.4 keV and approx. 88 keV Internal Conversion electrons), using the characteristic X-rays emitted after the decay of ^{109}Cd and detected by the SDD for energy calibration. The source employed in this measurement consists of two aluminised Mylar sheets (nominal thickness of $6\ \mu\text{m}$) with the radioactive isotopes deposited between them. The ^{109}Cd source was held at a fixed distance of 1.6 cm from the detector using a 3D-printed ring holder. Due to the self-absorption in the source Mylar, the monochromatic electron peaks in the experimental measurements are shifted to lower energies and show a pronounced tail to the left. To account for the complex electron interactions involved, a GEANT4 simulation of the experimental setup was developed. Penelope [5], a package optimised for low-energy electromagnetic physics, was selected as physics list of choice. The developed GEANT4 simulation was employed to generate a series of simulated datasets for a range of effective Mylar thicknesses. To compare the experimental and simulated datasets, the latter are processed using an analytical model of the detector response function. The best effective Mylar thickness value, which more accurately reflects the physical case, is identified through a parabolic fit of the obtained $\tilde{\chi}^2$ values. The best fit result, corresponding to a $7.5\ \mu\text{m}$ effective Mylar thickness, is reported in fig. 2. The next step undertaken in the characterisation of the detector response to electrons consisted in a measurement of the β spectrum of an allowed transition. ^{14}C was selected as the optimal candidate for the measurement, offering also the possibility to measure electrons with energies up to 156 keV. The measurement was performed using a commercial encapsulated source and followed the same methodology as for the ^{109}Cd measurement. The spectrum predicted by the Betashape software [6] using the Fermi theory was used as the theoretical input for the simulations. Figure 2 shows the best fit result for the ^{14}C data, corresponding to an effective Mylar thickness of $4.5\ \mu\text{m}$. The ^{14}C measurement was followed by a measure-

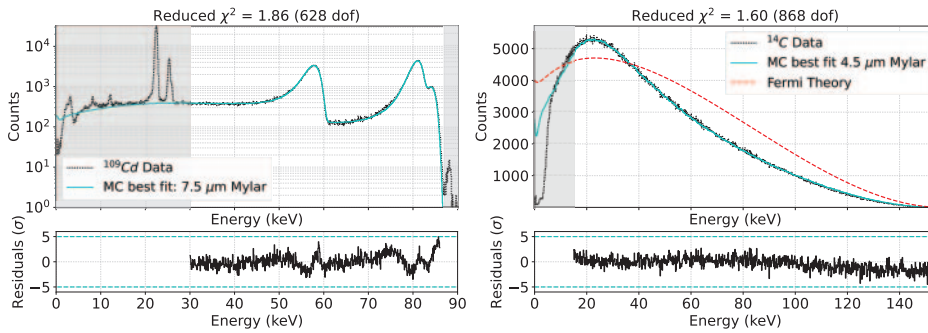


Fig. 2. – Data vs. MC Best Fit and residuals for ^{109}Cd (left) and ^{14}C (right), the fit is performed in the unshaded areas. In the latter is also reported the theoretical prediction of the spectrum.

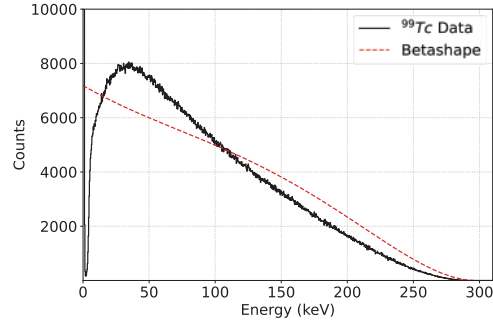


Fig. 3. – ^{99}Tc experimental spectrum and Betashape theoretical prediction.

ment of the β spectrum of ^{99}Tc , using yet again a commercial encapsulated source. This is the first measurement of a forbidden β transition performed with the ASPECT-BET spectrometer and it is the first spectroscopic measurement of electrons with energies up to 300 keV performed with an SDD-based setup. The measured spectrum is shown in fig. 3, as well as the theoretical prediction of the Betashape software.

3. – Results and future developments

The results obtained for the ^{109}Cd and ^{14}C measurements show a good agreement between the experimental and simulated data, highlighting the capability of GEANT4 to correctly simulate the low-energy electron interactions. Currently, the collaboration is focusing on the development of a GEANT4 simulation that correctly models the ^{99}Tc source, in particular the non-negligible thickness of the Tc deposition layer, thus enabling to compare the measured spectra with different predictions. Furthermore, a systematic study of the signal shape dependence on both position and energy will be performed, aiming to develop a robust procedure to reject boundary events. This will be conducted by performing a scan of the SDD surface with different collimated particle sources, such as pulsed LED coupled to an optical fibre and a monochromatic electron source (e-gun).

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REFERENCES

- [1] KOSTENSALO G. and SUHONEN J., *Int. J. Mod. Phys. A*, **33** (2018) 1843008.
- [2] BRUNST T. *et al.*, arXiv:1801.08182 [physics] (2018).
- [3] CARMINATI M. *et al.*, *Nucl. Instrum. Methods Phys. A*, **1049** (2023) 168046.
- [4] NAVA A. *et al.*, *Sensors*, **24** (2024) 8202.
- [5] ASAI M. *et al.*, *Front. Phys.*, **9** (2021) 738735.
- [6] MOUGEOT X., *Phys. Rev. C*, **91** (2015) 055504.