ASPECT-BET: An sdd-SPECTrometer for BETa decay studies

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Abstract. We present the status of the ASPECT-BET (An sdd-SPECTrometer for BETa decay studies) project which is aimed at developing a new detection strategy to perform high-precision, high-accuracy measurements of the energy spectra of beta decays of interest for the physics community, in particular in the field of nuclear physics, double beta decay and reactor neutrinos. The aim is to exploit a relatively novel spectroscopic technique based on Silicon Drift Detectors. An SDD-spectrometer, equipped with all the ancillary detectors required to reject events with only a partial energy deposition in the main sensitive elements, will provide high-statistics and virtually zero-background data. In order to isolate and study the systematic uncertainties, the statistical error on the measured spectra has to be reduced to a negligible level, balancing source activity, measurement duration and background. Reliable and well understood Montecarlo simulations are a key component of this application, as they provide a model for the response functions of the spectrometer, to be deconvolved from the data in order to correctly reconstruct the original spectral shapes. Thanks to the flexibility of the SDD detector technology, the here presented spectrometer could be coupled to a variety of beta sources, ranging from nuclei deposited on the surface of SDDs to minimise source self-absorpion to short-lived isotopes created and collected at unstable isotope beams like ISOLDE at CERN or the exotic beams at LNS, Catania. The current status of the technology, as well as some preliminary sensitivity studies, are presented and discussed.

1. Introduction

The emission of negatively charged particles from a nucleus is one of the first discovered forms of radioactivity. Beta decays have contributed enormously to the development of nuclear physics and to our understanding of weak interactions and neutrinos. Despite a strong effort to find a satisfactory description of this form of radioactivity, the theory describing nuclear beta decay is very complicated and still incomplete. Direct measurements which could provide important information for its development are very difficult and, with few exceptions, have been practically abandoned in the past 40 years. In the past decade, however, interest in beta decay has flourished as a possible way to continue to explore the neutrino-nuclear response, which is of fundamental interest in many fields of astro-, particle- and nuclear physics [1]. They are now the keystone of many academic studies and practical applications [2]. When coupled with the constant development of technology and theory, new perspectives have become possible. Indeed, while in the past beta decays were studied using gas counters or scintillators, which are characterized by limited energy resolutions and efficiencies and could provide therefore only inaccurate measurements, present low-temperature Metallic Magnetic Calorimeters (MMC) [3], developed for direct neutrino mass determination and neutrinoless double beta decay searches, have been used to measure a bunch of beta spectra with outstanding energy resolutions (between 5 and 75 eV in the region 70-300 keV) and efficiencies (larger than 95%) [4].

Despite these very promising results, MMC cryogenic detectors work at around 10-50 mK, with all the related difficulties. This solution, therefore, cannot be considered as a versatile, easy-to-use technique with negligible systematics, with which to carry out an extensive measurement campaign aimed at covering a wide range of isotopes. The combination of new high-resolution technologies for the measurement of the electron spectrum, coupled with more conventional detectors to intercept all escaping electrons or photons, can enlarge the list of beta-decay candidates that could be studied, thus helping in solving some of the open questions in fundamental physics [1] and having a direct impact on some practical applications, such as radionuclide metrology, nuclear medicine, nuclear power industry [2].

The spectroscopy of electrons in the 10 keV - 1 MeV energy range is challenging, when compared to other radiation types, due to the typically large systematic effects related to the detector response to the electron interaction. These effects depend on many different aspects of the detector technology:

- dead layer: a fraction of the volume, typically close to the surface where the electrons enter the detector, where no (or strongly non-linear) signal is generated in response to an energy deposition;
- response non-linearity: the signal generated does not depend linearly on the amount of deposited energy, and the non-linearity cannot be easily removed with simple calibration procedures;
- back-scattering: after some interactions in the detector material the electron can be reflected out of the detector, with only a fraction of its original energy being deposited and recorded in the spectrum;
- X-ray and bremsstrahlung escape: low energy photons are created as a result of ionization and electron scattering in the nuclear field. The corresponding energy is lost if the photons escape the detector's active volume;
- containment efficiency: depending on the size and geometry of the detector, an electron could escape the active volume before depositing all its energy;
- position dependence: the signal generated for a given energy deposition could depend on the position where the energy was deposited;
- pile-up: some detectors, depending on the signal speed and the interaction rate, are subject to wrong energy reconstruction if two interactions are too close in time, and the corresponding signals overlap without being identified and rejected.

As all these effects can lead to a distortion of the reconstructed energy spectrum, their understanding and characterization are mandatory. We are confident that our proposed SDD-based spectrometer will overcome all of them.

2. Main detector: SDD

Thanks to their low anode capacitance, SDDs are high-resolution, fast-response semiconductor detectors. Their application to high-precision beta spectroscopy is a largely unexplored field that would profit from the detailed study and mitigation of the above-mentioned sources of systematic effects. Very preliminary studies performed within the TRISTAN/KATRIN project

[5] have shown promising results [6] in terms of electron detection and modeling of the dead layer. SDDs have been already successfully and extensively employed for X-ray spectroscopy measurements either in scientific research [7] as well as in commercial applications, e.g. as X-ray detectors in SEM (Scanning Electron Microscopes) microanalyzers. The introduction of monolithic arrays of SDDs [8], [9] has allowed them to cover large sensitive areas with low dead margins and to develop high-throughput spectrometers. The technology for building custom-designed SDDs is available at a number of research institutions, including Fondazione Bruno Kessler (FBK) in Trento, Italy, where SDDs have been produced successfully both for direct X-ray detection [10], [11] and for scintillation light readout [12], and MPP-HLL, Munich, Germany, where the devices for the Tristan upgrade of the KATRIN experiment are produced (Fig. 1).

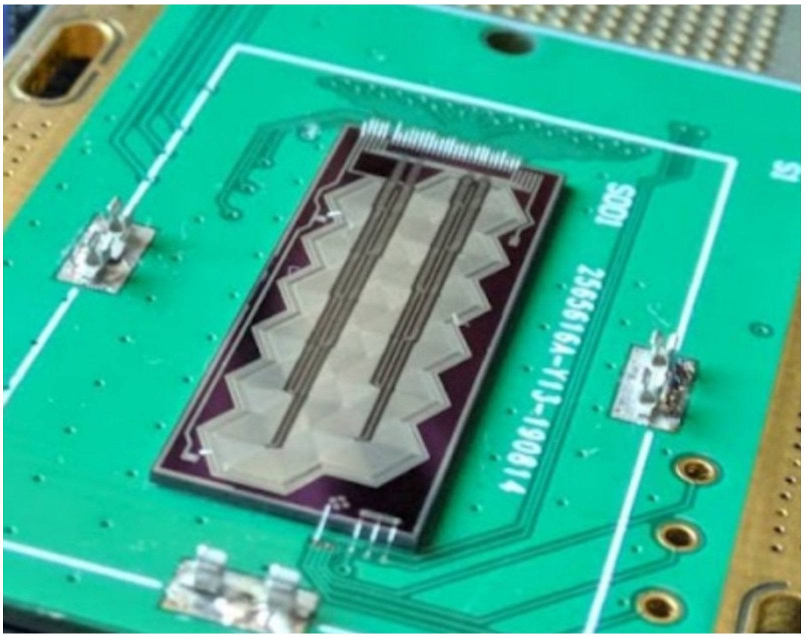

Figure 1. 12-pixel array of SDDs developed for the Tristan upgrade of the KATRIN experiment for the search for keV-scale sterile neutrinos.

The entrance window of the SDD represents a key technological aspect, as electrons unavoidably deposit energy in the non-active layer of the detector entrance window. An extremely uniform and thin entrance window, shallower than 100 nm, is needed to be sensitive to electron energies of a few keV [13]. Although different mechanisms rule X-ray and electron absorption in silicon, efficient detection of electrons would not be possible if the dead layer in the entrance window were not small enough also for soft X-rays detection. Measurements of soft X-rays down to the C-Kalpha line (277eV) have been performed with FBK SDDs [14]. In addition, the same entrance window has been implemented in SDDs able to detect scintillation photons at short wavelengths, as low as 360 nm from LaBr3(Ce) scintillators [12]. This performance is possible only with a dead-layer in the entrance window much thinner than 100nm [15], [16], [17].

The core of the system, or main detector, will be an SDD where the electron coming from the beta decaying source must be detected. Given the technological constraints on the SDD thickness, a stack of two (or in principle more) SDDs may be required to fully stop the electron, depending on the transition energy (Q-value) of the decay under study.

Based on the discussion about the importance of the entrance window for the efficient detection and accurate measurement of the energy of electrons, an extensive program of

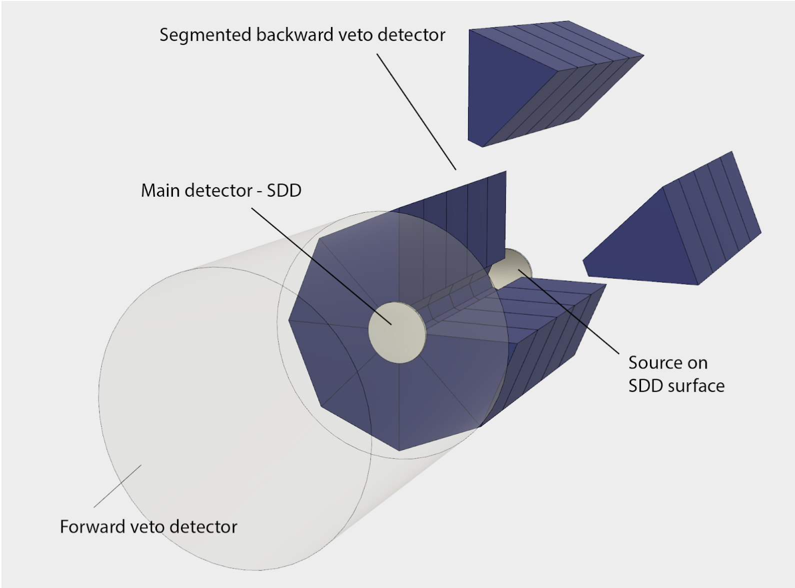

Figure 2. Schematic view of the spectrometer structure, with the main spectrometer, or stack of SDDs, at the core of the system. The surrounding devices are the ancillary detectors for vetoing the escaping radiation.

characterization of its features have been carried out[18].

3. Ancillary detectors: veto for escaping energy

In order to clearly separate signal-like events from spurious events based on their topology, ancillary detectors are required. In order to correctly reconstruct their energy, in fact, electrons must be completely contained in the main detector, while events where a fraction of the energy is deposited outside of it must be rejected (see Fig. 3 for examples of fully contained and vetoed event topologies and Fig. 4 for an example of the effect of the proposed veto on the reconstructed spectrum of 500 keV electrons).

These events are mainly due to:

- electrons that deposit only a fraction of their energy in the main detector before escaping its active volume (due to backscattering or non-unitary geometrical efficiency of the stack);
- Si X-rays produced as a by-product of the primary ionization process that escape from the SDD;
- Bremsstrahlung photons produced by the deceleration of electrons interacting with the detector material and escaping from the SDD.

The veto detectors must have high detection efficiency for photons in the few hundreds of keV range and a very low threshold (down to 10 keV or less) for both photons and electrons and provide large angular coverage (requiring minimal passive materials between the SDDs and the veto detectors). An overview of the required characteristics is reported in Fig. 5. The detectors that are closer to the source should be able to sustain the highest rate of incoming electrons while minimizing the back-scattering probability.

A possible configuration of the veto includes high-Z, high density scintillators for the forward veto and for the part of backwards veto closer to the main detector. LYSO inorganic scintillators are a promising choice and are being characterised with 5 to 30 keV electron beams in order to

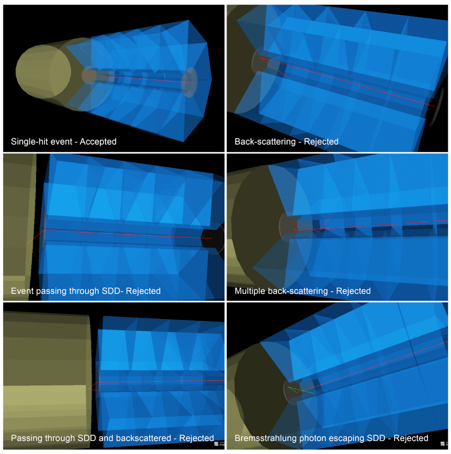

Figure 3. Few examples of events with different topological signatures, including single-hit fully contained events as well as higher multiplicity events due to electrons or photons escaping the main detector.

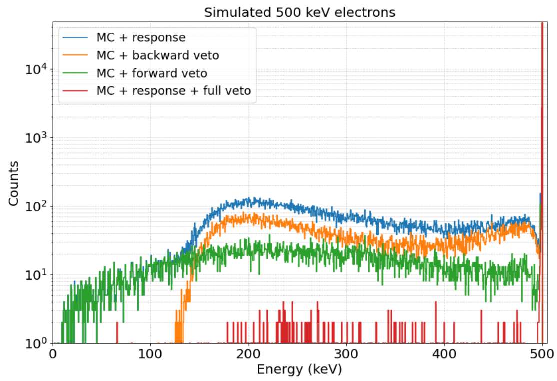

Figure 4. Effect of forward and backward veto detectors (as well as main detector response function) on the measured energy spectrum for mono-energetic 500 keV electrons. The veto system is very effective in making the overall response of the system monochromatic.

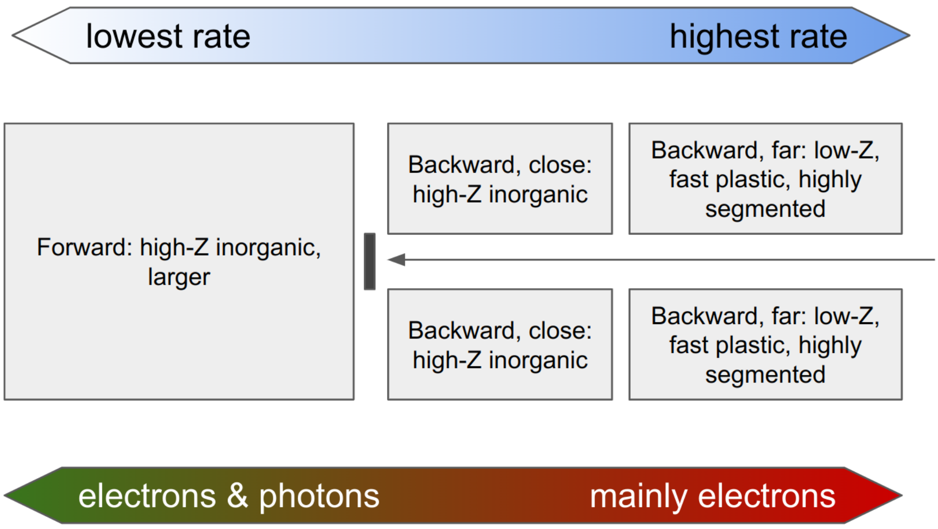

Figure 5. Required characteristics of the detectors used for the veto system. The arrow represents the direction of the electrons emitted by the source and impinging on the main detector.

assess the light yield and energy threshold when read out by SiPMs. The section of the veto closer to the source will have to sustain a high electron's flux while minimizing the backscattering probability. Either a layer of secondary SDDs or plastic scintillators will most likely be the final choice. The exact geometry of the setup will be defined based on MC simulations once a complete characterization of all the components will be available.

4. Sensitivity studies
Once the response function of the primary detector and the veto efficiency have been modeled, a study of the sensitivity of the setup to the shape of beta spectra can be evaluated. As an example we show in Fig. 6 the effect of the global response function (combining SDD response and the effect of the surrounding veto) on the shape of the electron energy spectrum for the ^{113}Cd.

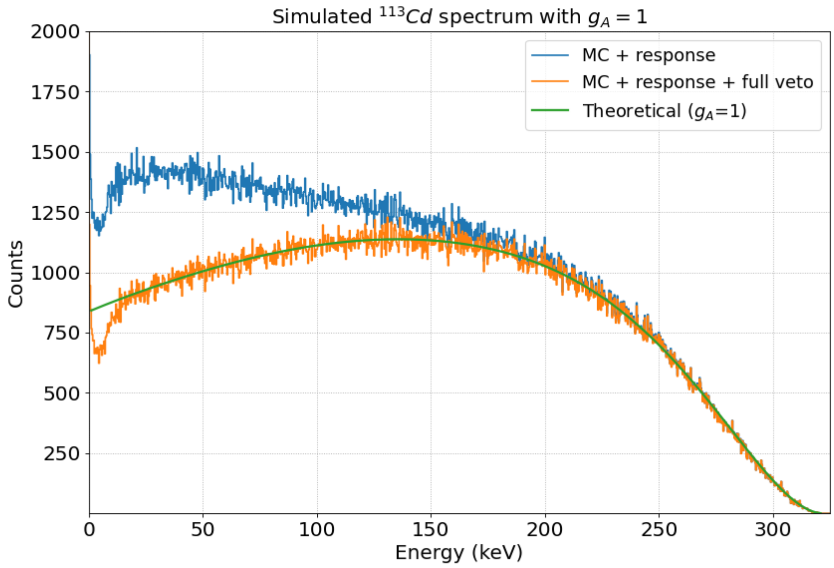

Figure 6. The effect of the detector response function on the spectral shape of the ^{113}Cd beta decay spectrum before (blue) and after (orange) the activation of the veto system. An almost-ideal response results from the application of the veto.

The shape of the beta spectrum is reconstructed with great accuracy across the full energy range above the primary SDD energy threshold (5 keV in this simulation), with only a relatively small loss in efficiency.

The spectral shape used in this study is obtained from [19]. The simulation can be run with a number of spectral shapes corresponding to different values of the g_A parameter. Each simulation is compared to a reference ($g_A = 1$) and the χ^2 is calculated. By varying the statistics of the simulated datasets a sensitivity study can be performed, computing the statistics required to distinguish a given value of g_A from the default value at the required confidence level. The results (together with the results of the same study performed for ^{99}Tc isotope) are shown in Fig. 7 and Fig. 8.

5. Conclusions
We demonstrated, through Montecarlo simulations based on data-driven detector models, that an electron spectrometer based on SDDs can be a very powerful tool to determine the shape of beta decay spectra with Q-values up to hundreds of keV. This promising results, together with an extensive characterization campaign to increase even further the knowledge of possible detector systematic effects, are driving the development of a complete instrument to be used to perform high-precision, high-accuracy studies of the beta decay. The detector system could be

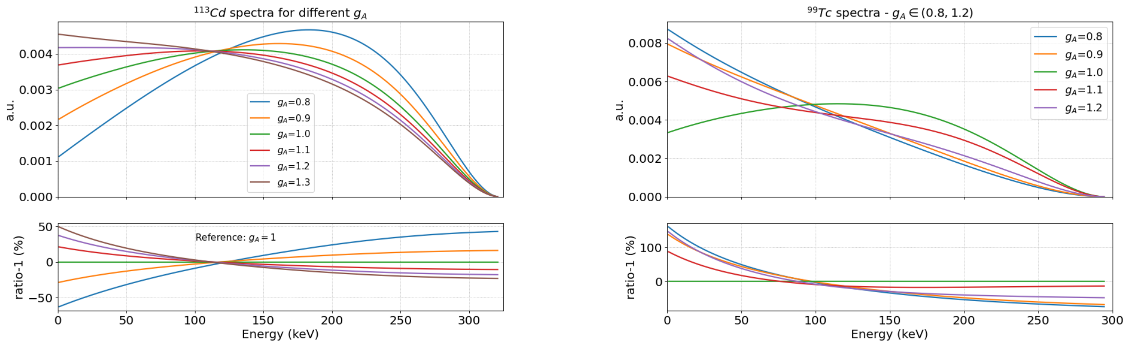

Figure 7. Spectral shape predicted by the model in [19] for ^{113}Cd (left panel) and ^{99}Tc (right panel) beta decay for different values of the effective coupling g_A, and relative variation with respect to reference value.

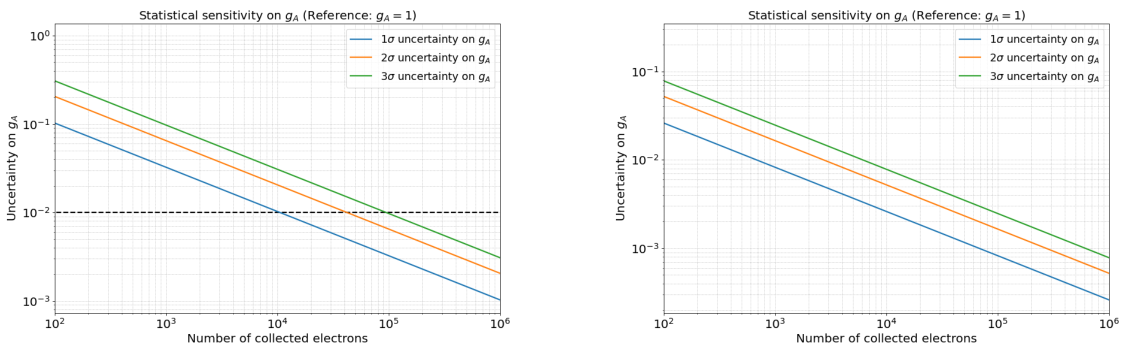

Figure 8. Expected sensitivity to a variation of g_A from the reference value as a function of collected statistics for ^{113}Cd (left panel) and ^{99}Tc (right panel). With $\sim 10^4$ electrons a discrepancy of 1% from the reference value can be detected.

used to detect electrons from a number of different beta sources, ranging from nuclei deposited on the surface of a secondary SDD to minimise source self-absorpion to short-lived isotopes created and collected at unstable isotope beams like ISOLDE at CERN or the exotic beams at LNS, Catania. The resulting data, in the form of the beta decay spectral shapes, will be used to benchmark and down-select nuclear models that are able to better reproduce them.

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