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High efficiency beta-decay spectroscopy using a planar germanium double-sided strip detector

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ABSTRACT

Beta-decay spectroscopy experiments are limited by the detection efficiency of ions and electrons in the experimental setup. While there is a variety of different experimental setups in use for beta-decay spectroscopy, one popular choice is silicon double-sided strip detectors (DSSD). The higher Z of Ge and greater availability of thicker detectors as compared to Si potentially offer dramatic increases in the detection efficiency for beta-decay electrons. In this work, a planar GeDSSD has been commissioned for use in beta-decay spectroscopy experiments at the National Superconducting Cyclotron Laboratory (NSCL). The implantation response of the detector and its beta-decay detection efficiency is discussed.

1. Introduction

Beta-decay spectroscopy experiments utilizing high-energy radioactive ions provided by fragmentation facilities are typically performed by stopping the ion of interest in a position-sensitive solid-state detector, monitoring the subsequent decay products, and correlating the decays with the previously implanted ions based upon both position and time information. The most frequently used stopping medium is a silicon double-sided strip detector (DSSD) [1–8] though other detector types have been used [8–11]. The DSSDs used for beta decay spectroscopy experiments have ranged between 0.3 and 1.5 mm in thickness. The thickness of the DSSD is chosen to maximize the detection efficiency for the particle of interest, such as alphas [12,13], protons [14], or electrons [15–17], while minimizing the probability of summing the energy deposition from the beta-decay electron and any coincident delayed emission. The Si DSSD is about 1 mm thick when optimized for a high beta-decay electron detection efficiency [1] and ions are deposited throughout the thickness of the detector. Due to the typically high beta-decay Q values (Q_β) of the nuclei being studied (Q_β~10 MeV), the emitted beta-decay electron deposits little energy in the detector and the beta-decay detection efficiency is approximately 40% depending on both the Q_β and the location of the decaying ion in the detector.

Germanium detectors offer the tantalizing possibility of a significantly higher beta-decay detection efficiency due to the higher Z of germanium and the availability of germanium in greater thicknesses in comparison with silicon detectors. In the present work, a germanium double-sided strip detector (GeDSSD) is used for beta-decay spectroscopy experiments following production of radioactive ions through fragmentation reactions at the National Superconducting Cyclotron Laboratory (NSCL). The detector is briefly described in Section 2. Section 3 will describe the triggering scheme as well as the general experimental setup used with the GeDSSD. A description of detector calibration is discussed in Section 4. Section 5 will present two radioactive ion beam experiments performed to determine the ion implantation response and beta-decay detection efficiency of the GeDSSD. Section 6 will conclude with a brief summary and outlook for future experiments.

2. Detector overview

2.1. GeDSSD crystal and cryostat

The beta-decay spectroscopy system is centered around a planar GeDSSD, depicted in Fig. 1. The GeDSSD is the NPX-M

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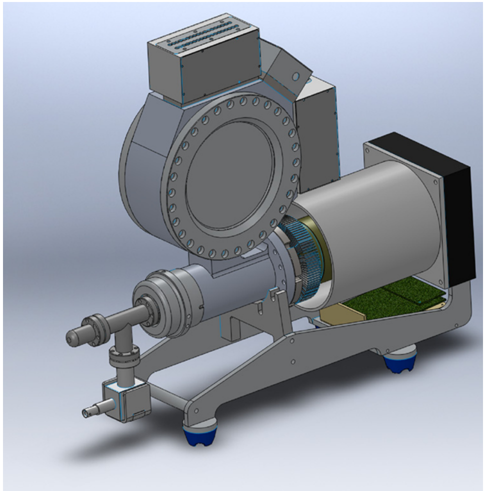

Fig. 1. GeDSSD schematic: The square boxes near the top and side of the detector are capacitively coupled preamplifiers. The ion pump is located on the bottom left hand side of the schematic (small square), while the mechanical cooler is located in the cylinder underneath the detector's surface.

detector manufactured by PhDs Co. [18], consisting of a single germanium crystal, 1 cm thick and 9 cm in diameter. The GeDSSD is electrically segmented into sixteen 5-mm wide strips on the front of the detector and sixteen orthogonal 5-mm wide strips on the back. Amorphous Ge contact technology was used in the construction of the GeDSSD [19,20]. The crystal is mounted in a transmission style so that the choice of front or back with respect to the beam is arbitrary. The crystal is self-contained in a roughly cylindrical cryostat 9 cm long, with an outer diameter of 19 cm. The front and back entrance windows of the cryostat are constructed from aluminum and are approximately 1 mm thick. The remainder of the cryostat is composed of stainless steel. An additional 0.143 mm of Al is used internally as an infrared radiation shield between the cryostat and the germanium crystal. The detector is placed at a short distance downstream from a thin kapton exit window at the end of the beamline.

2.2. Preamplifier

The GeDSSD preamplifier has to accommodate a large dynamic range to simultaneously measure the energy deposition of the radioactive ion (GeV) and the beta-decay electrons (keV–MeV). To achieve the required range, each strip on the GeDSSD is connected to a set of two capacitively coupled preamplifiers to produce two different gain ranges. The high-gain preamplifiers are suitable for the detection of beta-decay electrons and low-energy gamma rays and have a range of 0–15 MeV. The low-gain preamplifiers are optimized for high-energy ion detection with a range of 0–30 GeV.

2.3. Mechanical cooler and ion pump

The detector's crystal is mechanically cooled by a Sunpower Inc Sterling cooler, model CryoTel MT [21], and the vacuum is maintained in the cryostat by an active ion pump. The temperature inside the cryostat is maintained below liquid nitrogen temperature.

3. Experimental scheme

3.1. Electronics

The GeDSSD is used in conjunction with the NSCL Digital Data Acquisition System (DDAS) [22]. The preamplifier outputs of the 16 high- and low-gain signals from the front and back of the detector are directly input into individual channels on a XIA Pixie-16 module [23,24]. Each module has 16 channels and digitizes the incoming signal at 100 MSPS with a 12-bit ADC. Each channel performs independent time and energy measurements based on user-controllable algorithms and is able to record waveforms if requested.

3.2. Triggering and gating

There are three possible triggering schemes for the GeDSSD. The first mode is free-running: each channel independently triggers and records data to its internal memory buffer. The second mode requires the presence of an external validation signal to arrive in coincidence with the internal channel trigger. The external signal is used with the GeDSSD to selectively record data only if a signal from the front and back of the detector is present. An OR signal is generated whenever a signal above threshold is observed in any one of the 16 front channels. A similar OR signal is constructed from any one of the 16 back channels. The two OR signals are ANDed together to generate the external validation signal. The third and final mode uses the external signal to force the recording of data from all channels regardless of whether the channel has observed a signal above threshold. This mode is particularly useful when acquiring traces where the simultaneous start of all trace signals is necessary. However, the mode results in a very high data throughput. Most beta-decay experiments use the second triggering mode requiring a front/back coincidence.

3.3. General experimental scheme

The GeDSSD is the central implantation detector in the beta-decay spectroscopy program, and is typically surrounded by ancillary detector arrays for detection of delayed emissions. Radioactive ions produced by the coupled cyclotron facility (CCF) at the NSCL are separated by the A1900 Fragment Separator [25], individually characterized event-by-event using standard energy loss (ΔE) and time of flight (TOF) techniques, and delivered to the planar GeDSSD. The individual ions are deposited up to 2 mm deep into the GeDSSD crystal depending on their respective total energy. Any ion delivered to the GeDSSD must have enough energy to exit the beamline and implant into the detector, placing a lower limit on the total energy of the ions to be studied. Once implanted, the radioactive ion will decay, emitting beta-decay electrons/positrons and possibly other delayed radiations, which may be detected by an ancillary detector array, such as the Segmented Germanium Array (SeGA) [26].

4. Calibration

Several check sources were utilized to calibrate the high-gain output of each of the individual strips of the GeDSSD as well as to determine the absolute efficiency of the GeDSSD. A representative ^{137}Cs spectrum is presented in Fig. 2 for a single strip. The resolution of the individual strips before ion implantation ranged between 2.6 and 3.6 keV at 662 keV with an average of 3.0 keV. For a ^{57}Co source, the resolution of the 122 keV gamma-ray was 2.4 keV on average. The resolution of lower energy gamma-rays is expected to be improved with the implementation of the next generation of modules with a faster sampling rate (250 Hz) and higher precision (14 bit ADC). For comparison, the resolution at the same energy in SeGA was measured to be 2.9 keV. The full energy range in each SeGA detector is ~3000 keV.

The absolute efficiencies of the detectors utilized in the commissioning runs (GeDSSD and SeGA) were measured with a calibrated $^{154/155}$Eu source. Knowledge of absolute gamma-ray efficiencies is critical for correctly determining absolute gamma-