Investigation of SiC for dual timing and energy detection in fission-fragment mass spectroscopy

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Abstract

To identify fast-timing detectors suitable for picosecond-to-nanosecond nuclear state lifetime measurements in neutron-rich nuclei, three silicon carbide (SiC) detectors with sensitive layer thicknesses of 30 µm, 80 µm, and 150 µm (each having a 1×1 cm^2 active area) were characterized for both α-particle energy resolution and ^{252}Cf spontaneous fission fragment timing resolution. The radiation hardness of two SiC detector types (PIN and Schottky) was also evaluated under exposure to ^{252}Cf spontaneous fission fragments and α-particles. The results demonstrate that the SiC detectors exhibit excellent energy resolution (0.88%-1.12%) and timing resolution (132-284 ps), corresponding to mass resolution values of 2.5%-3.2%. Compared to conventional silicon detectors, under prolonged ^{252}Cf α-particle and fission-fragment irradiation, SiC detectors showed only minor degradation, with signal amplitude following an exponential decay with fluence. The PIN-type SiC detector displayed the slowest attenuation and best radiation tolerance, confirming the strong potential of SiC detectors for long-term charged-particle and heavy-ion detection in nuclear spectroscopy.

Full Text

Preamble

Investigation of SiC for dual timing and energy detection in fission-fragment mass spectroscopy

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To identify fast-timing detectors suitable for picosecond-to-nanosecond nuclear state lifetime measurements in neutron-rich nuclei, three silicon carbide (SiC) detectors with sensitive layer thicknesses of 30 µm, 80 µm, and 150 µm (each having a 1 × 1 cm^2 active area) were characterized for both α-particle energy resolution and ^{252}Cf spontaneous fission fragment timing resolution. The radiation hardness of two SiC detector types (PIN and Schottky) was also evaluated under exposure to ^{252}Cf spontaneous fission fragments and α-particles.

The results demonstrate that the SiC detectors exhibit excellent energy resolution (0.88% - 1.12%) and timing resolution (132 - 284 ps), corresponding to mass resolution values of 2.5% - 3.2%. Compared to conventional silicon detectors, under prolonged ^{252}Cf α-particle and fission-fragment irradiation, SiC detectors showed only minor degradation, with signal amplitude following an exponential decay with fluence. The PIN-type SiC detector displayed the slowest attenuation and best radiation tolerance, confirming the strong potential of

SiC detectors for long-term charged-particle and heavy-ion detection in nuclear spectroscopy.

Keywords: SiC detector, Radiation-hard detectors, ^{252}Cf fission fragments, Time resolution.

Introduction

The nuclear fission process serves as an efficient nuclear reaction pathway that produces a variety of neutron-rich, medium-mass nuclides. During fission, the compound nucleus splits into two fission fragments (FFs) that are typically left in highly excited states and subsequently de-excite through the emission of prompt neutrons and γ-rays. Investigation of these prompt emissions not only enhances our understanding of the nuclear structure of the fragments but also sheds light on the fundamental dynamics of the fission process [?]. In particular, lifetime measurements of nuclear states in the picosecond-to-nanosecond (ps–ns) range serve as an effective tool for probing structural properties of nuclei in neutron-rich regions [?]. The spontaneous fission of ^{252}Cf generates neutron-rich nuclei across a broad spectrum of isotopes, with mass numbers ranging from A 70 to 180 and atomic numbers from Z 28 to 66, most of which have unknown nuclear state lifetimes. Previous attempts to extract such information using the Ge-LaBr$_3$(Ce)-LaBr$_3$(Ce) coincidence method suffered from inadequate selectivity and background suppression. To address this, our group developed the fast-timing hybrid array HALIMA [?], designed for ps-ns nuclear state lifetime measurements in neutron-rich nuclei using a four-fold FF-Ge-LaBr$_3$(Ce)-LaBr$_3$(Ce) coincidence technique, thereby enabling the subtraction of the γ-ray background. Using HALIMA, fission fragment masses were determined through the E-V method, in which fragment energies were measured with a solar cell detector and fragment velocities were inferred from their mass dependence. This approach, relying only on energy measurements, resulted in a modest mass resolution of 7 atomic mass units (u), restricting lifetime studies to nuclei populated in the most intense channels. To extend measurements to weaker channels with yields down to 10^{-3}, improved mass resolution is essential.

The present work explores the use of silicon carbide detectors as fission fragment sensors, with the objective of establishing a detection system capable of 3 4 u resolution (2 3% relative), thereby facilitating more effective γ-ray background subtraction.

The principle of mass measurement, the so-called E-V technique [?], involves determining the mass of a fission fragment by measuring its velocity (v) and kinetic energy (E). In this approach, the particle velocity (v) is obtained using the time-of-flight (TOF) method: a particle of energy E travels a distance L with velocity v = L/t, where t is the flight time over the path L, which is defined by a start detector and a stop detector. The velocity (v) is thus determined from the measured flight path length (L) and the flight time (t). The non-relativistic mass of the particle can be calculated using $M = 2Et^2/L^2$. The mass resolution in the E-V method can be expressed in terms of the resolutions of different experimental quantities via the relation:

$$\left(\frac{\Delta M}{M}\right)^2 = \left(\frac{\Delta E}{E}\right)^2 + \left(\frac{2\Delta t}{t}\right)^2 + \left(\frac{2\Delta L}{L}\right)^2$$

where ΔE/E, Δt/t, and ΔL/L represent the relative standard errors of the energy, time, and path length, respectively. Here, M denotes the particle mass in atomic mass units (u), E is the particle energy in MeV, t is the time-of-flight in nanoseconds (ns), and L is the flight path length. Among these terms, the timing and energy resolutions contribute most to the mass resolution, motivating the choice of fast timing and high energy resolution detectors.

In the HALIMA setup, a semi-closed ^{252}Cf source is used, with the result that one fission fragment is stopped in the source backing while the complementary fragment travels freely toward the detector array. Figure 1 [Figure 1: see original paper] illustrates the proposed upgraded configuration for fragment mass measurements. The start signal for TOF is obtained by detecting the prompt fission γ-rays, which are simultaneous with the fission event, using a fast and efficient LaBr$_3$(Ce) scintillator positioned 1 cm from the source. The flight path length L is proposed to be 25 cm, resulting in a time-of-flight t of approximately 25 ns. Under these conditions, the characteristics of the stop detector govern the attainable mass resolution. Optimizing this detector response is thus essential to realize a resolution of 3 4 u (2 3%), enabling precise reconstruction of fission fragment mass distributions.

The fission fragment detector used in the HALIMA setup is exposed to intense alpha and neutron radiation. Conventional semiconductor detectors, such as silicon (Si), are widely employed due to their excellent energy resolution and mature fabrication technology \cite{5-7}. However, their limited radiation tolerance leads to performance degradation in high-radiation environments, rendering them unsuitable for fission fragment detection \cite{8-10}. Diamond detectors fabricated by single chemical vapor deposition (CVD) have demonstrated promising performance, with energy and time resolutions of 1.4% and 10.2 ps, respectively, for fission fragments with mass A = 98 at 90 MeV [?]. Nevertheless, their high cost and restricted active area (0.25 cm^2) hinder large-scale application. An attractive alternative is silicon carbide (SiC), whose detector technology has matured in recent years. SiC detectors exhibit high radiation resistance and excellent timing performance \cite{12-15}. Given these remarkable properties, SiC has been identified as a suitable choice for the stop detector in fragment mass measurements within the upgraded HALIMA setup.

Assuming a flight path of 25 cm with an accuracy of 0.1%, an energy resolution of 1% for the SiC detector and a time resolution of 260 ps for the LaBr$_3$(Ce) detector [?, ?], Eq. 1 indicates that the time resolution of the SiC detector must be at least 370 ps to achieve a fission fragment mass resolution of 3 4 units. The overall timing resolution Δt of the system is derived from the contributions of the LaBr_3(Ce) detector resolution (Δt_1) and the SiC detector resolution (Δt_2), combined in quadrature as expressed in Eq. 2:

$$\Delta t = \sqrt{(\Delta t_1)^2 + (\Delta t_2)^2}$$

In this work, the performance of silicon carbide (SiC) detectors with varying sensitive layer thicknesses was systematically evaluated. The energy resolution was measured using a triple-α source (^{239}Pu-^{241}Am-^{244}Cm) for PIN-type SiC detectors with sensitive layer thicknesses of 30 µm, 80 µm, and 150 µm. Timing resolution was assessed using a weak ^{252}Cf source, while radiation hardness was evaluated for both PIN-type and Schottky-type SiC detectors under exposure to a strong ^{252}Cf source. The SiC detectors used in this study are detailed in Sec. II. The performance of these detectors in terms of energy and timing resolution, radiation tolerance, and fission fragment measurement is presented in detail in Sections III–V. Comparisons with conventional silicon detectors under similar irradiation conditions are also discussed. Finally, a summary and conclusion are given in Sec. VI, and the potential application of SiC detectors for ^{252}Cf spontaneous fission studies combined with prompt γ-ray spectroscopy is addressed.

Figure 2 [Figure 2: see original paper] shows a schematic illustration of the layer structure of the PIN-type SiC detector. The layer thicknesses and widths are not to scale and are shown for illustrative purposes.

II. SiC Detector

Silicon carbide (SiC) detectors, as third-generation semiconductor devices, possess a wide band gap and feature a large active area with high charge collection efficiency (CCE 100%) \cite{12, 16-18}. They exhibit remarkable performance characteristics, including excellent thermal stability (remaining functional at temperatures up to 700°C) [**?**], ultrafast timing response [e.g., a 100 µm 4H-SiC PIN detector can achieve 94 ps (σ) [**?**]], high energy resolution (0.3%-1.78% for alpha particles) [**?**, **?**, **?**], high signal-to-noise ratio, and superior radiation hardness [**?**, **?**]. These characteristics make SiC detectors well-suited for applications in extreme environments, including charged-particle spectroscopy (e.g., alpha particles, protons, and fission fragments) [**?**, **?**, **?**], heavy-ion detection (e.g., achieving a resolution of 1.61% for 86 MeV oxygen ions) [**?**], and fast neutron detection \cite{21-23}. The combination of these properties makes SiC an excellent candidate for fission fragment detection.

The Silicon Carbide detectors used in the present study were supplied by the Nanjing Electronic Devices Institute. Two types of SiC detectors with distinct specifications and designs were employed. The first type features a PIN-type structure with three different sensitive layer thicknesses of 30 µm, 80 µm, and 150 µm, all having the same sensitive area of 1 × 1 cm^2. The second type is a Schottky-type structure with a sensitive layer thickness of 80 µm and a sensitive area of 0.5 × 0.5 cm^2. Figure 2 shows a cross-sectional schematic diagram of the PIN-type SiC detector structure. Both the front and back electrodes are composed of gold (Au) metallization. The detector structure comprises a doped P+ epitaxial layer, a N- epitaxial layer, a passivation layer, and the electrodes. The structure of the Schottky-type SiC detector is identical to that of the PIN-type, except for the absence of the P+ epitaxial layer.

Previous studies have shown that SiC devices exhibit substantially lower leakage currents compared to conventional silicon detectors, primarily due to their wider band gap, which reduces intrinsic carrier generation. This characteristic makes SiC detectors particularly attractive for applications requiring high-temperature operation or low-noise performance. Prior to evaluating the spectroscopic response of SiC detectors to fission fragments, a comprehensive set of electrical characterization measurements was performed to assess their suitability for such measurements. Figure 3 [Figure 3: see original paper] shows the leakage current of the PIN-type SiC detectors as a function of the bias voltage. It is evident from the figure that the leakage current is approximately two orders of magnitude smaller than that of traditional silicon detectors, confirming the low-noise advantage of SiC devices. The observed exponential increase of leakage current with reverse bias voltage may be attributed to enhanced carrier drift within the depletion region.

III. Energy Resolution for α-Particles

The energy resolution of SiC detectors with sensitive layer thicknesses of 30 μm, 80 μm, and 150 μm was investigated using a triple-α source. This source emits α-particles with characteristic energies of 5.156 MeV (^{239}Pu), 5.486 MeV (^{241}Am), and 5.804 MeV (^{244}Cm). The detectors and source were mounted inside a vacuum chamber maintained at a pressure of 10^{-3} mbar. The distance between the source and detector was 6 cm without any collimators. Detector signals were processed using a charge-sensitive preamplifier with a gain of 1/1 pF to enhance the signal-to-noise ratio, thereby improving the energy resolution. While this approach increases resolution accuracy, it also results in a longer signal rise time compared to fast wideband preamplifiers. Two digital acquisition systems were evaluated to identify the optimal configuration for the SiC detectors. The first one is based on the digitizer from XIA and the second is a CAEN digitizer. The output signals from the preamplifier of the 30 μm SiC detector are digitized at a sampling rate of 100 MHz with 14-bit resolution using a general-purpose digital data acquisition system (GDDAQ) [**?**, **?**]. The GDDAQ is based on XIA LLC' s Pixie-16 modules, providing 16-channel digitization with selectable 12 /14/16-bit resolutions and support for multi-channel synchronization. The energy signals from the 80 μm and 150 μm detectors were fed directly to a 14-bit 500 Ms/s DT5730 CAEN digitizer which applied a trapezoidal pulse-shaping algorithm to extract energies.

Figures 4 (a-c) [Figure 4: see original paper] show the energy-calibrated α-particle spectra obtained from the three SiC detectors, displaying three wellresolved α peaks. After minimizing electronic noise contributions, the ^{241}Am peak was selected as the reference for energy resolution calculations. Gaussian fitting was performed on the ^{241}Am peaks to determine the full width at half maximum (FWHM) for each detector's energy spectrum. The energy resolutions of the detectors with three different thicknesses were measured under various reverse bias voltages. Specifically, the 30 µm detector was biased from -50 V to -300 V, the 80 µm detector from -200 V to -350 V, and the 150 µm detector from -50 V to -300 V, with a bias step of 50 V for all measurements. The α-particle energy resolutions were then calculated for each detector at the applied biases. The optimal energy resolutions and their associated bias voltages were 0.90% at -300 V for the 30 µm detector, 1.12% at -350 V for the 80 µm detector, and 0.88% at -300 V for the 150 µm detector. Although these values are slightly below the highest resolutions reported in literature, they are comparable to the average performance observed for SiC detectors to date. It is also important to note that, due to the absence of a collimator between the α-source and the detectors, energy straggling contributes to spectral broadening, which can modestly reduce the measured energy resolution.

IV. Time Resolution for Fission Fragments

SiC detectors are known for their excellent timing performance, primarily due to their high carrier saturation velocities. Yang et al. [**?**] reported a time resolution of 220 ps (FWHM) for β-particles using a 4H-SiC detector with an active area of 5 × 5 mm^2 and a thickness of 100 µm. Despite these promising results, the timing performance of SiC detectors for heavy ions, especially fission fragments, remains unexplored. Given the substantially higher energy deposited by fission fragments compared to β-particles (several orders of magnitude), a correspondingly superior time resolution can be anticipated.

In the present work, the time resolution of SiC detectors for fission fragments was measured using detectors with sensitive layer thicknesses of 30 µm, 80 µm, and 150 µm, each having an active area of 1 × 1 cm^2. The fission fragments were produced by a weak ^{252}Cf source. This source was prepared through a self-transfer [**?**] from a mother source, in which ^{252}Cf was vacuum-deposited onto a 2 µm thick Mylar film. The resulting source provides fission fragment spectra whose characteristics closely resemble those from an ideal infinitely thin ^{252}Cf source. Figure 5 [Figure 5: see original paper] shows the schematic diagram of the experimental setup for measuring the time resolution of the SiC detector. A plastic scintillator detector served as the reference timer, consisting of an H10721-20 photomultiplier tube (PMT) coupled to a 100 µm thick, 8 mm diameter EJ-228 scintillator. Owing to its very fast rise time of 0.5 ns, which is well-suited to the H10721-20 PMT characteristics, the EJ-228 plastic scintillator ensures minimal contribution to the overall timing resolution, allowing the measured resolution to represent predominantly the intrinsic timing capability of the SiC detector.

The SiC detector and the plastic scintillator were mounted on opposite sides of the weak ^{252}Cf source, each positioned 8 mm from the source and enclosed within a vacuum chamber. Time information of fission fragments was obtained through particle coincidence measurements between the two detectors. The plastic scintillator, operated under a 0.7 V bias, exhibited a fast time response (up to 2 ns), making it ideal as the trigger for waveform acquisition. The ^{252}Cf source emitted fission fragments in both directions, allowing simultaneous energy deposition in the SiC and plastic scintillator detectors. Signals from the SiC detector were processed using a current-sensitive preamplifier (DBA-IV), chosen for its rapid response to preserve precise timing information. The SiC detector signals exhibited rise times within 2 ns. Considering the previously discussed energy resolution results and the need for optimal signal-to-noise performance, bias voltages of -200 V, -200 V, and -400 V were applied to the 30 µm, 80 µm, and 150 µm SiC detectors, respectively.

Signals from both the plastic scintillator and SiC detector were fed into a CAEN DT5742 digitizer, with the scintillator serving as the trigger for coincidence waveform acquisition. The DT5742 is a desktop module equipped with 16 + 1 channels, featuring a 12-bit, 5 GS/s switched capacitor digitizer. In this study, a sampling rate of 5 GHz was employed, and full waveforms of 1024 points were recorded within a 200 ns acquisition window. With a bandwidth of 500 MHz, the module can accurately process signals with rise times as fast as 0.7 ns. These features make the DT5742 well-suited for processing the fast signals from both the plastic scintillation and SiC detectors. A direct constant-fraction discrimination (dCFD) algorithm with a fraction of 0.45 was applied to extract signal timing, while the pulse-height of the fission fragments was determined using a peak-locating method [**?**].

The pulse-height spectra of fission fragments from the weak ^{252}Cf source, measured with the SiC detectors and the corresponding plastic scintillators, are presented in Fig. 6 [Figure 6: see original paper]. As evident from the figure, the pulse-height spectra obtained from the three SiC detectors (the green line) clearly exhibit the characteristic double-humped structure associated with heavy and light fission fragments, whereas the plastic scintillators (the red line) show a broad, unresolved distribution, highlighting the superior energy resolution of SiC detectors compared to the plastic scintillator. The counts associated with the light fission fragments (right hump) are consistently lower than those of the heavy fission fragments (left hump). This phenomenon, observed for all three SiC detectors, can be attributed to the fact that some heavy fission fragments —particularly those with lower kinetic energies—deposit insufficient energy to exceed the trigger threshold (50 mV) of the plastic scintillator and are therefore not registered [**?**].

The time difference in the time-of-flight (TOF) between coincident fission fragments detected by the SiC detector and the plastic scintillator was used to determine the overall time resolution of the detector system. Since fission fragments have a broad distribution in mass and kinetic energy, their velocities vary considerably, introducing a spread in the TOF spectrum. To minimize this effect, a specific subset of fragment pairs was selected for analysis: those where the heavy fragment produced a pulse amplitude below the left-hand peak in the SiC spectrum (the region with blue background in Fig. 6), and the complementary light fragment was detected by the plastic scintillator.

The TOF differences for the selected subset of fragment pairs are plotted in Fig. 7 [Figure 7: see original paper] for detector systems with SiC detectors having different thicknesses. Gaussian fits were applied to the time difference spectra, and the timing resolution was determined from the full width at half maximum (FWHM) of the fitted peaks. The measured timing resolutions were 321.9$±3.3*ps*, 248.9±1.6*ps*, *and*194.2±$2.1 ps, respectively, for systems with the 30 μm SiC detector at -200 V, the 80 μm detector at -200 V, and the 150 μm detector at -400 V. Among them, the 150 μm detector system exhibited the best timing performance, followed by the 80 μm and 30 μm detectors. This trend is consistent with the expected dependence of the time resolution on the detector capacitance. For a given active area, increasing the detector thickness reduces the capacitance, which in turn enhances charge collection speed and leads to faster signal rise times and improved time resolution.

However, the intrinsic time resolution of the SiC detector cannot be extracted directly from the measured width of TOF spectra, as various experimental factors contribute to the time resolution of the detector system. The dominant contribution arises from the time jitter associated with the velocity distribution of the fission fragments. This contribution was estimated using a Monte Carlo simulation performed with the CGMF code [**?**], applying the same fragment-pair criteria as in the experiment. The TOF difference distributions were simulated by assuming different intrinsic timing resolutions for the SiC detector until the best agreement with the measured TOF distributions was obtained. The simulated curves (green lines in Fig. 7) reproduce the experimental distributions very well. The corresponding intrinsic timing resolutions (σ_{int}) that best describe the data are 120.6$±1.7*ps*(284.0±4.0*psFWHM*)*forthe*30*mdetector*, 84.9±0.8*ps*(199.9±1.9*psFWHM*)*forthe*80*mdetector*, ps FWHM) for the 150 μm detector. These results confirm the strong potential of SiC detectors for fast-timing applications, rivaling the performance of microchannel plate detectors and meeting the benchmarks set for the HALIMA spectrometer.

V. Radiation Hardness to α-Particles and Fission Fragments

Semiconductor detectors suffer from a critical limitation: their crystal lattices are prone to radiation-induced damage. Such lattice defects result in increased leakage current, reduced charge collection efficiency, and degraded energy resolution [**?**]. While these effects have been systematically investigated in silicon detectors [**?**], the radiation hardness of silicon carbide detectors, particularly against fission fragments and their impact, has not been characterized. For SiC detectors to serve effectively in fission fragment mass measurements, they must exhibit robust resistance to radiation damage. In the present study, the radiation tolerance of SiC detectors was evaluated through observed variations in their spectral performance under continuous exposure to a ^{252}Cf source. The spontaneous fission source ^{252}Cf has a branching ratio of 97:3 between α-decay and spontaneous fission. Continuous irradiation by these energetic particles leads to progressive degradation of detector characteristics with increasing fluence. The α-particle radiation tolerance is particularly critical for ensuring the long-term operational stability of the detection system. Previous studies have shown that 4H-SiC Schottky barrier diode detectors with an active area of 20 mm × 20 mm and thickness of 20 µm exhibit excellent radiation resistance against α-particles, withstanding fluences up to 1.03×10^{10} cm^{-2} [**?**].

In this study, we examined the performance degradation of two different SiC detectors when subjected to prolonged irradiation from a strong ^{252}Cf source with an activity of 100 µCi. The first detector was a PIN-type SiC (active area of 1 cm × 1 cm, thickness 80 µm), and the second was a Schottky-type SiC (active area of 0.5 cm × 0.5 cm, thickness 80 µm). The irradiations were conducted at room temperature in a high-vacuum environment (10^{-6} mbar), with the detectors and source positioned coaxially and no collimator placed between them.

The PIN-SiC detector was placed 4 cm from the source and irradiated for 381 hours, receiving a maximum particle (α-particles + FFs) fluence of 1.8×10^{10} cm^{-2}. The Schottky-SiC detector was placed 3 cm from the source and irradiated for 264 hours, with a maximum fluence of 8.8×10^{9} cm^{-2}. To provide a clearer evaluation of the radiation resistance of SiC detectors against both α-particles and FFs, a silicon detector (Canberra time-optimised PIPS detectors of type TMPD 450-20NTD-300 AM) was used as a reference for comparison. It was positioned 20 cm from the source and irradiated for approximately 2000 hours with a count rate of 2000/s, corresponding to a maximum particle fluence of 2.88×10^{9} cm^{-2}. The detectors were connected to 16-channel integrated charge-sensitive preamplifiers, and the output signals from the preamplifier were digitized at a sampling rate of 100 MHz with 14-bit resolution using a general-purpose digital data acquisition system (GDDAQ). Figure 8 [Figure 8: see original paper] shows the fission fragment spectra recorded by the PIN-SiC, Schottky-SiC, and Si-type detectors before and after irradiation.

Prior to irradiation, both SiC detectors exhibited comparable spectral performance, though their energy resolutions were slightly inferior to that of the Si detector. This is evident from the broader fission fragment peaks and higher peak-to-valley ratios observed in the Si spectra. After irradiation, however, the SiC detectors show superior energy resolution compared to the Si detector, as indicated by the smaller reduction in peak separation between the light and heavy fragment peaks. As discussed later in Fig. 11 [Figure 11: see original paper], at an irradiation fluence of 10^{9} cm^{-2}, the Si detector' s energy resolution deteriorated significantly, whereas the PIN-SiC detector, even after exposure to a tenfold higher fluence (10^{10} cm^{-2}), retained nearly the same spectral resolution as the Schottky-SiC detector irradiated at 10^{9} cm^{-2}. Furthermore, the leakage current of the Si detector increased considerably from 0.1 µA up to 10 µA during the irradiation.

To further quantify the effect of irradiation on the energy resolution of SiC detectors, the 6.12 MeV α peak from ^{252}Cf was examined. Figure 9 [Figure 9: see original paper] illustrates the variation in α-particle energy resolution from the ^{252}Cf source measured by the PIN-SiC and Schottky-SiC detectors under different fluences. Due to the short source-to-detector distance, α particles were detected over a wide angular range, leading to considerable energy losses in both the source window and the detector dead layer. Additionally, the high count rates, approximately 37,000 s^{-1} for the Schottky-SiC and 15,000 s^{-1} for the PIN-SiC detector, may have caused pile-up of α-particles and fission fragments. These effects noticeably degraded the absolute α-energy resolution, as shown in Fig. 9, compared to the measurements reported in Section III. However, this does not affect the reliability of the observed trend of resolution variation with irradiation dose.

As seen in Fig. 9(a), the energy resolution of the PIN-SiC detector shows a steep decline in resolution with increasing fluence up to 1×10^9 cm^{-2}, after which it stabilizes and remains nearly constant up to 6×10^9 cm^{-2}, showing only small fluctuations beyond this point. Figure 9(b) shows the energy resolutions corresponding to the Schottky-SiC detector as a function of irradiation dose for two adjacent irradiations labeled "First Run" and "Second Run" (noting a five-hour power-off of the detector between these two runs), shown in red and blue, respectively. As seen in Fig. 9(b), the Schottky-SiC detector exhibits a more complex trend in the "First Run" : an initial deterioration followed by a brief improvement and a subsequent linear decrease. After cooling down the detector for five hours, at an irradiation dose point of 4×10^9 cm^{-2} in the "Second Run" , the energy resolution was restored and then followed by a linear decline in resolution, demonstrating a fast self-recovery behavior of the Schottky-type SiC detector. The observed non-monotonic behavior and differing degradation trends between the two SiC types likely originate from variations in their internal structure and defect dynamics. It is also noteworthy that the energy resolution of the Schottky-SiC detector is more than twice that of the PIN-SiC, which may be attributed to the absence of the P+ epitaxial layer (0.2 µm) in the former, thereby reducing the energy loss of α particles.

Prior to evaluating the energy resolution of SiC detectors for fission fragments, we address the pulse height defect (PHD). To investigate the PHD effect, the relationship between the observed pulse amplitude and the true fragment energies of the light and heavy peaks (104 MeV and 79 MeV, respectively) was analyzed, as shown in Fig. 10 [Figure 10: see original paper] for unirradiated detectors. A linear energy calibration curve derived from the single α and double αs (two single αs registered by the detector at the same time) from the ^{252}Cf source is also shown with a straight line for each detector under the assumption that for α-particles with energies above several MeV, the PHD is negligible. The calculated energy for light fragment peaks are 63.4 MeV, 64 MeV, and 93 MeV, corresponding to PHD values of 39%, 38%, and 11% for PIN-SiC, Schottky-SiC, and Si detectors, respectively. For heavy fragments, the corresponding PHD values are 48%, 47%, and 15%. The relatively higher PHD observed in SiC detectors can be attributed to a combination of factors, including energy loss in the detector dead layer, increased energy loss from atomic collisions, and charge loss through electron–hole recombination caused by the high ionization density of incident heavy ions. Using LISE++ calculations [**?**], the estimated energy losses in the SiC dead layers were found to be approximately 8 MeV and 5 MeV for the light fragments (^{106}Mo at 104 MeV) in the PIN-SiC and Schottky-SiC detectors, respectively, and 7.5 MeV and 4.7 MeV for the heavy fragments (^{144}Ba at 79 MeV). These values indicate that 20% of the PHD arises from energy loss in the dead layer, with the remaining contribution originating from collision and recombination effects within the active region. The magnitude of the PHD directly influences the achievable mass resolution in time-of-flight energy measurements of ^{252}Cf fission fragments, where a resolution of approximately 3 4 u is typically desired. Therefore, minimizing the detector dead layer and improving charge-collection efficiency are crucial steps toward enhancing the overall accuracy of fission-fragment mass determination using SiC detectors.

Figure 11 [Figure 11: see original paper] shows the fission fragment peak positions as a function of irradiation dose for light and heavy fragments for PIN-SiC, Schottky-SiC, and Si detectors, respectively. The corresponding variations in the fission fragment energy spectra with irradiation dose are shown in Fig. 11(d)-(f). To quantify the relationship between the irradiation dose and the observed peak positions, the data were fitted with an exponential function of the form:

$$A(f) = a_{H,L} e^{-\lambda_{H,L} f} + b_{H,L}$$

where A(f) is the amplitude of the peak position at flux f, and the parameters a_{H,L}, λ*{H,L}, b*{H,L} are constants for heavy (H) and light (L) fragments for a specific detector. As shown in Fig. 11(a)-(c), the exponential model reproduces the experimental data very well, indicating that the degradation of signal amplitude with increasing fluence follows a simple exponential law. The extracted decay constants (λ_{H,L}), summarized in Table 1 , quantify the rate of attenuation for each detector. The extracted values reveal that the Si detector displays the most rapid attenuation, followed by the Schottky-SiC detector, with the PIN-SiC detector showing the slowest attenuation rate. The slower attenuation rate of the PIN-SiC detector demonstrates its superior radiation resistance and enhanced defect tolerance under high-dose conditions.

The results shown in Fig. 11 indicate that, with increasing irradiation fluence, the detector degradation manifested primarily in two ways: (1) a gradual shift of the fission fragment energy peaks toward lower channels, and (2) a progressive reduction in the peak separation between the light and heavy fission fragments. Specifically, the silicon detector after an irradiation dose of 2.88×10^{9} cm^{-2} undergoes severe peak shifts and significant resolution degradation, with the heavy and light fragment peaks falling to only 29% and 32% of their pre-irradiation values, respectively. In comparison, the Schottky-SiC detector with a dose of 8.8 × 10^9 cm^{-2} exhibits far greater stability, with heavy and light fragment peaks decreasing to 70% and 76% of their initial magnitudes, respectively, indicating a much smaller reduction in peak separation. Although the distance between the two fragment peaks decreased, the extent of this reduction was significantly less severe than in the silicon detector. The PIN-SiC detector, subjected to the highest fluence of 1.8 × 10^{10} cm^{-2}, maintained the best performance, with the heavy and light fragment peaks decreasing to 68% and 74% of their pre-irradiation magnitudes. These results support previous findings that SiC detectors can remain fully operational at α-particle fluences up to 1.03 × 10^{10} cm^{-2} while retaining excellent resolution [**?**], a capability unmatched by silicon or other common semiconductor detectors.

Table 1 presents the exponential parameters obtained by fitting the changes in the peak positions of light and heavy nuclei with irradiation dose using Eq. 3. To enable a consistent comparison, the reduction in light and heavy fragment peak amplitudes was also evaluated for all detectors at an identical dose of 2 × 10^9 cm^{-2}. The obtained values are 61% and 63% for Si, 10% and 15% for Schottky-SiC, and 5% and 8% for PIN-SiC detectors, respectively. The results demonstrate that the PIN-SiC detector possesses the highest radiation resistance among the tested devices. Such resilience makes PIN-type SiC detectors particularly well-suited for prolonged operation in intense radiation fields and for experiments involving sustained heavy-ion exposure.

VI. Summary and Conclusion

In summary, the performance of silicon carbide (SiC) detectors with active layer thicknesses of 30 µm, 80 µm, and 150 µm has been systematically investigated to assess their suitability for fast-timing, energy, and fission fragment detection. The SiC detectors exhibited excellent α-particle energy resolution (at 5.4 MeV), measured as 0.90% for the 30 µm detector at -300 V, 1.12% for the 80 µm detector at -350 V, and 0.88% for the 150 µm detector at -300 V bias. Timing measurements with a ^{252}Cf source yielded full width at half maximum (FWHM) values of 321.9 ps, 248.9 ps, and 194.2 ps for the 30 µm, 80 µm, and 150 µm SiC detectors, respectively. After correcting for kinematic broadening using Monte Carlo simulations, the intrinsic timing resolutions were determined to be 284.0 ps, 199.9 ps, and 132.1 ps, corresponding to fission fragment mass resolutions of 3.2%, 2.8%, and 2.5%. These results indicate that the SiC detectors comfortably achieve the target mass resolution of 3 4 u required for the HALIMA array, confirming their strong potential for fast-timing applications.

The pulse height defect (PHD) for fission fragments in SiC detectors was found to be larger than in silicon, with values of about 39–48% compared to 11-15% for Si. This behavior arises from shorter carrier lifetimes and enhanced recombination losses in SiC, with roughly 20% of the total PHD attributable to energy loss in the detector dead layer. Optimizing device design to minimize the dead layer and improve charge collection can further enhance energy linearity and mass determination accuracy.

Radiation-hardness tests under prolonged ^{252}Cf α-particle and fission-fragment exposure revealed that the SiC detectors retained excellent structural and electronic stability. The α-particle energy resolution degraded only slightly with increasing fluence, whereas the fission-fragment peaks gradually shifted to lower pulse heights, consistent with charge trapping and defect-induced carrier loss. The reduction in signal amplitude followed a clear exponential dependence on fluence, confirming that degradation is governed by cumulative defect generation and the associated reduction in carrier lifetime. As shown in Fig. 11(a–c), the exponential function accurately describes the evolution of both light and heavy fragment peak positions with irradiation dose. The extracted decay constants (λ_{H,L}) indicate that PIN-type SiC detectors exhibit the slowest attenuation, followed by Schottky-SiC and Si detectors, demonstrating the superior radiation tolerance of the PIN configuration even beyond fluences of 10^{10} cm^{-2}. This slower attenuation rate directly reflects enhanced defect resistance and stable charge-collection behavior under high-dose conditions.

In conclusion, the SiC detectors evaluated in the present work exhibit an exceptional combination of high energy resolution (1%), fast timing response (132–284 ps intrinsic), and excellent radiation hardness, along with predictable PHD behavior compatible with precise fission-fragment measurements. These characteristics establish SiC detectors as robust candidates for long-term charged-particle and heavy-ion detection. In practice, the 30 µm PIN-type SiC detector has been successfully integrated into a fast-timing hybrid detection array (HALIMA) comprising high-purity germanium, lanthanum bromide, solar-cell, and additional SiC detectors. The array is currently employed for experimental investigations of nuclear state lifetimes in the picosecond-to-nanosecond range in neutron-rich nuclei, demonstrating both the practical applicability and versatility of SiC detectors in advanced nuclear physics research.

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Note: Figure translations are in progress. See original paper for figures.