Recent updates in the VERDI fission-fragment spectrometer

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Abstract. The VElocity foR Direct particle Identification (VERDI) is a spectrometer designed to determine fission-fragment mass distributions using the 2E-2v method, which measures both velocities and energies of the fission fragments. VERDI has two time-of-flight (TOF) sections, each with a Micro Channel Plate (MCP) Time-of-flight Start detector and up to 32 passivated implanted planar silicon (PIPS) detectors. Achieving the desired mass resolution is challenged by the need for high TOF and energy resolutions. Recent upgrades to the VERDI setup have improved its performance, achieving a TOF resolution as low as 355 ps (FWHM) and an energy resolution of 22 keV (FWHM) for α-particles. These enhancements in resolution demonstrate improved capabilities for achieving high-precision fission fragment yield measurements.

1 Introduction

Nuclear fission is a process where an atomic nucleus splits into two fragments with different masses and energies. The emitted fission fragments (FFs) are highly excited and quickly evaporate neutrons after formation. Precise measurements of FF mass yields, both before and after neutron emission, are important for nuclear technology applications, such as developing Generation IV nuclear reactors, and for validating theoretical models of nuclear fission. Additionally, fission observables like the average neutron multiplicity ($\bar{\nu}(A)$), estimated from pre- and post-neutron fission yield distributions, offer valuable data that complement other detection techniques and facilitate independent studies of excitation-energy sharing in nuclear fission.

The VElocity foR Direct particle Identification (VERDI) spectrometer is designed to precisely measure the mass and energy distributions of fission fragments. VERDI aims for a high mass A resolving power of $A/\Delta A$ of approximately 130, however, initial studies reached a resolution larger than 80, allowing studies of prompt neutron correlations with fission-fragment characteristics [1].

VERDI makes use of the double-energy double-velocity (2E-2v) method. Coincident measurements of two kinetic energies and velocities by means of the time-of-flight technique (TOF) of back-to-back ejected fission fragments are used to determine mass yields before and after neutron emission using non-relativistic kinematics. Assuming approximately equal pre- and post-neutron emission velocities $v_{pre} \approx v_{post}$, enables the measurement of $A_{1,2_{\rm pre}}$. Post- and pre-neutron emission mass distributions are given by:

$$A_{1,2_{\rm post}} = \frac{2E_{1,2_{\rm post}}}{(v_{1,2_{\rm post}})^2} \; ; \; A_{1,2_{\rm pre}} \approx A_{\rm Total} \frac{v_{2,1_{\rm post}}}{v_{1\,{\rm post}} + v_{2\,{\rm post}}}. \quad (1)$$

VERDI uses Passivated Implanted Planar Silicon (PIPS) detectors for energy and stop TOF detection. The mass resolving power is significantly affected by two effects in PIPS detectors: the Plasma Delay Time effect (PDT) that alters TOF distributions and the Pulse Height Defect (PHD) deforming energy distributions. If uncorrected, the PDT can lead to an inaccurate mass distribution measurement and yield flawed correlations with other fission observables, thereby increasing systematic uncertainties. Since the resolution of the TOF and energy distributions are also inherently related to the mass-resolving power of VERDI, the experimental setup needs to be optimized with respect to both characteristics.

In this contribution, we report the latest achievements in energy and TOF resolution following recent upgrades to the instrument compared to Ref. [1], including the results of an experimental campaign to measure the PDT and PHD effects in the PIPS detectors used in VERDI.

2 Experiment

Figure 1 shows a schematic view of VERDI. Each arm has a Micro Channel Plate (MCP) detector, which generates the start TOF signal via secondary electrons. In the two-arm version, the source backing acts as an electron emitter. In the current single-arm setup, electrons are generated using an emissive polyimide (PI) foil (with an areal density of 39.8 μg/cm^2) mounted above the FFs source.

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Electrons are deflected by a 45-degree electrostatic mirror onto a RoentDek DLD40 MCP detector, with signals decoupled by an FT12TP(hex) plug.

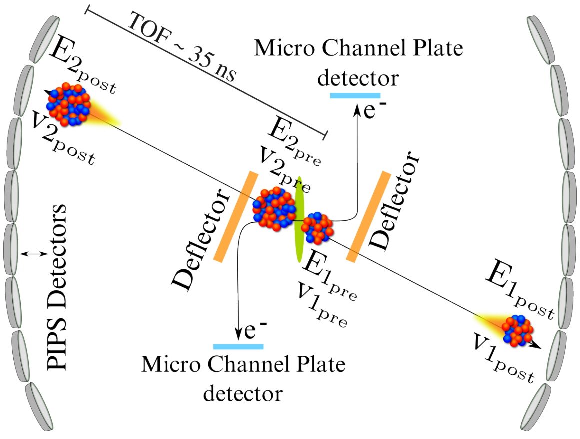

Figure 1. Schematic view of the VERDI-chamber, which holds an experimental array that measures fission observables by means of the double-energy double-velocity technique. The flight-path distance, between the target and the PIPS detectors, is approximately 50 cm.

VERDI uses Canberra PIPS detectors (TMDP450-20N TD-300AM) operated at 140 V bias. These detectors are connected on a flange with silver SMA feedthroughs, which avoid the previous arrangement of detectors on a frame and cable to connect to the exterior. This significantly reduces the noise level on the signals and allows up to 32 detectors for improved geometrical efficiency. For calibration, a ^{239}Pu-^{241}Am-^{244}Cm alpha source was used, while a ^{248}Cm(sf) source produced using the drop-on-demand printing technique [2] was used for fission-fragment experiments. The PIPS detectors were tested with both MPRT-16 and MSI-8 Mesytec charge-sensitive preamplifiers. MCP signals were preamplified using RoentDek FAMP1+ for timing and ORTEC VT120 for position-sensitive signals. The acquisition system used ADQ-36 SP digitizers (up to 5.0 GHz sampling frequency) with an independent triggering on PIPS channels and slave triggering for MCP signals and coupled to the ABCD DAQ framework.

3 Challenges in the VERDI instrument

Achieving the aimed mass resolution with VERDI presents three main challenges. First, assuming unchanged fragment velocity after neutron emission is problematic because neutron recoil alters fragment velocity on an event-by-event basis, leading to mass broadening and blurring fine structures of the mass distribution [3]. An iterative mass correction procedure has been proposed to address this issue [4].

The second challenge involves the complex energy and time calibrations required for PIPS detectors when detecting heavy ions. The interaction of heavy ions with the detector material creates a plasma, leading to a reduction in signal amplitude (Pulse Height Defect, PHD) and distortion of the signal's rise time (Plasma Delay Time, PDT). These effects degrade VERDI's mass resolving power, distort mass distributions, and produce inaccurate peak-to-valley ratios if not corrected. To address this issue, the PDT and PHD were fully characterized for the type of PIPS detectors used in VERDI in a dedicated experimental campaign [5], covering energies from 21 to 110 MeV and masses from 80 to 149 u. A new PDT parametrization was inferred from the data and is being used to reconstruct the post-neutron mass distribution in the current ^{248}Cm(sf) experimental campaign.

The third challenge concerns the need to improve energy and TOF resolutions to achieve the targeted VERDI mass resolution:

$$\frac{\Delta A}{A} = \sqrt{\left(\frac{\Delta E}{E}\right)^2 + 4\left(\frac{\Delta TOF}{TOF}\right)^2 + 4\left(\frac{\Delta d}{d}\right)^2}, \qquad (2)$$

where ΔE and ΔTOF are the energy and TOF resolutions, and Δd is the uncertainty in the flight path distance. For a pre-neutron mass resolution of $\Delta A_{pre} = 1.2$ u (FWHM) and a post-neutron mass of $\Delta A_{post} = 3.2$ u (FWHM), a pulse-height resolution of 0.3% and a TOF resolution of 200 ps are required [1]. To achieve these targets, several upgrades have been implemented in the VERDI system, including new flanges with optimized detector connections to improve signal noise-to-peak ratio, upgraded electronics with preamplifiers optimized for FF measurements, time-optimized PIPS detectors, a new MCP detector with position-sensitive capabilities, and a fully digital acquisition system with enhanced sampling frequency.

4 Results and Discussion

Earlier configurations of VERDI employed a diamond detector for stop signals and an MCP for start signals, achieving a TOF resolution of about 400 ps (FWHM) for 5.5 MeV α-particles [1]. In the same study, simulations of ^{252}Cf(sf) FF data showed that a detector with a TOF resolution of 400 ps reproduced the experimental FFs TOF distribution. With the present PIPS/MCP setup, we achieved a TOF resolution of 355 ps (FWHM) for 5.5 MeV α's (Fig. 2), along with an energy resolution of 22 keV (FWHM).

In the present ^{248}Cm(sf) campaign, we introduced new preamplifiers at a FF-optimized gain. This yielded a TOF resolution of about 900 ps (FWHM) and an energy resolution of 80 keV (FWHM) for α's. Although increasing the gain tends to degrade α-resolution due to an increased noise-to-signal ratio on the attenuated α-signals, closely spaced α-peaks remained well separated (Fig. 3). During the PDT experimental campaign [5, 6] with a similar PIPS/MCP arrangement, TOF resolutions of approximately 900 ps (FWHM) were also observed for 4.75 MeV α-particles, while FFs of 90 u and 99 MeV achieved a TOF resolution of 200 ps (FWHM). With upgraded detectors, electronics, and data-acquisition systems in VERDI, the ^{248}Cm(sf) measurements now exhibit an improved FF TOF distribution compared with Ref. [1] (see Fig. 4). The more pronounced separation of the FF peaks underscores the superior overall TOF resolution achieved in this new configuration.

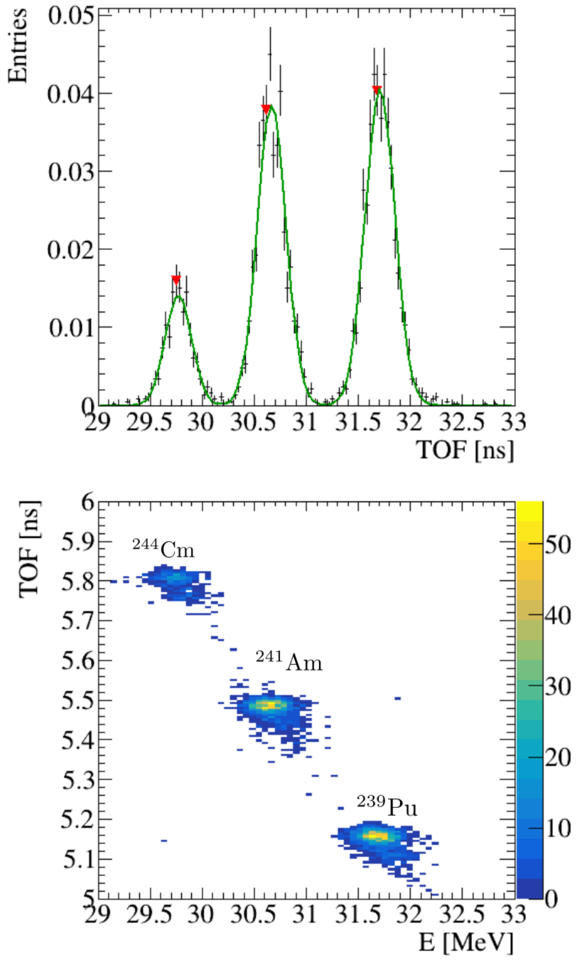

Figure 2. Energy vs Time-of-flight spectrum of α-particles from a ^{239}Pu-^{241}Am-^{244}Cm calibration source.

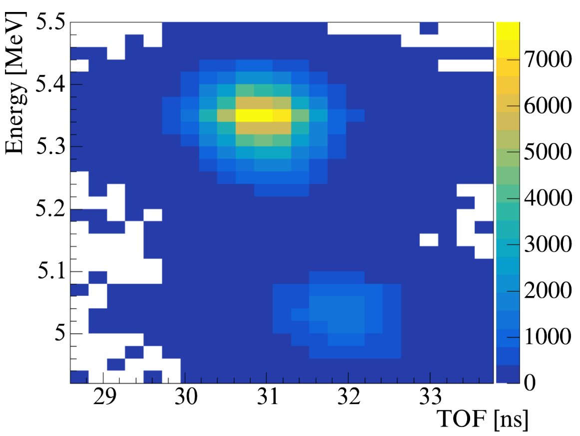

Figure 3. Energy versus TOF spectrum for α's from ^{248}Cm measured with VERDI.

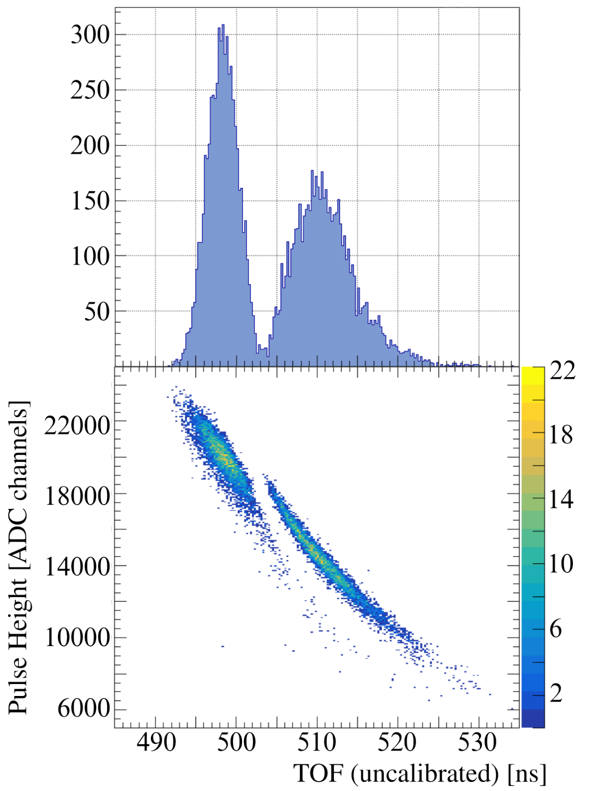

Figure 4. Pulse-height versus TOF (uncalibrated) and projection in TOF axis, for fission fragments from ^{248}Cm measured with VERDI.

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