Development of position-sensitive time-of-flight spectrometer for fission fragment research

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Abstract

A position-sensitive, high-resolution time-of-flight detector for fission fragments has been developed. The SPectrometer for Ion DEtermination in fission Research (SPIDER) is a $2E - 2v$ spectrometer designed to measure the mass of light fission fragments to a single mass unit. The time pick-off detector pairs to be used in SPIDER have been tested with α -particles from ^{229}Th and its decay chain and α -particles and spontaneous fission fragments from ^{252}Cf . Each detector module is comprised of a thin electron conversion foil, electrostatic mirror, microchannel plates, and delay-line anodes. Particle trajectories on the order of 700 mm are determined accurately to within 0.7 mm. Flight times were measured with 250 ps resolution FWHM. Computed particle velocities are accurate to within 0.06 mm/ns corresponding to precision of 0.5%. An ionization chamber capable of 400 keV energy resolution coupled with the velocity measurements described here will pave the way for modestly efficient measurements of light fission fragments with unit mass resolution.

Keywords: Spectrometers, fission, fission product yields, TOF, $2E - 2v$

1. Introduction

Mass spectrometers for fission fragment studies have been used for decades. Some common techniques for fission fragment spectrometers include electromagnetic separation (A/q) [1], measuring the energies of coincident fragments ($2E$)

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[2], measuring the velocities of coincident fragments ($2v$), measuring both the energy and velocity of a single fragment ($E - v$) or measuring the energies and velocities of coincident fragments ($2E - 2v$). In addition to the goal of achieving good mass resolution, previous spectrometer designs are based on user needs like compactness and low-weight [3–5], or coincident fragment determination [6, 7]. Often, design choices force the user to choose between large solid angle coverage and excellent mass resolution. The SPectrometer for Ion DEtermination in fission Research (SPIDER) is designed to be a $2E - 2v$ spectrometer that combines excellent mass resolution (1 amu) and modestly large solid angle coverage. We present here the results of tests designed to calibrate the detectors which measure particle velocities for SPIDER. SPIDER infers the masses of a pair of fission fragments by measuring their velocities (v) and kinetic energies (E_k). Particle velocity is determined by combining measurements of a particle’s path length and time-of-flight (TOF). When also combined with E_k measurements, the non-relativistic mass of the particle is uniquely defined as

$$m = 2 \frac{E_k}{v^2}. \quad (1)$$

To achieve the requisite precision of a single mass unit ($\delta m \leq 1$ amu) the resolution requirements for path length, TOF and E_k are straightforwardly constrained by

$$\frac{\delta m}{m} = \sqrt{\left(\frac{\delta E}{E}\right)^2 + \left(2\frac{\delta t}{t}\right)^2 + \left(2\frac{\delta r}{r}\right)^2}. \quad (2)$$

With an achievable energy resolution of 400 keV for 100-MeV fragments [4], path length accuracy of 0.7 mm over 700 mm, and TOF resolution of 250 ps (FWHM) for 50-ns transit times, SPIDER will meet the demands for unit mass resolution for light fission fragments.

Two standard sources, ^{229}Th and its decay chain, and ^{252}Cf , were used to determine TOF and path length resolution of the present system. The α -particles from ^{229}Th and its decay chain yield six well resolved α -particle energies. The α -particles and spontaneous fission fragments from ^{252}Cf test our system with heavy ions in addition to α -particles of known energy.

Figure 1: (Color Online) Schematic configuration of source and detector placement for TOF measurements in SPIDER. The aperture restricts the trajectories (blue band) of the α -particles which can be detected in the second detector. The aperture is removed for normal operation.

58 This manuscript will give detailed descriptions of the detector components
 59 and their performance in section 2 followed by a discussion of the experiments
 60 performed and the data collected in section 3. Section 4 describes simulations
 61 of the experimental setup and how they compare with the data. Finally, results
 62 and implications are discussed in section 5.

63 2. Detector Description

64 The TOF spectrometer consists of an evacuated chamber with two time
 65 pick-off detectors separated by 50 - 70 cm. An α -particle or a spontaneous
 66 fission source was placed close to one of the time pick-off detectors. The source
 67 and the detectors were arranged such that emitted particles can pass through
 68 both detectors. The detectors were mounted to platforms that were attached to
 69 rails welded into the base of the chamber, allowing for changes to the distance
 70 between the detectors as desired. A schematic drawing of the setup is given in
 71 Fig. 1.

72 The time pick-off detectors (see Fig. 2) are assemblies of electron conversion
 73 foils, electrostatic mirrors, microchannel plates (MCPs) and delay line anodes
 74 (DLAs). Both assemblies are kept under vacuum ($\leq 10^{-6}$ Torr) during operation.
 75 Herein we give details on the characteristics of each component and their
 76 purpose in the assembly.

77 2.1. Conversion Foils

78 As charged particles pass through a thin solid material they liberate elec-
79 trons. The typical energy of these secondary electrons (SE) is a few eV [8].
80 These SE can be accelerated under high voltage differences, and collected to
81 give information about the location and the time that the SE were created.
82 Carbon foils with thicknesses ranging from 20 to 100 $\mu\text{g}/\text{cm}^2$ and Mylar foils
83 with evaporated gold layers were tested in the present setup with considerations
84 made regarding straggling, efficiency and fragility. To minimize the effects of
85 straggling, thin foils are ideal. However, thinner foils are more prone to fail
86 structurally. Mylar is stronger than carbon and the high Z of gold increases
87 MCP signal size and thus detection efficiency. However, the Mylar and gold foils
88 induce too much straggling when considerations for future E_k measurements are
89 made. Thus, carbon foils of approximately $20\mu\text{g}/\text{cm}^2$ were determined to be op-
90 timal for fission fragment measurements.

91 2.2. Electrostatic Mirror

92 Electrostatic mirrors are designed to be mostly transparent to heavy ions
93 while reflecting SE onto a device like a microchannel plate. The first element in
94 our electrostatic mirror, the conversion foil, is mounted parallel to a wire frame
95 1 cm away. The wire frames are constructed with 0.02-mm thick gold-plated
96 tungsten wires spaced 1 mm apart. Each frame nominally has a geometrical
97 transparency of 98%. High negative voltage (-2000 to -3000 V) is applied to
98 the foil while the wire frame is grounded to create a potential difference that
99 accelerates SE. After accelerating, the SE ideally drift through a field-free region
100 to the mirror grids which are two wire frames (identical wire type and spacing)
101 spaced 1 cm apart, and mounted at 45 degrees with respect to the conversion foil
102 and first wire frame. The first mirror frame is grounded and the second mirror
103 frame is at high negative voltage (-2000 to -3000 V). The wires on one mirror
104 frame are orthogonal to the wires on the other mirror frame. The frame with
105 its wires stretched in the long (vertical) dimension has the same transparency
106 as the first accelerating frame (98%). The frame with wires stretched along the

Figure 2: (Color Online) (a) Exploded view of a time pick-off detector. (b) Two complete time pick-off detectors constructed for the present tests.

107 short (horizontal) dimension has lower transparency (97%) corresponding to a
 108 factor of $\sqrt{2}$ reduction in the space between wires that results from the angle
 109 of the grid. Figure 2 shows an exploded drawing of our time pick-off detector
 110 as well as a photo of the completed version. A typical time from creation of SE
 111 to collection in the MCP is about 3 ns. This SE transit time should be nearly
 112 identical for the *start* and *stop* detectors. Averaged differences in the transit
 113 time from two different electrostatic mirrors represent a determinable systematic
 114 factor in the TOF measurements that does not affect precision. However, small
 115 variations in this transit time are a source of uncertainty in the measurement
 116 of TOF.

117 2.3. MCPs and DLAs

118 The MCPs are electron multipliers. Two impedance-matched MCPs are
 119 arranged in a “Chevron configuration” (see Fig. 3) for optimum performance,

Figure 3: (Color Online)(a) MCPs used in the present setup are 75 mm in diameter with 12 μm channel diameter. Two plates are stacked in a “Chevron configuration” for optimal performance. (b) Inverted MCP signal (blue) has a rise time of approximately 2 ns (blue band). An accompanying DLA signal (red) has a rise time of approximately 8 ns (red band).

and stacked between two insulating ceramic rings that have been metalized in chosen locations for the purpose of applying the desired voltage. The SE strike the top of the MCP which is grounded relative to the high positive potential applied to the base (2200 to 2500 V). The signal produced by the MCP is fast having typical rise times of 2 ns and full width of 10 ns (see Fig. 3). This signal is used as a time stamp for charged particles passing through the conversion foils. The highly multiplied electrons are ejected onto the DLA where they are collected to reconstruct the position of the interactions between the fission fragment and the conversion foil. Typical DLA signals have 8 - 10 ns rise times and 25 ns full widths. The DLA consists of two orthogonal dual-wire wrappings for x and y position determination. The constituents of the wire pairs are labeled *signal* and *reference* by convention and are completely isolated from each other when working properly. Wire pairs had a spacing of approximately 1 per mm. The DLA floated at high positive voltage (2300 to 2600 V) employing a splitter with a +36 V battery on one side of the split to keep the *signal* and *reference* wires of the DLA at a small voltage difference. The collected electrons propagate away from the spot where they struck the DLA in both directions producing two signals for each dimension (e.g., x_1 and x_2). By taking the time difference of the signals (e.g., Δx and Δy), a two dimensional projection of the x and y position of the fission fragment can be interpreted.

140 2.4. Detection Efficiency

141 The efficiency of our time pick-off detectors will depend on several factors
142 including the number of SE created, the energy of the electrons striking the
143 MCP, the angle of incidence of electrons on the MCP, etc. Maximum detection
144 efficiency for a single electron is approximately 85%. Each α -particle or fission
145 fragment will produce multiple SE with the SE yield depending the velocity
146 and Z of the particle [9]. Tests of the detection efficiency of similar time pick-
147 off detectors conducted at the University of New Mexico determined that this
148 kind of time pick-off detector will be approximately 100% (70%) efficient for
149 detecting fission fragments (α -particles) [10].

150 2.5. Signal Processing and Data Acquisition

151 In order to achieve the target temporal resolution, the hardware needs to be
152 optimized for fast timing signals. Thus, the data acquisition system must be
153 designed to measure time differences on the order of 10s to 100s of picoseconds.
154 The preamplifiers, discriminators and data acquisition system that we used were
155 chosen to be optimized for the fast timing requirements.

156 The five signals (one fast timing signal and four position signals) from each
157 timing detector are amplified using ORTEC VT120C preamplifiers [11] devel-
158 oped for signals with fast rise times (e.g., microchannel plate signals). The
159 signals from the detectors have rise times of approximately 2 ns; the amplifier
160 has an intrinsic rise time of <1 ns. The amplified signals are then sent through
161 a Phillips Scientific 715 constant fraction discriminator (CFD) with 1 ns (5 ns)
162 delay for timing (position) signals. These CFDs are specified by the manu-
163 facturer to exhibit very small (± 75 ps) time walk. A comparison of the time
164 walk of several different discriminators for MCP signals made by Kosev in 2007
165 showed that among several CFDs, the Phillips Scientific CFD module had the
166 best performance [12].

167 A VME-based data acquisition from CAEN S.p.A [13] is used for the digiti-
168 zation of signals. The NIM signals from the discriminators are sent to a time-
169 to-digital converter (TDC) CAEN model V1290N. Ten of 16 available channels

Figure 4: (Color Online) (a) Simulated α -particle energy spectrum for ^{229}Th and its decay chain given realistic branching ratios. (b) TOF spectrum for ^{229}Th and its decay chain. Simulation (red line) of 250 ps timing resolution reproduces the data (black dots). Details of the simulation are discussed in section 4 (c) Decay scheme for ^{229}Th and its decay chain. Solid red arrows indicate alpha decay. Dotted blue arrows indicate beta decay.

were used to accommodate the signals from two timing detectors. The fast timing signal from the *stop* detector is used as the external trigger of the TDC. The timing of other signals is analyzed relative to the *stop* detector timing signal on an event-by-event basis. The TDC stored the time differences with 25 ps least significant bit, and has a resolution of 35 ps. The TDC is read out by a crate controller to a PC over an optical connection. The data is monitored and stored to disc using the MIDAS [14] software package.

3. Detector Performance

Given the fixed distance between the *start* and *stop* time pick-off detectors, the timing of the fission fragments is generally predictable. A fragment with 1 MeV per nucleon will spend approximately 50 ns traveling 70 cm. To achieve 0.5% timing precision, the TOF measurement requires a precision of 250 ps. Well known α -particle energies from ^{229}Th and its decay chain and ^{252}Cf were used as a standard to determine the timing and position properties of these detectors.

185 The source was mounted a few cm from the first conversion foil. The α -
 186 particles with suitable trajectories pass through the time pick-off detector, tra-
 187 verse the length of the chamber, and pass through the second time pick-off
 188 detector. The second time pick-off detector is a mirror image of the first time
 189 pick-off detector (see Fig. 1). Thus, the α -particle encounters the mirror grids
 190 of the second mirror before traversing the second carbon foil. SPIDER uses
 191 forward-biased SE from the first foil, and backward-biased SE from the second
 192 foil. This has been shown to have high efficiency by Kosev [12] and maximizes
 193 the TOF distance because of the orientation of the time pick-off detector mod-
 194 ules.

195 3.1. Timing Resolution

196 The α -particles from ^{229}Th and its decay chain are ideal for testing the
 197 timing of the present system because the source has six fairly well separated
 198 energy groups (4.8, 5.8, 6.1, 6.3, 7.05, and 8.4 MeV) which result from five
 199 strong alpha emitters (^{229}Th , ^{225}Ac , ^{221}Fr , ^{217}At , and ^{213}Po respectively). The
 200 decay daughter ^{213}Bi is a weak alpha emitter which hardly contributes (see
 201 Fig. 4). The first timing tests using ^{229}Th and its decay chain were performed
 202 using small carbon foils suspended across rings with a 1-2 cm diameter aperture.
 203 A 9.9 mm diameter collimator was placed near the center of the TOF chamber in
 204 order to restrict acceptance only to flight paths which were nearly centered (See
 205 Fig. 1). This restriction makes the TOF spectrum indicative of the attainable
 206 timing precision without requiring position information. Subsequent tests were
 207 performed with larger area foils (rectangular 50 mm $\times$ 75 mm; 22 $\mu\text{g}/\text{cm}^2$) and
 208 with the collimator removed. Data taken in this manner were corrected using
 209 position data (See Sect. 3.1.1). Time-dependent corrections to systematic drifts
 210 in the detector response also provided improvement to TOF reconstruction.
 211 The best timing resolution was achieved when position-dependent and time-
 212 dependent corrections were applied in the data analysis. Figure 4 shows the
 213 results of corrected TOF data compared with simulations.

214 Californium-252 is an excellent source for testing the timing of our time pick-

Figure 5: (Color Online) TOF spectrum for spontaneous fission fragments from ^{252}Cf for time pick-off detectors separated by 700.0 mm. The fast (blue) and slow (red) fission fragments have almost no overlap under these conditions and the number of integrated counts in each region are in agreement to within $< 1\%$. The enhanced background at 40 ns is caused by the strong 6.217 MeV α -particle from ^{252}Cf . Most α -particle events were below threshold.

off detectors because it emits α -particles and spontaneous fission fragments. ^{252}Cf emulates the experimental conditions to which we will ultimately subject our detectors. Tests with ^{252}Cf were performed using conversion foils that were rectangular ($8.7\text{ cm} \times 6.7\text{ cm}$) Mylar foils with a thin evaporated gold layer. Fig. 5 shows two very well separated regions corresponding to the light and heavy fission fragments from ^{252}Cf . Signals from α -particles were below the threshold settings in the spectrum shown in Fig. 5. The integral of the light fission fragment peak and the heavy fission fragment peak are identical to within 1% indicating that the efficiency for detecting light and heavy fragments is essentially identical.

3.1.1. Spatial Resolution

Given the spacing of the wires on the DLAs, 1 mm spatial resolution or better should be possible. The precision of the optics in our electrostatic mirror impose limits on the resolution of the image projected onto the MCPs. Understanding the position resolution of our system is important because we will reconstruct event-type data. Though these corrections are small, they improve the overall precision of the velocity measurement.

A mask was constructed from 1 mm thick aluminum with 1 mm diameter

Figure 6: (Color Online) The image produced when using a mask of 1 mm diameter holes arranged in a 1 cm $\times$ 1 cm matrix. A projection of a representative row and column indicated position resolution of approximately 2 mm FWHM. To remove signals resulting from dark current and show the mask image more clearly the 2D histogram is shown with a 10 count/bin threshold. Corrections to warping of the image near the edges of the MCP have not yet been made.

233 holes arranged in a 1 $\times$ 1 cm matrix (see Fig. 6). We placed the mask between
 234 the source and the first foil as close to the foil as possible. The mask tests
 235 revealed that the present system can resolve the location that a charged particle
 236 traversed the foil to within 2 mm. For two conversion foils separated by 700.0
 237 $\pm$ 0.5 mm, the uncertainty of the $x - y$ spatial position introduces less than 0.2
 238 mm of additional uncertainty to the path length for an overall uncertainty of $\leq$
 239 0.1%.

240 4. Simulations

241 In an effort to understand better some of the individual contributions to
 242 the uncertainty in fragment velocity measurements, we drafted a simple simu-
 243 lation of the α -particles from ^{229}Th and its decay chain using ROOT [15] and
 244 {SRIM} [16] software. The program simulates energy losses that result from
 245 straggling during the epoch of an α -particle that goes through both detectors.
 246 In addition to the energy losses and broadening that result from straggling, a
 247 user-defined broadening term is incorporated to adjust for the remaining sources

248 of broadening (e.g., spread in secondary electron transit times, analog hardware,
 249 digitization). Straggling out of the source material reduces and broadens the
 250 α -particle energy initially, but has no real effect on the precision of the TOF
 251 measurement. The straggling in the first conversion foil will reduce the energy
 252 of the α -particle and broaden the attainable timing precision. The second foil
 253 will have the same affect on the α -particle, however, only the energy broadening
 254 will affect the TOF measurement.

255 The {SRIM} (Stopping Range of Ions in Matter) software simulates the en-
 256 ergy losses of ions traveling in and through matter. A series of {SRIM} simula-
 257 tions were run for α -particles of energies ranging from 4.5 to 8.5 MeV through
 258 carbon foils of thicknesses ranging from 20 to 100 $\mu\text{g}/\text{cm}^2$. The data sought
 259 from these simulations were the average energy loss and the width of the dis-
 260 tribution of the energy loss of the α -particles. Histograms of energy losses for
 261 10000 α -particles were fit with Gaussian functions. The mean and sigma of the
 262 Gaussian fit are measures of the average energy loss and energy spread for α -
 263 particles. Compilations of the parameters obtained from these simulations over
 264 the ranges mentioned above were fit, often with a simple linear function. Under
 265 the assumption of a good fit to the simulations, the average energy loss and
 266 width of the distribution can be interpolated for α -particles and foil thicknesses
 267 within the simulated ranges. A separate {SRIM} simulation of the straggling of
 268 α -particles out of the source material was generated making some assumptions
 269 about the source thickness and other properties of the source material.

270 Next, the formulas derived from {SRIM} simulations are imported into a
 271 ROOT simulation. The ROOT simulation chooses an α -particle from ^{229}Th and
 272 its decay chain and subjects it to the straggling effects listed above. That is, in
 273 the ROOT simulation a number is randomly sampled from a Gaussian function
 274 representing the correct energy loss distribution for the given α -particle energy
 275 and foil thickness. After straggling out of the target and through the first foil,
 276 the energy and velocity of the simulated α -particle is known. The distance
 277 between the two foils is an input parameter which determines the time that the
 278 α -particle spends drifting between the foils. After straggling through the second

279 foil, the time difference is recorded.

280 Figure 4 shows the comparison of a simulated α -particle TOF spectrum
281 and data. The simulation reproduces analyzed data using 250-ps resolution
282 (FWHM).

283 5. Summary and Conclusions

284 The goal of this work was to optimize and characterize the timing properties
285 of position-sensitive, time pick-off detectors to be used in SPIDER. In order to
286 measure the mass of light fission fragments to a single mass unit, the detectors
287 must exhibit timing resolution of 250 ps (FWHM) or better. The timing reso-
288 lution of the time pick-off detectors presented here was verified to be at least
289 250 ps (FWHM) using α -particles from ^{229}Th and its decay chain. Optimal
290 timing measurements were realized when (1) the distance between time pick-off
291 detectors was maximized (70 cm in the present arrangement), (2) carbon foils of
292 $20\text{ }\mu\text{g}/\text{cm}^2$ thickness were used and (3) time-dependent and position-dependent
293 corrections were applied in the data analysis. With 250 ps (FWHM) timing
294 resolution for fission fragments, coupled with E_k measurements with 400 keV
295 energy resolution, SPIDER will successfully resolve light fission fragment masses
296 to 1 mass unit.

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