The SPIDER fission fragment spectrometer for fission product yield measurements

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Abstract

The SPectrometer for Ion DEtermination in fission Research (SPIDER) has been developed for measuring mass yield distributions of fission products from spontaneous and neutron-induced fission. The 2E-2v method of measuring the kinetic energy (E) and velocity (v) of both outgoing fission products has been utilized, with the goal of measuring the mass of the fission products with an average resolution of 1 atomic mass unit (amu). The SPIDER instrument, consisting of detector components for time-of-flight, trajectory, and energy measurements has been assembled and tested using ²²⁹Th and ²⁵²Cf radioactive decay sources. For commissioning, the fully assembled system measured fission products from spontaneous fission of ²⁵²Cf. Individual measurement resolutions were met for time-of-flight (250 ps FWHM), spacial resolution (2 mm FWHM), and energy (92 keV FWHM for 8.376 MeV). Mass yield results measured from ²⁵²Cf spontaneous fission products are reported from an E-v measurement.

Keywords: Spectrometer, fission mass yields, 2E-2v method, ²⁵²Cf.

1. Introduction and Background

Measurements of fission mass yields have been ongoing since the discovery of fission [1–4]. Methods of measurement have included radiochemical separations, mass separators, and measurements with gridded ionization chambers,

commonly referred to as the 2E method [5]. Radiochemical separations directly measure the cumulative yields of products with high accuracy but are limited to products with half lives longer than the time scale of the separation technique. Mass separators have been used successfully to measure mass yields with high resolution but are severely limited in efficiency and are typically limited to neutron energies available at reactors [6, 7]. The 2E method measures mass yields with a small, simple detector with high detection efficiency but limited in mass resolution to 3-5 amu. Presently, no technique is able to combine high resolution with high efficiency. Measurement limitations (e.g. half-life limits or only energy measurement) require assumptions to be made during analysis that leave ambiguities in final reported values and uncertainties.

The 2E-2v method for fission mass measurements was introduced by the COSI-FAN-TUTTI spectrometer in the 1980's at Institut Laue-Langevin in Grenoble, France [8–10]. This technique determines the mass of fission products by measuring the energy and time-of-flight over a measured path length of both fission products. In this paper fission products are defined as the products created by fission after prompt neutron and gamma emission but before beta-delayed neutron emission. All results shown are post prompt-neutron emission yields. By combining measurements of energy (E), time-of-flight (t), and particle trajectory/flight path length (l), the mass of the fission product can be determined from the classical formula for kinetic energy, solved for mass:

$$M = \frac{2Et^2}{l^2}$$

High mass resolution results are achievable with this method by maximizing the resolution associated with each individual measurement. The formula for the mass resolution is:

$$\frac{\delta M}{M} = \sqrt{\left(\frac{\delta E}{E}\right)^2 + 2\left(\frac{\delta t}{t}\right)^2 + 2\left(\frac{\delta l}{l}\right)^2}$$

. Measuring both fission products in coincidence effectively measures the neutron emission spectrum during analysis. This is important for converting post-

neutron emission measurements to pre-neutron emission mass distributions. The best mass resolution achieved by the COSI-FAN-TUTTI spectrometer using this method was 0.64 amu for the light fission products from ^{229}Th . Other reactions measured by this spectrometer included ^{239}Pu , $^{241}\text{Pu}(\text{n}_{th},\text{f})$ [9, 11–13]. However, the efficiency of this detector was extremely low, making measurements of fission products in the tails of the mass yield distributions a lengthy endeavour and any measurement of fissionable species with low cross sections, particularly in a survey of neutron energy dependence on yields, very difficult and time consuming. SPIDER will combine the resolving capabilities of the COSI-FAN-TUTTI spectrometer with comparably higher detection efficiencies by increasing the physical acceptance of the instrument. The need for high resolution mass yields of neutron-induced fission of actinides, in particular over a large range of incident neutron energies, has been articulated by both the theoretical modeling community and the applications community [14–16]. This paper covers the details of the detector components of the SPIDER instrument, detector testing with alpha and ^{252}Cf spontaneous fission sources to establish individual measurement resolution capabilities. Neutron-induced fission measurements are planned at the Los Alamos Neutron Science Center (LANSCE) at Los Alamos National Laboratory. Building SPIDER at LANSCE takes advantage of the expansive neutron energy range available through spallation reactions with the proton beam on two separate metal targets.. These two targets produce intense neutron beams with energies between 10^{-3} eV and several hundred MeV. [17].

2. SPIDER Instrument

The SPIDER instrument consists of opposing detector arms (currently two) each containing two timing detectors with position-sensitive readout and an energy detector, all oriented along one central trajectory. For 2E-2v measurements the arms are paired to measure binary fragment emission, one on either side of the target. The following subsections describe each detector component

Figure 1: Cartoon of E-v detection method. Each arm in SPIDER will incorporate this method. Fission products from source shown on right travel through two timing detectors (MCPs) and an energy detector (ionization chamber).

in detail.

A diagram of one arm is shown in Fig. 1. The source or target material is placed in front of the electrostatic mirror in the first timing detector setup.

2.1. Timing and position detection

The two timing detectors of each arm register when a fragment passes through. The timing detectors consists of a carbon foil for production of conversion electrons via interaction with the fission product, an electrostatic mirror for directing the conversion electrons 90° relative to the fission trajectory, a pair of microchannel plates (MCPs), and a delay line anode (DLA) for readout of the electronic signal from the MCPs. The MCPs are 75 mm in diameter and stacked a Chevron configuration. The plates amplify the signal by electron multiplication of the initial secondary electrons. The DLA has two wire pairs that provide lateral x,y position information for each event, four signals per DLA. These signals provide path length corrections for fragments traveling at angles relative to the central trajectory. This detector setup was chosen based on the fast timing characteristics of MCPs, the scalability of the MCPs to the desired diameter for the efficiency goals, and the ability to integrate position-sensitive readout which enables a detailed measurement of the particle trajectory. More detailed information about the timing and position detector components can be found in Ref. [18].

67 2.2. Energy detection

68 The energy detector for each SPIDER arm is an axial ionization chamber.
69 Axial ionization chambers are built with the electron drift direction parallel
70 to the trajectory of the ion. Figure 2(a) shows a schematic of the ionization
71 chamber for SPIDER while figure 2(b) is a picture of the internal components
72 of the ionization chamber.

73 The entrance window is constructed by the Norcada company [19] out of a
74 200 nm thick silicon nitride membrane. The membrane is laid down on a 200
75 μm thick silicon wafer. After application of the thin membrane to the wafer, a
76 13 x 13 array of 3.7 mm by 3.7 mm openings is etched into the wafer leaving
77 only the membrane to serve as the window. Figure 3(a) is a picture of one
78 of these windows. The transmission of fission fragments through the window
79 array is approximately 50% relative to the MCP solid angle acceptance. The
80 delicate structure of the silicon wafer requires an additional support structure to
81 withstand the pressure differential of 85 Torr between the vacuum chamber and
82 the ionization chamber. A stainless steel plate with a matching 13 x 13 array
83 was designed to hold the silicon wafer. A layer of Torr seal epoxy was then
84 applied to create the vacuum seal on the window. Figure 3(b) is a schematic of
85 the window-mounting components. The entrance window structure also serves
86 as the cathode plate of the ionization chamber. The electric field maintains
87 a uniform drift velocity for the ionization electrons by employing ten copper
88 guard rings 7.64 cm in diameter spaced 0.655 cm apart and connected together
89 through 1 M Ω resistors, bringing the field up to negative high voltage between
90 -2 and -4 kV on the Frisch grid. The Frisch grid is made of a copper mesh with
91 20 wires per inch (7.9 per cm), permitting 95% electron transmission. A 2.54
92 M Ω resistor creates the collection field between the Frisch grid and the anode
93 with a ratio of electric fields between the drift region and the collection region
94 of 1:2.54, similar to the design used in COSI-FAN-TUTTE [20]. The resistors
95 used in the circuit have a 0.1% uncertainty to ensure uniform electric fields are
96 generated. The full drift length between the cathode and the Frisch grid is 8.7
97 cm. The operating drift field is approximately 400 V/cm.

(a)

(b)

Figure 2: Parallel ionization chamber for measuring total kinetic energy of fission products. (a) Schematic of ionization chamber components with a check source at the top. The source holder and cathode are replaced by the entrance window during normal operation. (b) Photograph of internal structure of ionization chamber. The fragments enter from the top in this picture.

(a)

(b)

Figure 3: Silicon nitride entrance window for ionization chamber. (a) Silicon nitride membrane on silicon support wafer. (b) Exploded view of window mounting apparatus and support structure for entrance window.

98 The fill gas used is high purity isobutane at 85 Torr (11.3 kPa) for fission
99 products and 200 Torr (26.7 kPa) for alpha particles (up to approximately 7
100 MeV). The gas was continuously exchanged with an approximate flow rate of
101 14.5 sccm (0.87 l/h). The continuous flow of gas was necessary to maintain the
102 pulse height of the peaks over the course of data acquisition.

103 The readout of the ionization chamber is through the anode. The signal is
104 sent directly through an Ortec 142PC preamplifier before entering the acquisi-
105 tion electronics.

107 2.3. Acquisition Electronics

108 The electronics setup consists of CAEN V1290N time to digital converters
109 (TDCs) with a 40 MHz sampling frequency for the MCP timing signals and the
110 four delay line anode signals for lateral position from each TOF detector and a
111 CAEN VX1724 digitizer with 14-bits and 100 Msamples/s for the energy signals
112 [21, 22]. The digitizer board uses an on-board trapezoidal filter to extract pulse
113 height in real time [23]. The pulse height of the flat top of the trapezoid and
114 the zero crossing of the second time derivative are saved to disk along with the
115 timing values from the TDCs. The trigger for data collection is based on a
116 logic AND requirement between a “computer ready” signal and a timing signal
117 from the accelerator at LANSCE (labeled as ‘t0’ in far left of Fig. 4) indicating
118 the beginning of the neutron pulse. Once this requirement is met, a ‘looking-
119 time’ window is generated with a gate and delay generator and sent to both the
120 digitizer and the TDCs for data acquisition. Figure 4 diagrams the components
121 and logic requirements of the trigger scheme for one arm of SPIDER. The ‘t0’
122 accelerator timing signal is distributed to all modules in order to reconstruct
123 events on the MCPs and ionization chamber that are coincident in time. At
124 the end of the looking time window the data is read off the electronics with
125 MIDAS-based data acquisition software. [24]

Figure 4: Schematic of data acquisition with trigger setup for one arm of SPIDER.

2.4. 1-arm Set-up

Two timing detectors and one energy detector constitute an arm of SPIDER, shown schematically in Fig. 5. The main vacuum chamber is approximately 32.5 cm in diameter and 92.5 cm long, containing the target mounting structure and the timing detectors. The MCPs, electrostatic mirrors, and DLAs are mounted on rails, allowing for a precise selection of the distance between the two timing detectors. This distance defines the nominal flight path length of the fission product as well as the central trajectory. The entrance window of the energy detector is situated directly after the second timing detector, followed immediately by the active detection area of the energy detector mounted to the end of the vacuum chamber.

3. Characterization and Calibration

Radioactive sources with well-known characteristics were placed in front of each detector to test, characterize, and calibrate each detector in the SPIDER

Figure 5: Schematic of one arm setup of SPIDER. Fission product trajectory shown with dashed line moving right to left.

instrument. Two types of sources were used: a ^{229}Th alpha source and a ^{252}Cf source. The ^{229}Th and its decay chain provided 6 alpha lines with well known energies for calibration over a range of energies (for the ionization chamber) and velocities (timing detectors).

3.1. Time-of-flight and path length detectors

The high voltage settings for the MCPs and electrostatic mirrors were investigated to determine the optimal values for minimizing channel cross talk, signal noise, and maximize signal-to-noise ratios. The final value of the high voltages 2450 V, 2550 V, and 2700 V for the back, anode holder, and DLAs respectively. These values follow the manufacturer's recommendations for operation of the detectors [25]. After the noise and cross talk were reduced, the ^{229}Th was put in place and the alpha particles' time-of-flight were measured. These measurements were used to determine the timing resolution and linear response of the MCPs. A position mask with 1 mm holes spaced 1 cm apart was placed directly in front of the conversion foil in order to determine the position resolution of the DLAs. A resolution of 250 ps was found for the time-of-flight measurement. A lateral position resolution of 2 mm was also determined. More details about each of these measurements can be found in the Nuclear and Instrumental Methods in Physics Research A paper published for the timing and position detectors of SPIDER [18].

3.2. Energy detector

A similar search for optimal operating settings was performed for the ionization chamber. Based on the available drift length (8.7 cm between the cathode and Frisch grid) and the chosen fill gas (isobutane), the applied electric field was chosen to stay within the 'plateau' region of the electron drift velocity in order to have stable charge collection even amidst small voltage drifts. The circuit was first tested for discharge points with nonflammable fill gas of P10

Figure 6: Energy spectrum of alpha particles from ^{229}Th and its decay chain as measured with the ionization chamber of SPIDER. The detector was operated with 200 Torr (26.7 kPa) of isobutane gas flowing continuously and with an applied electric field of approximately 230 V/cm.

171 (90% argon and 10% methane) prior to operation with isobutane. The ^{229}Th
 172 source was also placed inside the IC directly in front of the cathode to deter-
 173 mine the energy resolution of the detector. 200 Torr (26.7 kPa) of isobutane
 174 gas was required to stop most alpha particles within the active region of the
 175 detector. These measurements also allowed for optimization of the trapezoid
 176 shaping-parameters used in the on-board pulse height analysis firmware. The
 177 major shaping-parameters adjusted were the rise time, flat top width, sampling
 178 size, digital gain, and peaking time [26]. Figure 6 shows a spectrum of alpha
 179 peaks collected after adjusting the hardware and firmware parameters. As can
 180 be seen by the wide peaks, the numerous alpha particles below approximately 7
 181 MeV were not completely resolved. Therefore these were not used in the calcu-
 182 lation of the energy resolution. The FWHM energy resolution for the stopped
 183 alpha particles is 1.1% or 92 keV for 8.376 MeV.

184 The ^{252}Cf source was also placed inside the IC. The operating pressure was

185 85 Torr (11.3 kPa) with continual gas flow. Placing the source inside the detec-
 186 tor measures the fission spectrum without needing corrections for energy loss
 187 through the entrance window. The relative peak heights and peak-to-valley ra-
 188 tios were determined to be similar to previous publications ([27] page 155); an
 189 indication that the IC detector was working properly and optimized for fission
 190 products.

191

192 4. Signal Processing and Data Analysis

193 The first mass yield measurements with SPIDER were taken with one arm
 194 of the instrument. An E-v measurement determined the mass of the measured
 195 fission products from the spontaneous fission of ^{252}Cf . A sample of ^{252}Cf , 5
 196 mm in diameter with a $50\text{ }\mu\text{g}/\text{cm}^2$ gold cover and an approximate activity of
 197 $0.73\text{ }\mu\text{Ci}$, was placed approximately 3 cm from the conversion foil of the first
 198 or *start* timing detector. The second or *stop* timing detector was placed 70.0
 199 cm downstream, measured from conversion foil to conversion foil. The IC was
 200 mounted directly after the stop timing detector with an approximately 6 cm
 201 gap between the conversion foil and the entrance window. Data were collected
 202 for all components of the one arm of SPIDER; the two timing MCPs, the two
 203 DLAs, and the IC. The following sections describe the data analysis involved
 204 and the mass yield results of the measurement.

205 Data analysis falls into two main categories: calibrations and corrections.
 206 The timing and position signals were calibrated using the previously discussed
 207 alpha measurements from ^{229}Th and its decay chain. The IC signal was cali-
 208 brated relative to previous measurements [28, 29] of the average peak energies of
 209 the ^{252}Cf energy distribution and corrected for energy loss based on TRIM cal-
 210 culations, a software package for calculating the transport of ions in matter. [30].

211

212 4.0.1. Timing and position signals

213 The raw and calibrated timing signals for ^{252}Cf are shown in Fig. 7. The
214 timing signals collected were calibrated using the ^{229}Th alpha decay chain data.
215 The known energies and masses of the alpha particles were used to calculate
216 time-of-flight values for the 70.0 cm flight path length. The range of alpha
217 particles measured enabled the calculation of gain and offset parameters. The
218 raw timing signals shown in Fig. 7(a) varied over time consistent with a shift
219 in raw peak position of the 6.118 MeV energy alpha from ^{252}Cf . This shift was
220 accounted for by a time-dependent offset value in the calibration, resulting in
221 figure 7(b).

222 Eight position signals were collected in addition to the timing spectrum -
223 four from each DLA. This placed a small limitation to data analysis as every
224 event did not contain all 8 signals. Future analysis will use the position signals
225 to calculate the path length on an event-by-event basis.

227 4.0.2. Energy signals

228 The energy signals produced by the ionization chamber are shown in Fig.
229 9. A representative raw waveform from the IC after pre-amplification, shown
230 in Fig. 8(a), illustrates the clear signal with an excellent signal-to-noise ratio.
231 An example output of the trapezoid-filter waveform from the on-board digitizer
232 firmware is shown in Fig. 8(b). The energy value was determined by the height
233 of the flat top region of the trapezoid shaped waveform. The overshoot at
234 the beginning of the flat top region is a common effect and can be bypassed
235 with firmware settings. The timing values were obtained from the zero-crossing
236 point of the second derivative of the raw waveform. The initial linear calibration
237 parameters for the energy signal were determined by fitting the peaks in the raw
238 spectrum (shown in Fig. 9(a)) with literature values of post neutron-emission
239 peak kinetic energies for the light and heavy fission peaks [28, 29]. Energy loss
240 corrections, calculated with TRIM [30] were necessary to account for energy
241 loss of the fission products in materials prior to measurement in the ionization

(a)

(b)

Figure 7: (a) Raw and (b) calibrated time-of-flight spectra for spontaneous fission fragments from ^{252}Cf . Sharp leftmost peak is 6.12 MeV alpha particle emission.

(a)

(b)

Figure 8: Example (a) raw waveform and (b) trapezoid outputs of ionization chamber as a function of time. Trapezoid shaped waveform made with on board pulse height analysis firmware. The waveforms were sampled for 4000 channels.

242 chamber. The materials upstream of the ionization chamber included a gold foil
 243 layer on the ^{252}Cf source, carbon conversion foils in the timing detectors, and the
 244 silicon nitride entrance window of the ionization chamber. TRIM calculations
 245 estimate the total energy loss through these materials to be 5.5 MeV on average.
 246 This energy loss calculation is dependent on initial mass, charge, and energy of
 247 the fission products and has a reported uncertainty of 5.8% [30]. Energy loss was
 248 approximated for the entire energy spectrum by a linear fit to calculated energy
 249 loss values for a representative set of fission product masses, charges, and initial
 250 energies, based on the reported average masses, energies, charges, and neutron
 251 emission as a function of mass for the ^{252}Cf fissioning system. [28, 29]. Figure
 252 9(b) is the resulting calibrated energy spectrum.

253

254 5. Results and Discussion

255 This section discusses the first results from the SPIDER instrument. The
 256 first distributions of energy and velocity for ^{252}Cf fission products are presented.
 257 The post-neutron-emission mass distribution of ^{252}Cf , determined using the E-v
 258 method is also presented with measured mass uncertainties and calculated mass
 259 resolution capabilities of SPIDER.

260 The measured kinetic energy distribution of the fission products is shown
 261 in Fig. 9(b). The energy loss corrections for material loss, initially calculated
 262 with TRIM, were small - on the order of 5.5 MeV. The resulting calibrated and
 263 corrected spectrum in Fig. 9(b) is based on these estimates of energy loss. The
 264 average kinetic energies of the light and heavy products measured here are 103.5
 265 ± 1.8 MeV and 78.7 ± 1.3 MeV.

266 The velocity distribution of the fission products shown in Fig. 10 is based
 267 on the measured time-of-flight of the products and flight path length of 70.0 cm
 268 based on the measured distance between the two timing detectors. The deduced
 269 average velocities of the post-neutron-emission ^{252}Cf products were 13.5 ± 0.1
 270 mm/ns for the light products and 10.13 ± 0.08 mm/ns for the heavy products.

(a)

(b)

Figure 9: (a) Raw and (b) calibrated energy spectra for spontaneous fission of ^{252}Cf .

Figure 10: Velocity distribution for post-neutron emission ^{252}Cf fission products measured with SPIDER. Data from Schmitt *et al.* from Ref. [28].

Figure 11: Single fragment average velocity as a function of fragment mass. Data from Whetstone from Ref. [31]. SPIDER data is reported as post-neutron emission data and Whetstone data is reported as pre-neutron emission data.

271 The average single fragment velocity is plotted in Fig. 11 as a function
 272 of mass. The symmetric mass division occurs at the dip in the overall linear
 273 regression of the two parameters similar to Fig. 7(a) of [31].

274 The post-neutron-emission mass yield distribution obtained from this exper-
 275 iment is shown in Fig. 12. The peak values of the light and heavy masses for
 276 ^{252}Cf are 107.1 ± 0.8 amu and 140.7 ± 1.1 amu, respectively. The final energy
 277 calibration parameters used to obtain this spectrum were determined by a χ^2
 278 minimization search between the measured mass spectrum and the evaluated
 279 mass spectrum from England and Rider [32]. The resulting estimate of exper-
 280 imental energy loss for the heavy ion energy peak is approximately 33% larger
 281 than the value obtained from the TRIM calculation. This difference in energy
 282 loss is suspected to be a mixture of reported TRIM uncertainties in this mass

283 and energy region, uncertainties in material properties, including the molecular
 284 composition of the silicon nitride membrane, and the response of the detector
 285 for these types of ions, in particular pulse-height defect effects. Further inves-
 286 tigation of both the molecular composition of the thin windows and a more
 287 thorough calibration of the ionization chamber at a heavy ion facility will con-
 288 strain these uncertainties in the calibration and correction methods currently
 289 being applied to the energy spectrum. The timing calibration described previ-
 290 ously, along with energy loss corrections calculated using TRIM, were also used
 291 in the calculation of the final mass spectrum shown in Fig. 12. The full integral
 292 of the mass result was normalized to 200%.

293 The mass uncertainties shown for the SPIDER mass distribution were cal-
 294 culated using standard error propagation techniques and included several com-
 295 ponents. Systematic uncertainties based on calibration and correction param-
 296 eters used in the analysis of the raw energy and timing signals were the largest
 297 contributors to the mass uncertainty. Specifically the linear calibration of the
 298 energy and timing measurements contained uncertainties for both the gain and
 299 offset terms. The calculation of the velocity uncertainties included the timing
 300 calibration uncertainties and the measured uncertainty of the nominal flight
 301 path length (0.1%). The uncertainty of the energy component also included the
 302 uncorrelated uncertainty in the energy loss correction. This uncertainty was set
 303 to 5.8% based on the reported uncertainty in the TRIM calculation for ions of
 304 this mass and charge range through materials [30].

305 The mass result shown in Fig. 12 is compared to the yield results from the
 306 mass yield data evaluation by England and Rider in 1993 [32]. This evaluation
 307 is the current recommended yield data for spontaneously fissioning ^{252}Cf in
 308 ENDF/B-VI. The evaluated yield values range from 66 to 172 amu with yield
 309 uncertainties approximated by reported experimental variances. The two yield
 310 distributions are in good agreement with each other, particularly at the peak of
 311 the light and heavy mass yields. It should be noted that no broadening of the
 312 evaluation data was necessary to make a comparison to the SPIDER result. As
 313 more statistics are collected with SPIDER on ^{252}Cf and other fissioning systems,

Figure 12: Mass yield distribution of spontaneously fissioning ^{252}Cf . SPIDER data shown as filled black squares, England and Rider evaluation [32] shown as filled red triangles and solid red line.

314 mass regions with rapidly changing yields will be thoroughly investigated.

315 The current mass resolution capabilities of SPIDER have been calculated
 316 based on the individual measurement resolutions for energy, time-of-flight, and
 317 path length and an energy resolution component from calculated energy strag-
 318 gling through material. The measured energy resolution of 1.1% for alpha parti-
 319 cles is similar to reported alpha resolutions for optimization ionization chambers
 320 [33]. This resolution was reduced by a factor of two to 0.55% for fission frag-
 321 ments based on the assumption of optimized the SPIDER ionization chamber
 322 and reported energy resolutions of fission fragments in similarly designed and
 323 optimized detectors [20]. A second energy resolution component was added
 324 into the resolution equation discussed earlier to approximate the limit in reso-
 325 lution based on energy straggling of the fragments through the materials. This

326 resolution is dependent on fragment species and was estimated using TRIM cal-
 327 culations of energy straggling for mass 107 and mass 141 to be 0.25% and 0.47%,
 328 respectively. The measured resolution for time-of-flight was 0.5%. Finally, the
 329 path length resolution of 0.03% was based on the extrapolated position reso-
 330 lution over the nominal 700.0 mm path length. The four components of the
 331 resolution were added in quadrature to determine the mass resolution of the
 332 mass peak values: 1.2 amu at 107 amu and 1.7 amu at 141 amu.

333 **6. Future Work**

334 The goal of measuring coincidence fission products with the 2E-2v method
 335 has progressed with the construction and initial testing of a two-arm system for
 336 SPIDER. The coincidence measurements will allow for determination of several
 337 fission properties including total kinetic energy (TKE) of the products, TKE vs
 338 mass studies, and neutron emission as a function of mass. The fully constructed
 339 and assembled SPIDER two-arm system shown in Fig. 13 is installed currently
 340 at a Lujan Center flight path at the LANSCE facility. Source tests of the system
 341 are ongoing as are additions to software to accommodate the additional data.
 342 The Lujan Center provides a thermal neutron spectrum and will be used to
 343 measure neutron-induced fission mass yields and coincidence studies, starting
 344 with ^{235}U and ^{239}Pu isotopes. Fast neutron-induced yields will be studied at
 345 the WNR facility. The size of the detectors was chosen to accommodate the
 346 small shift in the reaction kinematics with increasing excitation energy and is
 347 not expected to decrease the efficiency of SPIDER.

348 **7. Summary**

349 The energy-velocity method of measuring mass yields of fission products has
 350 been successfully applied using the newly constructed SPIDER instrument. The
 351 individual detector components for measuring time-of-flight, path length, and
 352 energy have met resolution requirements necessary for meeting the goal of one
 353 atomic mass unit resolution. The first results reported for mass yields of Cf

Figure 13: Picture of two-arm setup of SPIDER installed on flight path 12 at the Lujan Center at the LANSCE facility.

fission products are consistent with an average mass yield resolution of 1 amu. Future work will consist of coincidence product measurements with the 2E-2v method with a focus on neutron-induced fission of actinide species.

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