

Project No. 13-4815

Fission Fragment Yield Data in Support of Advanced Reactor Technology

Fuel Cycle Research and Development

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M2NU-13-NM-UNM_-0601-013-Year 3 Annual Report and Final Report
for Project 13-4815
1/15/2014-7/16/2017
**Fission Fragment Yield Data in Support of Advanced Reactor Technology
DE-NE0000732**

Prepared by

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1 Developments:

a) DOE award number: DE-NE0000732

b) Recipient name: University of New Mexico

c) Project Title: Fission Project Yield Data in Support of Advanced Reactor Technology

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e) Submitting Official: Same as PI

f) Project start/end date: January 15, 2014 - January 14, 2017 with NCE to July 16, 2017

g) Report submission date: November 17, 2017

h) Reporting period start and end date: 1/15/2014-7/16/2017

This is the year 3 annual report and the full project final report.

2. Comparison of actual accomplishments with goals and objectives.

In year one we built a fission fragment spectrometer based on transmission ion time-of-flight coupled with an ionization chamber for fragment energy. We were successful. The goals and objectives for the second year were to improve spectrometer resolution and perform tests with fission and alpha sources. We were successful.

Goals for the third year included building a second arm of the fission fragment spectrometer for back-to-back fission fragment analysis. This requires a thin Cf target at UNM for development, and was considered to be high risk for breaking and a duplication of LANL efforts on a multi arm spectrometer. The work where we stand out from our LANL collaborators is in detector development and characterization, working out the details so LANL can implement new detection systems we develop. In this we developed and improved Z determination in the ionization chamber, giving us E, v, cross section, and both A and Z data, correlated for each particle.

As this is the final report for the project, the "proposed work" and "path to accomplishment" are reproduced below in italics, with comparison in standard font.

Proposed work:

Within the 3 year POP we propose to continue to test and further develop the fission

spectrometers, to do development tests and full data acquisition runs at the national laboratory neutron beam facilities, to measure correlated fission fragment yields at low neutron energies with ^{235}U fission targets, and make these data available to the nuclear community. The spectrometer development will be both on the university based prototype and on the National Laboratory Spectrometer, and measurements will be performed with both.

Over the longer time frame of the collaboration, we will take data over a range of low energies, and use other fission targets available to the laboratory. We will gather energy specific fragment distributions and reaction cross sections. We will further develop the data acquisition capabilities to take correlated fission fragment/gamma ray/neutron data, all on an event-by-event basis. This really is an enabling technology.

* We have accomplished this. We developed and built a fission fragment spectrometer. We tested and rebuilt and improved to have mass resolution on the order of 1 amu with energy, velocity, and mass all correlated particle-by-particle. We have modified and tested the ionization chamber and developed capability to extract Z information correlated with these data by particle range in the ionization chamber gas. We have developed analytical techniques to extract the information from the data. We have used these for several Cf-252, U-235, and Pu-239 data sets. Presented here are results from U-235.

Path to work accomplishment:

The groundwork is currently in progress, the PI's research group at the university is currently working with the National Laboratory on prototyping this spectrometer. Progress to date includes building, testing, and characterizing an ionization chamber and a TOF detector.

Years 1, 2, 3: We are part of the National Laboratory Spectrometer collaboration, so all our work feeds into and informs the design and development of the National Laboratory Spectrometer detector, and our work helps in finding issues and limitations in the detector which we are working to overcome, such as edge effects in the ionization chamber. We will participate in National Laboratory Spectrometer (n,f) experiments. In addition, the independent measurements from the university based spectrometer will be a confirmation of data, and add to the statistics of the general collaboration.

* We have several independent data sets, each better than the last as far as precision and reducing uncertainties as we continually develop the detection system and analytical techniques.

Year 1: With NEUP help, we will continue the development and will test the performance of the single arm prototype on the low energy neutron beam line at the National Laboratory. We will test the single arm prototype with a longer TOF path length than the National Laboratory Spectrometer test detector to evaluate the actual experimental improvement in timing, and thus mass, resolution. Several steps will happen, including implementing and testing the thin SiN ionization chamber window and the fast digitizing electronics. At this point we will gather single fragment data on $^{235}\text{U}(n,f)$ at low energies.

* We were successful, and this informed subsequent progress.

Year 1 and 2: Further development will be Z determination by examining depth of ionization in the IC, such as the method of JINR, Dubna¹. We will also build, test, and incorporate into the full detector an active cathode following Sanami et al.⁸ for the ionization chamber to help improve Z separation in the data. Testing with sources and with the National

Laboratory beam line will give us true cost-benefit evaluation. At this point we will gather single fragment data on $^{235}\text{U}(n,f)$ at low energies with improved Z determination.

* We have successfully implemented an active cathode to the ionization chamber and made range measurements, which are part of the input data to understanding the particle atomic number, Z. This continued beyond year 2, in fact it is still continuing as this is extremely involved.

Year 2 and 3: Further development will be to build and test a second arm to make a dual arm spectrometer for use for binary fission fragment coincidence measurements. This will be tested with sources and then tested with experiments on the National Laboratory beam line. At this point we will gather correlated binary fragment data on $^{235}\text{U}(n,f)$ at low energies. This coincidence measurement will also allow determination of fragment total kinetic energy - very important for fission models - and neutron multiplicity.

* We are collaborating with Los Alamos on this project, and they are building their own spectrometer with multiple arms. They have far more expensive detectors and are working on not only two arms but up to 10 arms to increase geometric efficiency. Our value added to the collaboration is not in duplicating their work but in developing and testing new detectors and analysis techniques. For this then we did not build a second detector arm. We put our efforts into improving the mass resolution and the Z determination both by developing and improving the detectors and by developing and improving analytical techniques to extract mass and atomic number, A and Z.

Year 3: The university PI has experience with particle tagging with gamma ray spectroscopy and is looking forward to putting it to use on this project. In subsequent experiments we will incorporate coincidence measurements using fragment particle tagging, with neutron and gamma detectors, to examine both prompt and delayed radiation correlated with specific (n,f) reactions and specific fission fragment production.

* We tested with gamma ray detectors. We found that the background level was high enough that further development is needed for good gamma ray tagging. This includes shielding of the detectors, changing to more and smaller detectors, modifying the vacuum chambers to be able to pull the detectors in closer to the fission target and/or the ionization chamber, and modifying the data stream to allow more detectors and analysis to extract coincidence measurements. We did not refocus to build on this but would like to in the post-grant period.

Beyond Year 3: In future work we will move beyond low energies and examine (n,f) reactions to several MeV, and examine all available actinide targets. This will be a long term project and will be important to the dissertation work of many PhD students at the university. Correlated data are very important for theory, understanding secondary reactor heating, and for using specific nuclides produced to characterize the amount of fuel used. There is a wealth of information important to advanced reactor simulation and development and we are poised to gather that information.

*We are continuing to gather data with the UNM fission fragment spectrometer, we currently have a Pu-239 run at LANL and are continuing analysis of our most recent U-235 data set. Some results from the U-235 analysis are presented here. We will continue

to put in neutron beam time proposals at LANSCE at LANL and continue to take data. We are also graduating graduate students, with several MS students graduated, and a PhD student defending in very early 2018. We are assembling papers on detector development and on data and results.

3. Discussion of accomplishments.

Over the project we designed a fission fragment spectrometer, prototyped detectors for this, built and bought the final detectors we used, took data, tested and rebuilt and improved the system, and took high resolution data on U-235, Pu-239, and Cf-252 fission fragments. We took data particle-by-particle for correlated data on E, v, cross section, A, and Z. Details are below.

Our group at the University of New Mexico (UNM) is working in collaboration with Los Alamos National Laboratory to develop a multi-arm spectrometer to be used with the Los Alamos Neutron Science Center (LANSCE) to study binary fission. The LANL project is headed by Morgan White and the experimental work was headed by Fredrik Tovesson and now Shay Moseby. The UNM effort is headed by the proposal PI, Adam Hecht, associate professor of Nuclear Engineering.

The LANL led effort:

The LANL led effort is to develop and run a spectrometer for high resolution and, by adding detectors, high efficiency fission measurements. The spectrometer is called the Spectrometer for Ion DEtermination in fission Research (SPIDER). The UNM effort is twofold: we are part of the LANL collaboration and are designing, prototyping and testing detectors for the LANL based spectrometer project; and we will use our UNM developed detectors and data acquisition for a complementary data collection effort on the low neutron energy beam line at LANSCE.

The UNM led effort:

The UNM effort is detector prototyping, testing, characterizing, and trouble shooting in support of this effort, with results feeding in to the LANL spectrometer. We also run our UNM prototype detector system, the UNM Fission Fragment Spectrometer (UNM-FFS) on the neutron beam downstream of the LANL spectrometer, testing different design parameters, with UNM data complementing the LANL spectrometer data.

Background on the spectrometer:

The spectrometer is based on time-of-flight (TOF) fragment velocity measurements and ionization chamber (IC) energy measurements. Arm pairs on opposite sides of a fission target will take simultaneous data on binary fission products. By combining energy (E) from the ionization chamber and velocity (v) from TOF measurements, and combining them particle by particle via $E = 1/2 m v^2$, we extract the mass (A) of the fission fragments particle by particle. A schematic of an E-v spectrometer is presented in Figure 1. A CAD modeling of the UNM fission fragment spectrometer is presented in Figure 2. With velocity being $v = l/t$ where t is TOF and l is length of TOF path, the uncertainty accounting then follows

$\frac{\partial m}{m} = \sqrt{\left(\frac{\partial E}{E}\right)^2 + \left(2\frac{\partial t}{l}\right)^2 + \left(2\frac{\partial t}{t}\right)^2}$. For 1 amu resolution for light fragments (1/90) this is limited to $\sim 1.1\%$ and for heavy fragments (1/140) $\sim 0.7\%$. A goal is to decrease sources of resolution broadening, with the uncertainty accounting to help determine the most significant sources of resolution broadening.

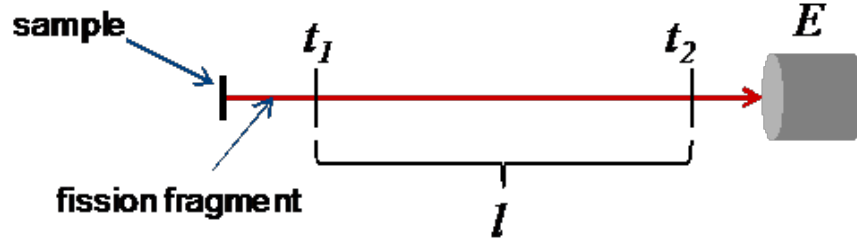


Fig. 1: Schematic view of the basic concepts for the instrument. The sample may be a U-235 or Pu-239 target hit by a neutron beam, or a Cf-252 fission source, for example.

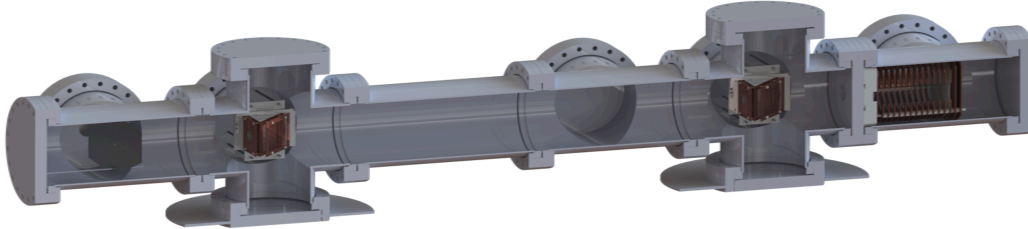


Fig. 2: Computer model of the UNM fission fragment spectrometer as built. The target is placed in the chamber on the far left, the timing detectors are visible in the vacuum crosses, and the ionization chamber for energy determination is on the right. The cross near the center is for the vacuum turbo pump attachment.

Early data of velocity and KE, correlated for each particle, is presented in Figure 3 from the winter 2016/7 LANSCE run with U-235. To extract mass there are many corrections to apply, such as for pulse height defect and energy losses in the foils and IC entrance window. A reconstruction is presented in Figure 4 for part of that data set. It is not the complete data set, but demonstrates the quality of the data and analysis. Comparison of our data with table data with various broadenings suggests our resolution is on the order of 1 amu. This analysis is ongoing.

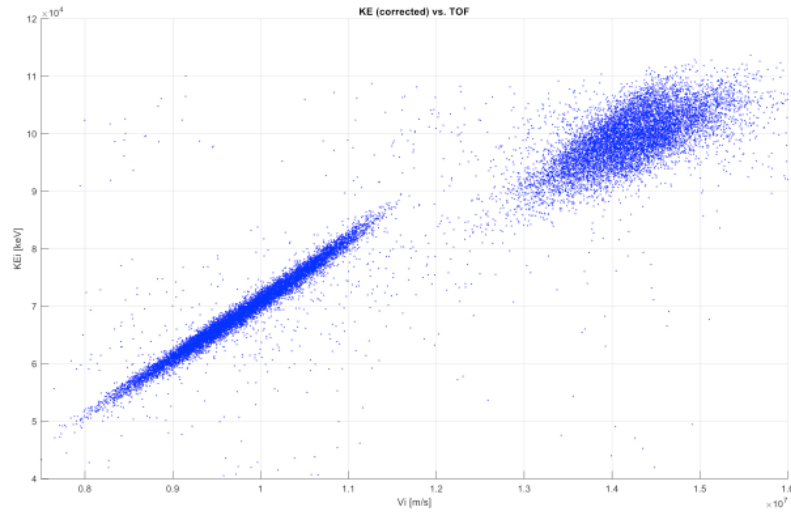


Fig. 3: Scatter plot of KE vs. velocity data from the U-235 run at LANSCE, winter 2016/7. Each point is data from a single atom.

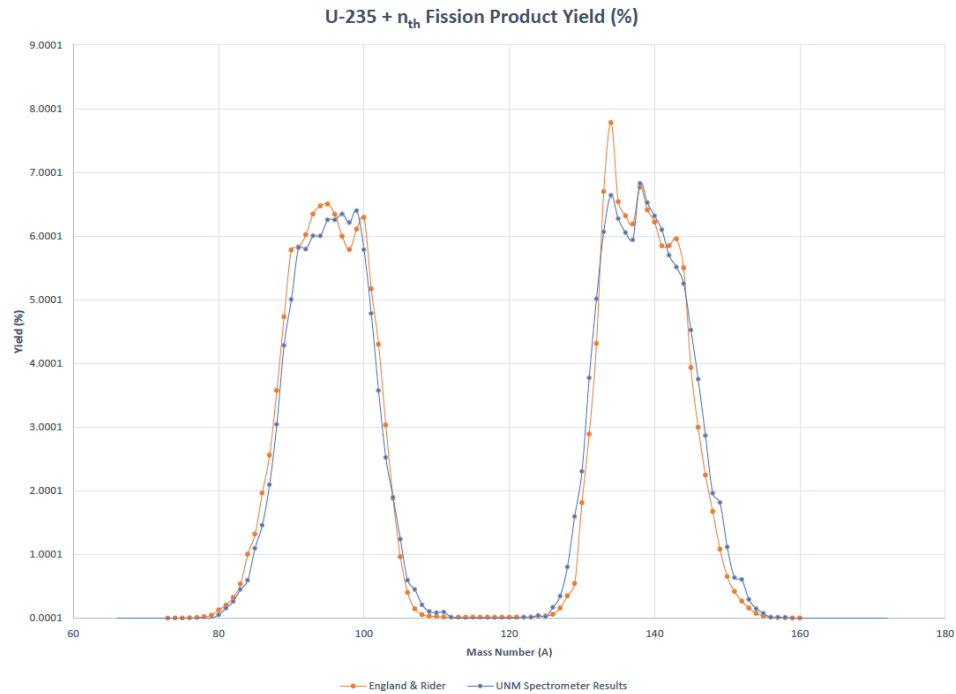


Fig. 4: Mass reconstruction from KE and velocity data with energy and velocity loss corrections applied. This is compared with table data from England and Rider.

Z determination of the particles can be performed with information from the ionization chamber energy detector. The ionization chamber electrodes are represented in Figure 5, with a picture of the actual electrodes in Figure 6. The cathode is the orange plate on the left, anode on the far right, and the Frisch grid is the grid near the anode. The particles enter through a thin window on the left and ionize gas. The electrons start

to drift away from the cathode towards the Frisch grid, inducing a pulse on the cathode. Once they pass the Frisch grid they induce a pulse on the anode. With the electrodes set up like a time projection chamber, with guard rings to keep the E field uniform, the time difference between the cathode and anode signals then gives information where the front of the electron bunch began, or how deeply the particle penetrated and thus its range in gas. This required reconstruction of the ionization chamber with a Teflon insulator between the cathode and the vacuum chamber flange, requiring many months of development, testing, and redesign to hold vacuum, hold the electrodes properly and repeatably, and to not arc.

The Bethe equation describes the stopping power and thus range as a function of velocity (or kinetic energy and mass) and Z . Methods have been developed to extract the effective charge of an atom from range in gas, such as Tyukavkin et al. [*A.N. Tyukavkin et al., Instruments and Experimental Techniques, 2009, Vol. 52, Pp. 508-518*], though this is the first application of high-resolution data to fission fragments. That paper suggests a range relation of $R = \beta (EM)^{1/2} Z^{-2/3}$ where β is a fit parameter, and R , E , M , Z are range, energy, mass, and Z , respectively. We have range extracted from the electrode timings; Figure 7 shows a plot of range vs. mass for our data. Figure 8 shows range vs. extracted Z using this technique. We are further developing our analysis methods guided by that work, we have range measurements but we do not yet feel confident about our extracted values of Z , which are complicated by assumptions on partial ionization charge states.

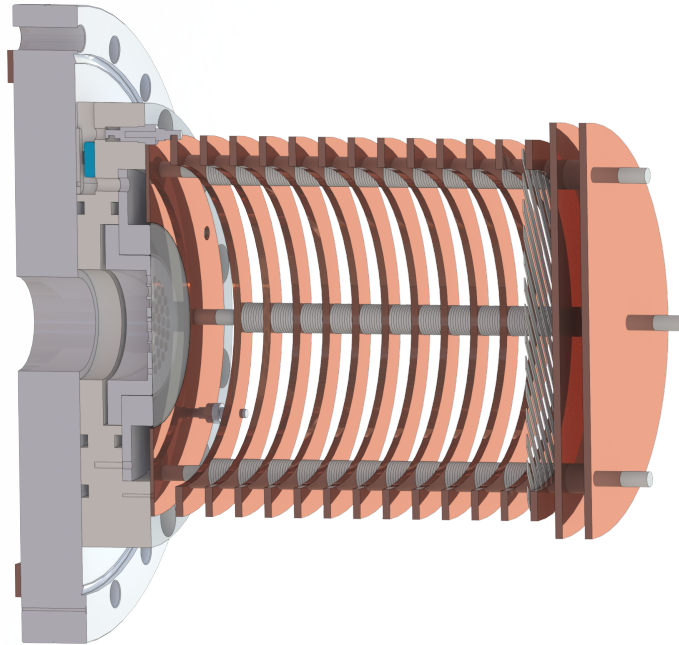


Fig. 5: Schematic showing the (previous) entrance window to the IC, within the cathode annulus. The window holder is electrically connected to the cathode annulus to create a more uniform, full cathode face.

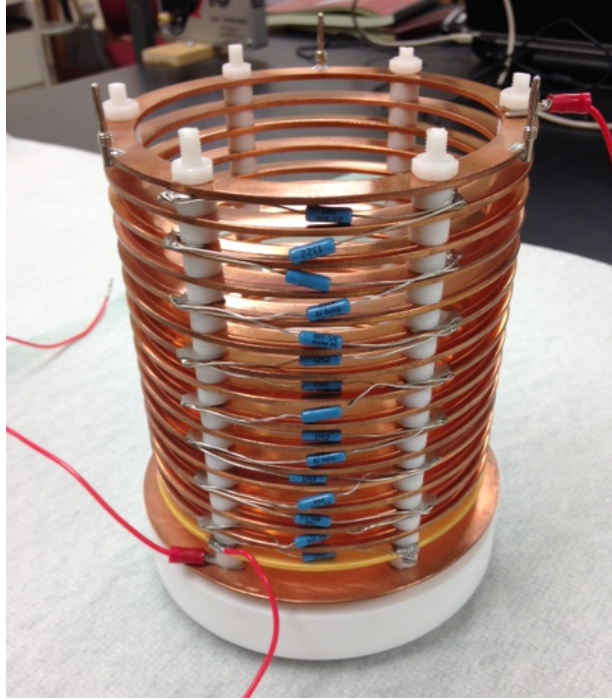


Fig. 6: UNM FFS ionization chamber as built. Cathode is at the bottom, attached to the Teflon insulation plate.

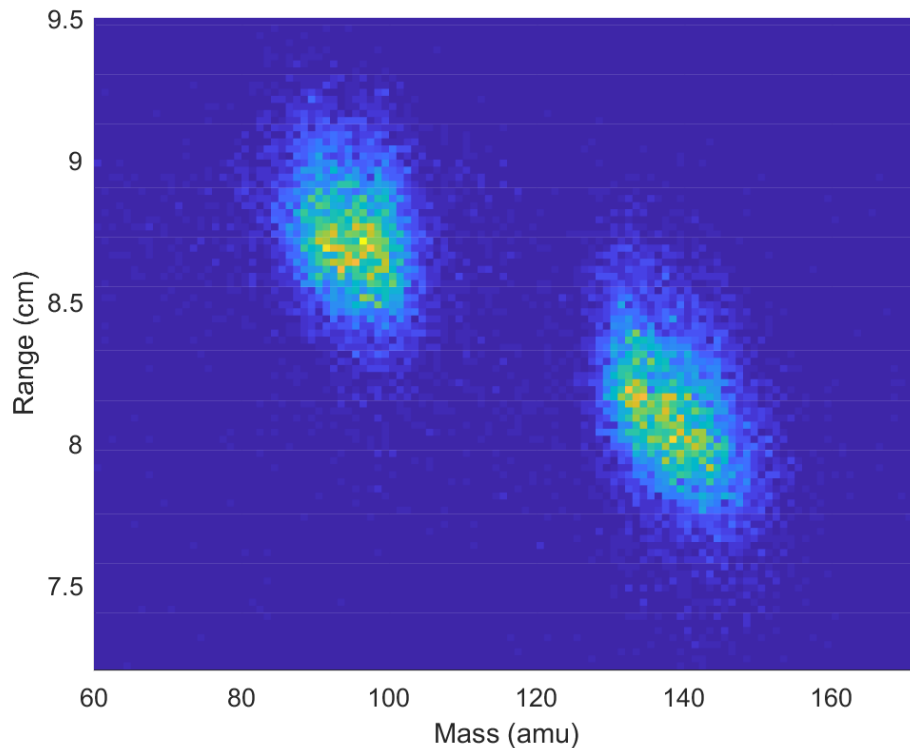


Fig. 7: Scatter plot of range within the ionization chamber gas vs. mass for each particle. The range gives the particle stopping power, which is a function of mass, KE, and Z. With the mass and KE already determined, Z may be extracted.

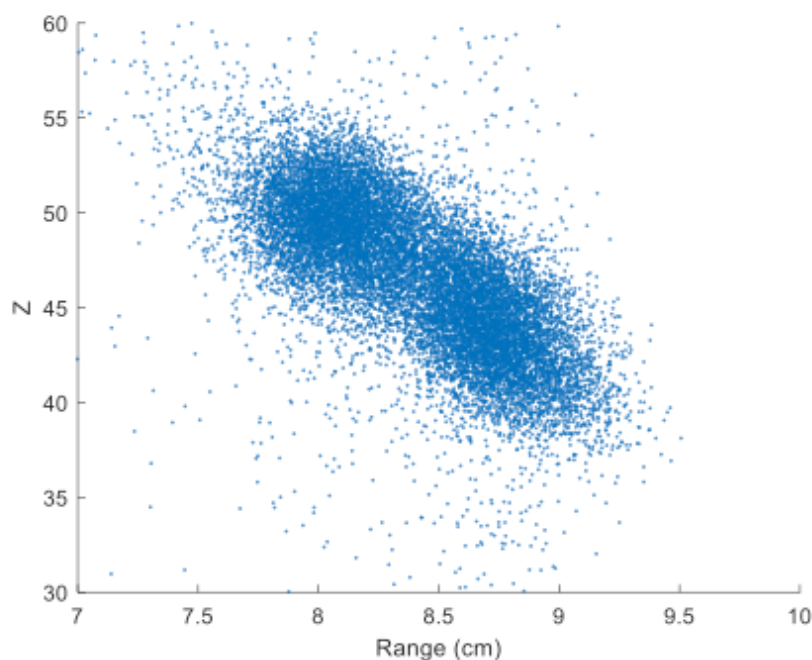


Fig. 8: Scatter plot of range vs. extracted Z. The clear overlap between light and heavy fragment Z values shows difficulties in analysis. The analysis is ongoing.

The UNM Spectrometer serves as a test bed for further development of the LANL spectrometer and will provide both a unique data set and add to the statistics of the LANL spectrometer data. Design and development will continue to increase detector resolution and implement Z determination in the ionization chamber. The ionization chamber work has informed the Los Alamos collaborators efforts and the Z determination work will help with new designs of the LANL Spectrometer, SPIDER.

Report on 3rd year work:

We built the fission fragment spectrometer in year 1: We built the ionization chamber and time of flight setup, we coupled the two, and we took preliminary KE vs. TOF data with each the KE and TOF for each individual atom correlated in order to determine masses, atom by atom.

For year 2 we focused on improving the system in several ways by reducing electrical noise, improving energy resolution, and reconfiguring the ionization chamber to study cathode vs. anode timing for particle range measurements, to be used for Z determination.

In year 3 and the no cost extension period we focused primarily on 1) improving analysis techniques for mass reconstruction, 2) range determination in the ionization chamber, and 3) analysis techniques for extracting Z. Experimentally we 4) improved the system efficiency by increasing the size of the TOF conversion foils, and increasing the number of tiled SiN entrance windows to the ionization chamber. By doing so we increased the efficiency by about 7 times. We 5) took data on U-235 winter 2016/7 and performed analysis, and we began taking data on Pu-239 starting in the no cost extension period (January - July 2017) of this grant with the beamtime still continuing now. These

efforts are described below.

1. The mass of the particles is determined from the measured velocity in the time-of-flight region and the energy measured in the ionization chamber. We try to reduce energy and velocity loss in the system so there is minimal change in the KE and v between the TOF region and the ionization chamber. We do this by using extremely thin carbon foils for the TOF detectors - the electrons ejected from the foils are reflected to microchannel plate (MCP) detectors to give the start or stop pulse for the TOF - but we are also limited by the possibility of breaking the foils, so we ran with 40 microgram/cm² thickness foils. We attempt to reduce the energy loss into the ionization chamber by using very thin entrance windows. The windows separate the gas region, about 1/10 atm of isobutane, from the high vacuum TOF region. The windows are 200 nm thick SiN. Again, thinner may be more prone to breaking.

Even with these measures, there is energy loss between the TOF region and the inside of the ionization chamber, so the v measurements for each particle are at a slightly higher energy than the E measurements for each particle. To correct for this we were comparing energy values with table values for what is known about fission particle emission from U-235. This was then corrected for energy loss from the target into the TOF region. This process allowed a correlation of E in the TOF region with v in the TOF region. A study was performed comparing energy loss calculations of fission fragments through carbon foils and SiN windows and the manuscript is in preparation. An example measurement setup is presented in Figure 9.

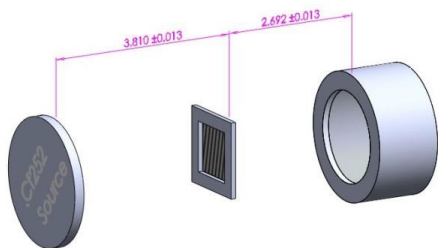


Fig. 9: Schematic (left) and experiment setup (right) of energy loss measurements of fission fragments from Cf-252 through carbon conversion foils from the TOF setup and through SiN windows used on the ionization chamber.

This method was modified this year to back out both the energy and the velocity to known values for emission from the target. The distributions were fit en masse to these known values. The extracted E and v values for each particle are then correlated and the mass extracted, which gave much better results, as seen in Figure 4. Some of this analysis is presented in Figure 10 for mass vs. KE. The energy and velocity changes between the target and the measured values in the ionization chamber and TOF region, respectively, are noted and these can be used for similar fragments from other parent fissioning nuclei such as U-233.

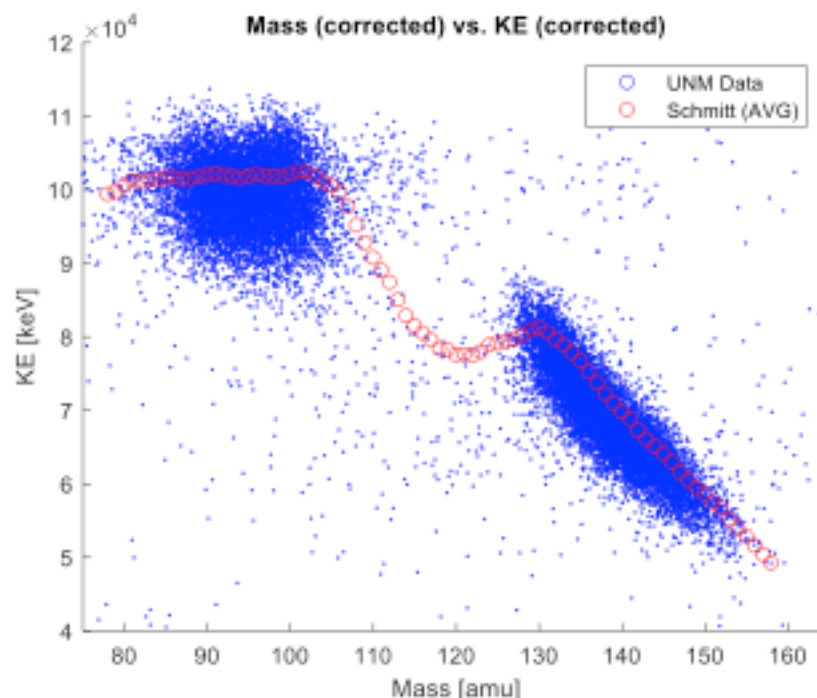


Fig. 9: Plot of Schmitt table values of average KE per mass for U-235 fission vs. UNM spectrometer data, with the energy and velocity addback adjusted to best fit the known values.

2. For range determination in the ionization chamber - the range of the fission fragments in the isobutane gas within the ionization chamber - we worked on the timing between the cathode and anode. The values for range for our calibration source, a Cf-252 fission source, initially did not correspond well with range values when we used either SRIM or MCNP for simulations. The electrode timing difference for the range was extracted from a time to pulse height convertor fed to the computer through a digitizer. Using timing differences with a split signal using a delay we were able to properly adjust the digitizer to read in the signals linearly. This seems a small thing but many of these small things go into developing an experimental apparatus from scratch. This recalibration of the system with delays allowed us to read fission fragment ranges which then matched calculated ranges quite well.

3. For analysis techniques for Z determination, I mentioned adapting the Tyukavkin methodology for fission fragments. This is an ongoing process. This is extremely important to me since we are making our mark in the SPIDER spectrometer collaboration with LANL by developing new capabilities for fission fragment spectrometry and working out the issues and developing the techniques, not only for our own data taking but to inform improvements in the LANL spectrometer. The range measurements are very good, and we are working on correlating these ranges with fission fragment Z values. While this would be simple with known calibration beams, we have the very mixed nuclide distribution from fission sources.

4. Efficiency improvements include both increasing the size of the carbon foils used

for the TOF detectors and increasing the total SiN window size to the ionization chamber. An image of the conversion foil mounted to the electrostatic mirror, which reflects the ejected electrons to the MCP detector, is presented in Figure 10. The foil was increased from about 1 cm² to about 4x4 cm², and a gold plated tungsten wire grid was developed to hold the foil in place and reduce breaking.

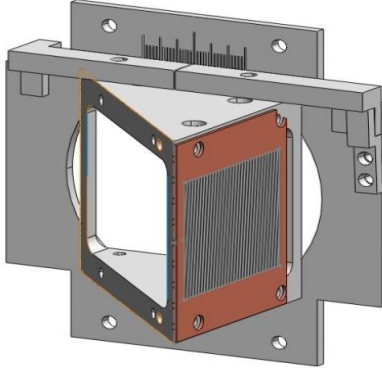


Fig. 10: Rendering of carbon conversion foil for the TOF system mounted to the electrostatic mirror.

For the entrance to the ionization chamber we originally used thin Mylar, which we found to seep gas. We later changed to thin SiN, which does not seep but is more fragile. We used a single 1 cm² SiN window as a first step, mounted on a flange to the ionization chamber, to test the gas tightness and energy loss into the ionization chamber. Following those successful tests, in year 3 we changed to a bank of seven windows tiled into the flange. The windows are shown in Figure 11. Increasing the carbon foil areas allowed fission fragments to strike a wider region of the IC entrance flange, and the seven windows then were "illuminated" by these fragments, and we were able to increase the efficiency seven times.

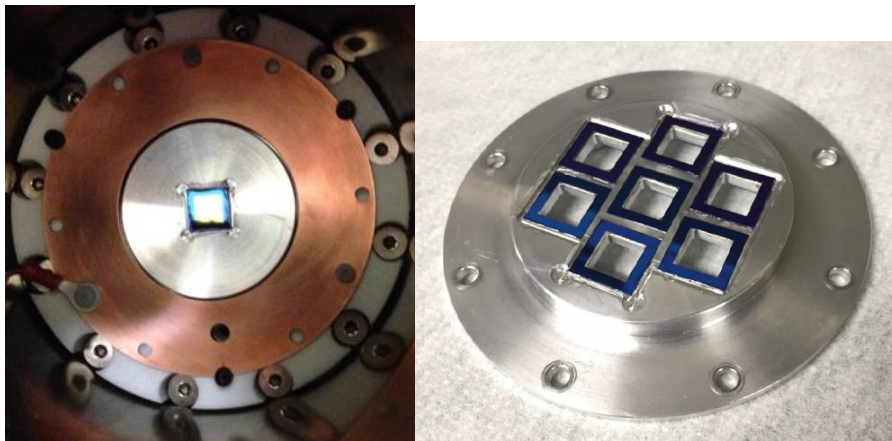


Fig. 11: (left) 200 nm thick SiN window in center of window frame as mounted within the ionization chamber vacuum chamber. (right) The seven window frame with the very transparent 200 nm thick SiN windows mounted.

5. In year 3, which ran from January 2016 through January 2017, we were able to use the improved efficiency system for our beamtime at LANSCE on U-235 in winter 2016/7. This allowed us to get a very rich data set, part of which went into the results

presented here.

As we were adjusting experimental parameters during the run, to show the results from the full data set we will extract mass plots independently for the different segments of the run and combine. This is being performed and will be included in the dissertation of student Rick Blakeley, who is defending his PhD in very early 2018, and will be presented in the associated manuscript being prepared. An additional manuscript is being prepared on Z determination.

In the no cost extension period of this grant, from January 2017 through July 2017, we were able to begin another beamtime run at LANSCE, on Pu-239. As this run time is now, results are not presented here.

We expect many more years of taking correlated data. We have a close collaboration with Los Alamos and success with beamtime proposals at LANSCE and will continue to take fission data on parent nuclei important to the nuclear community, not only on U-235 and Pu-239. This spectrometer system is an enabling technology, allowing us to take fission fragment data with E, v , A, Z, and thus N, and cross section, correlated particle-by-particle for years to come in service of the nuclear community needs.

Accomplishments:

In this project we designed, prototyped, built, tested, and improved a fission fragment spectrometer, and took data on Cf-252, U-235, and Pu-239.

In year 3 and the NCE period specifically we further improved the energy and velocity, and thus mass, measurement stability and resolution of the system. We also worked on improvements to the range determination in the ionization chamber, which is used for extracting stopping power and thus Z information. We improved analysis techniques on mass and are working on analysis techniques for extracting Z well from the range. We increased system efficiency which improves statistics. We took data at LANSCE on U-235 fission fragments and began a data run at LANSCE on Pu-239 fission fragments.

4. Cost Status: Comparison of approved budget and actual costs.

We operated past the January 15, 2017 end on a no cost extension. As this is a final report, we can report that the spending was very close to the budget, being \$800 below the total budget.

Since LANL developed a multiple arm spectrometer, we did not duplicate efforts there. Our value added in the collaboration with LANL discussed in the original proposal is in developing, testing, and improving new detectors and analysis techniques towards high resolution fission fragment data. Funding in the line item for equipment was for the second spectrometer arm we would have built. To work on the very labor intensive detector and analysis development this went towards student salaries.

5. Schedule Status:

Completed Milestones:

Milestones listed in the proposal are presented below in italics, with comment following. The milestones have almost all been met, and the other cases we realized we should put emphasis on developing other parts of the program to best push the spectrometer and data forward.

Year 1:

- *Test and evaluation of the dual arm test version of the National Laboratory Spectrometer. Measurement and initial evaluation of $^{235}\text{U}(n,f)$ for thermal neutrons, including fission cross section, fission fragment cross section, and fragment energy for single fragments on an event-by-event basis.*

Accomplished

- *Completion of a single arm coupled TOF-IC spectrometer at the university. Test and evaluation of the single arm efficiencies and resolutions.*

Accomplished

- *Measurement both with the National Laboratory Spectrometer and with the University Spectrometer.*

Accomplished

- *Analyze data sets independently and also combine data sets for full evaluation.*

Accomplished analysis and evaluation. Work continues on improving resolution and efficiency so did not export data for external evaluation.

Year 2:

- *Work on multi-arm (>2) spectrometer development for the National Laboratory Spectrometer. Refine, redesign, and further test National laboratory Spectrometer.*

With LANL collaboration have multi-arm spectrometer. To not duplicate efforts we continued focus on detector development and analysis development.

- *Further development of techniques and hardware for Z determination with an active cathode in the University Spectrometer ionization chamber. Design and construct second arm for dual fragment coincidence measurements. Testing of single arm spectrometer with active cathode. Refine, redesign, and further test dual arm spectrometer as part of national laboratory collaboration.*

Accomplished and continue to work on improving.

- *Take $^{235}\text{U}(n,f)$ fragment data with higher fidelity with both spectrometers.*

Accomplished and continue to work on improving.

- *Analyze data sets independently and also combine data sets for full evaluation.*

Accomplished analysis and continue to work on improving. We compare data sets and analysis with LANL and this has been extremely useful. We have not export data for external evaluation as we are continuing to improve.

Year 3:

- *Refine, redesign, and test National Laboratory Spectrometer with several arm pairs to increase efficiency, as part of national laboratory collaboration.*

Accomplished. National Laboratory Spectrometer (SPIDER) has been evaluated with a back-to-back pair of arms and multiple arms are being constructed.

- *Test, characterize, and take $^{235}\text{U}(n,f)$ fragment measurements for binary fission fragments with the National Laboratory Spectrometer and the University Spectrometer.*

Accomplished for the most part. This has been done with the National Laboratory Spectrometer with multiple arms, but not on the single arm UNM spectrometer.

- *Analyze data sets independently and also combine data sets for full evaluation.*

Accomplished. We have high resolution data and are comparing with LANL high resolution data, which - as mentioned - is extremely useful. We may or may not combine these data sets when submitting these externally.

- *Submit high resolution $^{235}\text{U}(n,f)$ cross section data set to data evaluators.*

In Process. We have great results on U-235 and we will publish. See Fig. 4 for example.

6. Changes in Project Approach:

Our goal was to develop a high resolution fission fragment spectrometer with particle-by-particle correlated A, Z, E data, and on taking this high resolution data. We accomplished our goals.

One detail on the road to this was to increase geometric efficiency by building a second detector arm. We are in collaboration with Los Alamos in this project, the SPIDER collaboration, and they built multiple arms for the spectrometer, so this goal was accomplished. To not duplicate efforts we did not build another multiple arm spectrometer at UNM but pushed on further development of detectors and improving both mass (A) resolution and atomic number (Z) determination. Our value added in the collaboration is putting in the time and effort to develop detectors and analysis techniques, to test and improve these for the benefit of the full collaboration with LANL.

I think in some correspondence I may have mistakenly called not building a second detector arm at UNM a change in scope. We did not change scope. As promised, we developed a high resolution fission fragment spectrometer with particle-by-particle correlated A, Z, E data. We accomplished our goals and are continuing to take high resolution fission fragment data.

7. Problems or Delays:

We have developed the fission fragment spectrometer with high resolution mass capabilities and ionization chamber range capabilities to extract Z information. We have developed techniques to correct for energy and velocity losses in the system and extract the high resolution mass information. The challenges going forward are developing analysis methods to extract Z from the range data.

8. Changes of Key Personnel:

There are no changes of key personnel.

The current Nuclear Engineering student list is:

Rick Blakeley, US citizen, expected PhD very early 2018

Phoenix Baldez, US citizen, expected PhD 2020

Graduated Nuclear Engineering students who were on this project are:

Shelby Fellows, US citizen, MS 2017

James Cole, US citizen, MS 2016

Lena Heffern, US citizen, MS 2015

Drew Mader, US citizen, MS 2013

9. Product produced or technology transfer activities:

a) Publications; conference papers:

Publications

1. *A high resolution ionization chamber for the SPIDER fission fragment detector.* Meierbachtol, Krista C., Fredrik K. Tovesson, Charles Arnold, Alexander B. Laptev, Todd Allen Bredeweg, Marian Jandel, Ronald O. Nelson, Morgan C. White, A. A. Hecht, D. Mader. LA-UR-13-20402. Los Alamos National Laboratory, 2013.
2. *Development of position-sensitive time-of-flight spectrometer for fission fragment research* C.W. Arnold, F. Tovesson, K. Meierbachtol, T. Bredeweg, M. Jandel, H.J. Jorgenson, A. Laptev, G. Rusev, D.W. Shields, M. White, R.E. Blakeley, D.M. Mader, A.A. Hecht, Nuclear Instruments and Methods A 764, 53 (2014); <http://dx.doi.org/10.1016/j.nima.2014.07.001>
3. *The SPIDER fission fragment spectrometer for fission product yield measurements* K. Meierbachtol, F. Tovesson, D. Shields, C. Arnold, R. Blakeley, T. Bredeweg, M. Devlin, A.A. Hecht, L.E. Heffern, J. Jorgenson, A. Laptev, D. Mader, J.M. O'Donnell, A. Sierk, M. White, Nuclear Instruments and Methods A 788, 58 (2015); <http://dx.doi.org/10.1016/j.nima.2015.02.032>

Invited Talks

1. *The University of New Mexico fission fragment spectrometer with preliminary results from LANSCE*, Adam Hecht, Richard Blakeley, Lena Heffern, 23rd International Conference on the Application of Accelerators in Research and Industry (CAARI), San Antonio, TX, May 2014.
2. *Radiation detection development at the University of New Mexico*, Adam Hecht, Richard Blakeley, Lena Heffern, Drew Mader, James Cole, Erin Vaughan, Corey Vowell, Paul Gilbreath, Department Seminar: Aerospace, Mechanical, and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, NY, September 2014.

Contributed Talks

1. *The University of New Mexico Fission Spectrometer for High-Resolution Fission Fragment Yield Data, With Initial Results*, Adam Hecht, Rick Blakeley, Lena Heffern, Drew Mader, James Cole, Paul Gilbreath, Corey Vowell, Institute of Nuclear Materials Management (INMM) 55th Annual Meeting, Atlanta, GA, July 2014.
2. *The University of New Mexico Fission Fragment Spectrometer*, Adam Hecht, Richard Blakeley, Lena Heffern, James Cole, LANL Fission ExperimentS and Theoretical Advances (FIESTA) Fission School and Workshop, Santa Fe, NM, September 2014.

Contributed Poster

1. *The University of New Mexico spectrometer for high resolution fission fragment yield data, with preliminary results from LANSCE*, Adam Hecht, Rick Blakeley, Lena Heffern, James Cole, Corey Vowell, Paul Gilbreath, Symposium on Radiation Measurements and Applications (SORMA) conference, Ann Arbor, Michigan, June, 2014.

Conference Proceedings

1. *Fission Fragment Spectrometer Development in Support of Active Interrogation Data Needs*, Adam Hecht, Rick Blakeley, Drew Mader, American Nuclear Society (ANS) 2012 Winter Meeting, San Diego, CA November 11-15, 2012, Transactions of the American Nuclear Society, vol 107 (2012)
2. *Spectrometer development for high-resolution fission fragment yield data* Adam Hecht, R.E. Blakeley, Drew Mader, Erin Dughie INMM annual meeting proceeding, 2013
3. *SPIDER: A new instrument for fission fragment research at the Los Alamos Neutron Science Center*, Fredrik Tovesson, Charles Arnold, Rick Blakeley, Adam Hecht, Alexander Laptev, Drew Mader, Krista Meierbachtol, Lucas Snyder, Morgan White, EPJ Web of Conferences 62, 05002 (2013).
<http://dx.doi.org/10.1051/epjconf/20136205002>
4. *Spectrometer development for high-resolution fission fragment yield data*, Adam Hecht, R.E. Blakeley, Drew Mader, Erin Dughie, *Proceedings of the Institute of Nuclear Materials Management (INMM) 54th annual meeting*, July 2013 annual meeting proceeding, July 2013 (2013)
5. *The University of New Mexico Fission Spectrometer for High-Resolution Fission Fragment Yield Data, With Initial Results*, Adam Hecht, Drew Mader, Rick Blakeley, Lena Heffern, James G. Cole, Paul Gilbreath, Corey Vowell, *Proceedings of the Institute of Nuclear Materials Management (INMM) 55th annual meeting*, July 2014 (2014)
6. *SPIDER: A New Instrument For Fission Yield Measurements*
F. Tovesson, C. W. Arnold, T. Bredeweg, M. Jandel, A. B. Laptev, K. Meierbachtol, A. Sierk, M. White, A.A. Hecht, D. Mader, R. Blakeley, U. Greife, B. Moore, D. Shields, L. Snyder. In *Fission and Properties of Neutron-Rich Nuclei, Proceedings of the Fifth International Conference on ICFN5* Sanibel Island, Florida, USA, 4 – 10 November 2012: Edited by Hamilton Joseph H & Ramayya Akunuri V. Published by World Scientific Publishing Co. Pte. Ltd., 2014. ISBN# 9789814525435, vol. 1, pp. 361-368 (2014); doi: 10.1142/9789814525435_0039
7. *A High Resolution Ionization Chamber For The Spider Fission Fragment Detector*
K. Meierbachtol, F. Tovesson, C. W. Arnold, A. B. Laptev, T. A. Bredeweg, M. Jandel, R. O. Nelson, M. C. White, A.A. Hecht, D. Mader.
In *Fission and Properties of Neutron-Rich Nuclei, Proceedings of the Fifth International Conference on ICFN5* Sanibel Island, Florida, USA, 4 – 10 November 2012: Edited by Hamilton Joseph H & Ramayya Akunuri V. Published by World Scientific Publishing Co. Pte. Ltd., 2014. ISBN# 9789814525435, vol. 1, pp. 682-684 (2014); doi: 10.1142/9789814525435_0083

MS Theses (plus PhD dissertation in progress)

1. A time-of-flight spectrometer for fission fragment identification, Rick Blakeley, *MS University of New Mexico, 2013*
2. An ionization chamber for fission fragment analysis, Drew Mader, *MS University of New Mexico, 2013*
3. *Ionization Chamber Design, Development, and Testing for the UNM Fission Fragment Spectrometer*, Lena Heffern, *MS University of New Mexico, 2015*

4. An Ionization Chamber for High Resolution Fission Product Spectroscopy, *James Cole, MS University of New Mexico, 2016*
5. Time-Of-Flight And Energy Loss Analysis On The Unm Fission Fragment Spectrometer, *Shelby Fellows, MS University of New Mexico, 2017*
6. *High Resolution Fission Fragment Spectrometer*, Rick Blakeley, PhD University of New Mexico, In progress (expected very early 2018)

b) Web sites: N/A

c) Networks or collaborations fostered:

This grant has continued to foster the collaboration between Los Alamos National Laboratory and the University of New Mexico.

d) Technologies/Techniques:

This grant has supported the technologies and techniques for fragment mass spectrometry described in the previous sections.

e) Inventions/Patent Applications: N/A

f) Other Products: N/A