Investigation of Neutron Induced Ternary Fission with the NIFFTE Time Projection Chamber

A Senior Project

By

Alex Kemnitz

Advisor, Dr. Jennifer Klay

Department of Physics, California Polytechnic State University
San Luis Obispo

November 17, 2017
Approval Page

Title: Investigation of Neutron Induced Ternary Fission with the NIFFTE Time Projection Chamber

Author: Alex Kemnitz

Date Submitted: November 17, 2017

Senior Project Advisor: Dr. Jennifer Klay

_____________________________________
Signature

_____________________________________
Date
ABSTRACT

Ternary fission is a rare occurrence in which three particles are produced from a single fission event. This analysis uses tracked fission event data recorded by NIFFTE’s time projection chamber with a series of refined cuts to isolate all possible ternary events. The experiment used two targets, each consisting of two isotopes; one target was Pu-239 and U-235, and the other was U-238 and U-235. The data was used to measure the ternary/binary fission ratios for each isotope. The ratios for the Pu-239 and U-235 target that were found are shown to be too high due to alpha contamination. The U-238 and U-235 results were determined to be 0.60% and 0.59%, closer to expectations from previous measurements, but are still preliminary and subject to further investigation. An interactive 3-dimensional model was constructed in order to better visualize these events and improve the sorting of ternary fission candidates. The ternary fission candidates were analyzed for proper track lengths, energies, and vertexing.

SECTION 1

INTRODUCTION

1.1 Nuclear Fission

Discovered in 1938, nuclear fission is the process in which a nucleus is excited, breaking into fragments accompanied by neutrons and photons. [1] Fission can occur by a number of means, such as spontaneous decay or neutron bombardment. The study of fission impacts the fields of energy, defense, and nuclear medicine. Despite continuous research undertaken since the discovery of fission, there remain a number of open questions about the underlying physics. Providing new fission data and analysis from neutron induced reactions will help us understand theories and models that have not been fully validated by experimentation. [1]

Neutron induced fission is the process in which a neutron collides with a nucleus and is absorbed, causing the nucleus to become excited and split into fragments. These fragments, daughter nuclei, may also split into more fragments if they are unstable or excited. Figure 1 illustrates this phenomenon by noting the changing atomic number through the fission process, as well as the release of other particles along with the daughter nuclei.

1.2 Ternary Fission

Generally when only two fragments are produced in nuclear fission, this is called binary fission, but there are cases in which there are three daughter particles; these cases are called ternary fission events. Ternary fission by uranium was theoretically determined to be energetically possible in 1941 by R.D. Present. [20] Further predictions were made using the liquid drop model with ternary fission expected to produce roughly 20 MeV more fragment kinetic energy than binary fission.
Figure 1. Diagram of a nucleus absorbing a neutron, becoming excited, and breaking into two fragments, plus photons and neutrons. [61]

Figure 2. Top: Evolution of binary fission from the point of neutron impact to daughter particles. Bottom: Evolution of ternary fission from point of neutron impact to daughter particles.
Fission takes place when a neutron is absorbed by a nucleus, deforming it. The deformation can produce a point of weakest bonding, the scission point, which allows the nucleus to break apart. The top panel of Figure 2 shows the case when two fission fragments are produced, conserving the energy and momentum delivered by the incident neutron. The bottom panel of Figure 2 illustrates the same process, but where three fission fragments are produced in the final state.

Experimental studies suggest that there are three types of ternary fission modes. The most common is the event in which a fission produces two fragments and a long-ranged alpha (LRA) particle. Similarly, there is an event which produces two fragments plus a short-range light charged particle; commonly called tripartition. There is also the possibility of a nucleus fissioning into three fragments with similar masses; this process is called true-ternary fission.

Alpha-accompanied fission is the most common mode of ternary fission, followed by tripartition, with true-ternary fission being the rarest. The smaller of the three fragments in tripartition and alpha-accompanied fission is referred to as the light charged particle (LCP).

![Figure 3. Energy and atomic number, A, distributions for Cf-252 spontaneous fission.](image)

In tripartition, the LCP is commonly found to be peaked at atomic mass of 20, as shown by fragment $A_1$ in the right panel of Figure 3, for the spontaneous fission of Cf-252. The left panel of Figure 3 shows the energy spectrum of the fragments for spontaneous ternary fission of Cf-252 at a low energy threshold of 25 MeV and the corresponding mean emission angles. The right panel shows the atomic mass of the daughter particles, where $A_1$, $A_2$, and $A_3$ are the fragments. The dotted lines in the right panel show the expected mass distribution from binary fission, for comparison.

There have been many other investigations of ternary fission. These investigations range from looking at the theory behind ternary fission, to the types of devices and techniques used to study fission events. There are dedicated studies of methods and analyses on how to approach studying ternary fission; as well as attempts to explain how ternary fission works. On the experimental end, there are investigations into alpha accompanied ternary fission, angular analysis of ternary events, and studies focusing on the kinetic energy of the daughter particles.

Out of the various types of ternary fission investigations, some experiments focus on measuring the ratio of ternary to binary fission events. Pomme and collaborators used a Frisch gridded, twin ionization chamber with two solid state detectors and a neutron beam from GELINA to measure the ratio.
of LRA ternary fission events to binary fission events of U-235 in the thermal neutron energy regime. [28] Pomme’s experiment results provide a point of reference in a length vs energy distribution, shown in Figure 6.

Figure 6 shows LRA-ternary to binary fission ratio as a function of energy along with the resonance spectrum. [ADD REF or make clear it is part of previous sentence discussion] The data were measured in the resonance region below 0.1 MeV. The ratios were normalized to 1 with the deviations serving as a point of reference for probabilities as a function of energy.

Table 1. LRA-Ternary and binary fission data for events counted at 0 and 90 degrees. [60]

<table>
<thead>
<tr>
<th></th>
<th>$E_n$</th>
<th>$N_t^0$</th>
<th>$N_b^0(\times 10^7)$</th>
<th>$N_t^{90}$</th>
<th>$N_b^{90}(\times 10^7)$</th>
<th>$R^0/R^{90}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}$U</td>
<td>therm.</td>
<td>5177</td>
<td>1.5243</td>
<td>5570</td>
<td>1.6229</td>
<td>0.99±0.02</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>14 MeV</td>
<td>5587</td>
<td>1.4971</td>
<td>3961</td>
<td>1.2781</td>
<td>1.20±0.04</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>14 MeV</td>
<td>4684</td>
<td>1.5795</td>
<td>3364</td>
<td>1.4441</td>
<td>1.14±0.05</td>
</tr>
</tbody>
</table>
Table 1 shows collected data for U-235 and U-238 ternary and binary events from [60]. The counts at 0 and 90 degrees can be used to determine the ratio of ternary to binary events at 14 MeV. For U-235, the ratio at 0 degrees was found to be $(3.73 \pm 0.05) \times 10^{-4}$ and $(3.09 \pm 0.05) \times 10^{-4}$ at 90 degrees. Likewise, the U-238 ratios are $(2.96 \pm 0.04) \times 10^{-4}$ at 0 degrees and $(2.33 \pm 0.04) \times 10^{-4}$ at 90 degrees. These provide a baseline for comparison of our results at 14 MeV.

This paper will present work in progress on the ternary to binary fission ratios of neutron induced fission of U-238, U-235, and Pu-239 recorded by the Neutron Induced Fission Fragment Tracking Experiment (NIFFTE). The ultimate goal is to measure ternary to binary ratios over the range from 0.1 to 100 MeV neutron energy to be compared with previous measurements and to provide input to nuclear theory modelers.

SECTION 2
EXPERIMENTAL METHODS

2.1 NIFFTE

Nuclear fission, taking place at the subatomic level, is not something that is easily observed. Only the products of the reaction can be measured. There is debate over what exactly happens to the nucleus during the fission process, but theorists can use the results of experiments to help constrain the possible conditions and mechanisms that enable fission to occur. To date, measurements of the daughter nuclei and other particles have not been made with enough precision to resolve the debate. The Neutron Induced Fission Fragment Tracking Experiment (NIFFTE) hopes to provide better, more precise data to help resolve open questions in the theory of nuclear fission.

Figure 5. The world’s current fission cross-section ratio data for Pu-239 and U-235.
The NIFFTE collaboration is investigating fission at energies ranging from 0.1-100 MeV with the primary goal of reducing the uncertainties in inclusive fission cross-sections to sub-1% precision. Figure 5 shows the world’s data on Pu-239/U-235 cross-sections. The fine line surrounded by the green band represents the evaluated average of all the measurements shown with ±1% precision. The data in Figure 5 easily shows the need for improvement in the data as its scatter significantly exceeds the ±1% precision range. In this paper we are exploring neutron induced ternary fission using data collected by NIFFTE.

2.2 Experimental Design

Located at the Los Alamos Neutron Science Center (LANSCE), the experiment uses a fission time projection chamber (fissionTPC) designed and constructed by the NIFFTE Collaboration.[4] The fissionTPC is a MICROMEGAS TPC and serves as a 3D digital camera that records fragment tracks, including fragment specific ionization energy loss, angle of trajectory, and track lengths. The fissionTPC is approximately the size of a 2-liter bottle that is split into two internal chambers, volume 0 and volume 1, separated by the target plane where actinide deposits are bombarded by the neutron beam. The device has a cathode common to each chamber and the chambers provide 4\(\pi\) coverage using two readout planes divided into 5952 hexagonal pads.

Figure 7. The NIFFTE fissionTPC rendering, internal hardware, and pad size.

Figure 7 shows the fissionTPC design and the size of the hexagonal pads. The experiment directs a neutron beam at a foil target, at the center of the chamber between the two volumes, inducing fission. The fissionTPC is filled with a mixture of argon and isobutane used as a drift gas, serving as the medium for charged particles to deposit energy, through ionization. The uniform axial electric field allows the ionization electrons to drift to the pad plane, where their signal is amplified by the MICROMEGAS and their signal is read out on the hexagonal pads.

For this analysis, the experiment used two target foils each with two isotopes distributed in semi circles around the center of the target plane. These targets are Plutonium-239/Uranium-235 (P9/U5) and
Uranium-238/Uranium-235 (U8/U5). The high data rates of this experiment required custom readout electronics, called the EtherDAQ [5]. Each EtherDAQ card services 32 pads, resulting in a total of 192 cards for the entire experiment. The data collected by the EtherDAQ cards are read out continuously (ungated) and are stored as raw waveforms for further processing and analysis. Fission events are identified by the large, fast signal recorded on the cathode plane when fragments are released. This also provides the stop time for measuring the neutrons’ time-of-flight from creation at the production target approximately 9 meters upstream of the experiment.

2.3 Neutron Beam

The experiment uses a “white” neutron source to induce fission events in the fissionTPC. The neutron source is produced by a high energy proton beam colliding with a tungsten target to produce neutrons. The target is encased in cement with narrow openings for neutron collimation. Electric and magnetic fields are used to “sweep” away any charged particles. Figure 8 shows the data recorded by the fissionTPC at the 90-Left flight path of the Weapons Neutron Research (WNR) facility of the Los Alamos Neutron Science Center (LANSCE).

![Figure 8. Neutron Time of Flight (nTOF), All Fission Events, 123 hours](image)

Figure 8 shows the neutron time of flight (nToF) distribution of counted fission events. The inset shows the peak created by photon-induced fissions (photo-fission) due to a small number of earliest-arriving photons produced at the tungsten target. The bulk of the distribution shows neutron-induced counts. Since the mass of a neutron is a known quantity and the distance between the
neutron source and target foil can be obtained from the photo-fission peak location, the measured nToF are used to determine the kinetic energy of the neutrons.

Figure 9. Rendering of the fissionTPC with captured two and three track events.

2.4 Methods of Analysis

Figure 9 shows two images of reconstructed data from the fissionTPC with two actual events recorded by the experiment. In the image to the right, the left and right of the y-axis are labeled as Plane 0 and Plane 1. This coincides with the volume 0 and volume 1 mentioned earlier. Each voxel is the integrated signal from differentiating the raw waveforms recorded on each pad. Their locations in (x,y) are determined by the specific hit pad. For the gas mixture, pressure, and temperature conditions in the chamber, the drift velocity is measured to be approximately constant, allowing the z location of a voxel to be determined from the drift time to the pad plane that the ionization electrons take from their creation point.

Information from the specific ionization trails of the charged fragments in the gas can be used to help identify the various types of particles recorded by the detector. The particle identification (PID) parameters used in this analysis are shown in Figure 10. The curves shown are the characteristic specific ionization energy loss as a function of distance along the track, also known as the “Bragg” curve. The PID variable “Energy” is represented as being the area under the Bragg curve, while “Length” is the full distance along that same curve. The “Bragg Position” is the location on the track where the highest specific ionization occurs, and the “Bragg Value” is the peak energy at the Bragg Position.

Length and energy values are used to construct plots which provide information about the type of particle that produced a given trajectory. For this experiment, the length is measured in centimeters and the uncorrected energy value is represented as ADC counts (ADC). These Length vs ADC (LvsADC) plots have different regions in which daughter particles are classified.
Figure 10. NIFFTE PID Parameters for fission analysis.

Similar to the length and energy measurements, Bragg Position and Bragg Value provide information about the identity of a particle trajectory. The key difference between these pairs of variables is that length and energy represent global track information, whereas Bragg measurements are connected to a particular segment of the track. A Bragg value vs Bragg position plot represents the greatest energy released from the fission product at a particular position on the track. Bragg position is usually normalized to the length of the track so it should span values from 0 to 1.

Figure 11 displays a Length vs ADC plot on the left and a Bragg position vs Bragg Value plot on the right from data collected with the U-238/U-235 target. The LvsADC plot labels the regions for fission fragments and alpha particles, as well as protons and recoil ions. These labeled regions serve as a reference for fission product categorization in this experiment. Likewise, the Bragg Position vs Bragg Value plot also labels particular regions for alphas and fission fragments.

An important difference between alphas and fragments in LvsADC plots is that fragments have generally shorter track lengths and a greater energy than alphas, which have smaller energies and longer
track lengths. In Bragg plots, fragments are expected to have low relative Bragg positions and large Bragg values, whereas alphas are the opposite with greater Bragg positions and significantly smaller Bragg values.

For the analysis of ternary fission events, the fragments can be categorized by their total energy (in ADC counts) into high, middle, and low energy tracks which are then respectively labeled as the High Fragment (HighFr), Low Fragment (LowFr), and the Light Charged Particle (LCP). The charge and mass of these fragments are correlated with their energy. Table 2 shows the notation and color coding used for all subsequent analysis in this paper.

Table 2. Fragment Notation

<table>
<thead>
<tr>
<th>Label</th>
<th>Energy (ADC)</th>
<th>Mass (A)</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>HighFr</td>
<td>High</td>
<td>Highest</td>
<td>Black</td>
</tr>
<tr>
<td>LowFr</td>
<td>Middle</td>
<td>Middle</td>
<td>Red</td>
</tr>
<tr>
<td>LCP</td>
<td>Low</td>
<td>Lowest</td>
<td>Blue</td>
</tr>
</tbody>
</table>

Figure 12 shows a 3-dimensional illustration of a ternary event. The illustration is the general model used for analysis: the neutron travels parallel to the z-axis, colliding with the nucleus at the origin of the z-axis and some varying position on the xy-plane, within 2 cm of the origin. The fragments are emitted into one of the two volumes and their coordinates and angles are all measured with respect to the target plane between the volumes.
Because of the energy distribution during scission, the High and Low fragments are always emitted at large angles with respect to each other. Conservation of energy and momentum prevents the HighFr and LowFr in a 3-body decay from being emitted truly back to back. In addition, the absorbed neutron imparts a small forward momentum to the system, affecting the emission angles up to a few degrees.

SECTION 3
ANALYSIS

3.1 Data Cuts

The experiment collected data that needed to be analyzed to select candidate ternary events. This analysis looks at data from 315 runs with the P9/U5 target and 423 runs with the U8/U5 target. These runs were recorded from 11 January 2016 to 17 February 2016 and 27 October 2015 to 22 November 2015, respectively. The P9/U5 data set had 10 - 20 million events per run, while the U8/U5 data set had roughly 20 million events per run. A series of cuts was applied to isolate events that fit the ternary fission candidate model. The cuts applied to select ternary candidates were:

- Only events with 3 tracks originating from a common vertex
- HighFr and LowFr not in the same volume
- Track lengths longer than 0.2 cm
- Event vertex within 1 cm of the origin (x-y)
- 3-track ADC sum greater than 4500
- Relative Bragg position between 0 and 1

Figure 13 shows the quantity of data removed by each cut as it is applied sequentially, with the final bin, called GOOD TERNARY, being the remaining candidate ternary vertices selected for further investigation. The mass of data removed by the cuts shows the rarity of the ternary events.

3.2 Vertexing

The histograms on the left in Figure 13 display the overall vertex locations for all fission events, selected by requiring the cathode signal to indicate that a fission event occurred and the daughters point to a location within 1 cm of the origin without any other applied cuts. The upper row is for the P9/U5 target and the lower row shows the U8/U5 target. The middle and right-hand plots show the locations of ternary candidate vertices, after ternary cuts were applied, for each target actinide separately. The red and blue lines show the cuts used to select the different isotopes. The small gap between them is to remove overlap between the isotope event vertices.

An immediate observation from this vertex display is the significantly greater number of Pu-239 vertices compared to U-238 and U-235. This occurrence is expected because of the properties of each isotope. All of the isotopes decay via alpha decay and can be induced to fission by beam neutrons, but they have significantly different spontaneous fission probabilities and decay half-lives.
Figure 13. Sequential cuts on P9/U5 and U8/U5 data sets.
Figure 14. Two-Dimensional vertex location histograms of P9/U5 and U8/U5 targets.

Table 2 displays the half-lives and spontaneous fission probabilities for the isotopes. Pu-239 has the lowest probability for spontaneous fission but remains the most active. This is because it has a much shorter half-life for alpha decay than either of the other two isotopes. Much of the increased signal observed in the Pu-239 region of the vertex plots likely comes from misidentified fission events where an isolated decay alpha particle has been erroneously correlated with a fission vertex. For this reason we have more confidence in the results from U8/U5 data and will need to further investigate the P9/U5 data set to characterize and quantify these effects.

Table 2. Experiment isotopes and their primary decay modes, half-lives, and spontaneous fission probabilities.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-Life</th>
<th>Primary Decay Mode</th>
<th>Spontaneous Fission Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu-239</td>
<td>24110 y</td>
<td>α</td>
<td>$3 \times 10^{-10}$ %</td>
</tr>
<tr>
<td>U-235</td>
<td>$7.04 \times 10^8$ y</td>
<td>α</td>
<td>$7 \times 10^{-9}$ %</td>
</tr>
<tr>
<td>U-238</td>
<td>$4.5 \times 10^9$ y</td>
<td>α</td>
<td>$5.4 \times 10^{-5}$ %</td>
</tr>
</tbody>
</table>
3.3 The Visualizer

In order to investigate ternary fission candidates more closely, an event visualizer was constructed so these ternary candidates could be analyzed on an event by event basis. Figure 15 displays the 3D visualizer created for event analysis. The visualizer reconstructs ternary event candidates, color coordinating the HighFr, LowFr, and LCP.

Figure 15. 3D Visualizer for P9/U5 and U5/U8 ternary event candidates.
The events are organized by the RunID and Event # labeled at the top of the diagram. The visualizer provides a qualitative observation of the reconstructed event, while the LvsADC and Length vs Bragg value plots are provided for additional quantitative analysis. The difference between this visualizer and the one shown in Figure 9 is that this one uses post-reconstruction analysis data in which only trajectory information is available. The individual voxels shown in Figure 9 that were grouped to form the tracks are only available in the raw data.

The LvsADC plots show whether the event fragments meet the track length requirements for a ternary event. The fission products can be identified by referencing the general regions labeled in Figure 11. The Length vs Bragg value is used in contrast with the LvsADC plot to see how much of the total energy is in the Bragg value. The Length vs Bragg value plots are shifted left from the LvsADC because they only show the greatest energy deposited along the track, whereas the LvsADC shows the integrated energy for the track. These plots can reveal questionable candidates that may have a significantly lower Bragg value than expected.

3.4 Length vs ADC

Analysis of a single event’s LvsADC plot can help visualize individual ternary candidates and investigate odd phenomena, but viewing the overall LvsADC distribution for all events allows for better relating data sets to Figure 11. Figure 16 shows the LvsADC for ternary candidates, color coded by the particle type, for each target’s individual isotopes.

Using the regions labeled in Figure 11, the proton, alpha, and fragment regions are quite easily identified in Figure 16 where the HighFr, LowFr, and LCP tracks are color coded. In the P9/U5 plots, most of the LCP fall within the alpha region, with most of the activity near length = 5 cm, ADC = 100, which is probably due to decay alphas not associated with ternary fission. These candidate events are most likely misidentified and would need to be cut from further analysis. Due to the difficulty in creating unbiased cuts, the P9/U5 dataset was abandoned for further inquiry in this analysis in favor of the less contaminated U8/U5 data.
3.5 Ternary to Binary Cross-Sections

The U8/U5 plots do not appear to share the same alpha decay problem as the P9/U5 data. The secondary LCP band with lesser energy is likely due to LCP that lose energy inside the target before entering the detector volume. They are reconstructed with lower energy and shorter length but otherwise match the profile for alpha tracks.

Figure 17 shows the measured raw ratio of candidate ternary events to binary events vs the neutron time of flight (nToF). nToF is inversely related to the neutron energy, so lower energy neutrons move slower and have longer nToF than high energy neutrons, which move faster and thus have shorter nToF. The plots reveal the ratios to be constant and independent of nToF (neutron energy). The ratios for the P9/U5 target are 6.21% for P9 and 0.88% for U5 but are known to be too high, given the high level of alpha contamination in the data. Likewise, the ratios for U8 and U5 are also constant, at 0.60% and 0.59%, respectively. The U8 and U5 ratios can be compared to the 14 MeV results listed in Table 1.

For the NIFFTE detector configuration, 14 MeV neutron kinetic energy corresponds to nToF = 150-160 ns. The Table 1 U8 ratios were determined to be 0.0373% and 0.0309%, and the U5 ratios were 0.0296% and 0.0233%. These ratios are much lower than the ones from Figure 17. The measured U8/U5 ratios also require further investigation of the ternary candidates and analysis cuts to draw meaningful...
conclusions. The lack of statistics at high nToF (low energy) suggest that more data will need to be collected to quantify the ternary/binary ratio in U8 and U5 at lower neutron energies.

Figure 17. Ternary/Binary fission ratio plots for P9/U5 and U8/U5 as a function of neutron time of flight.

SECTION 4
DISCUSSION

4.1 Bragg Measurements

In order to better understand the characteristics of the ternary fission candidates, further analysis was conducted. Figure 18 shows the Bragg value vs Bragg position plots for the targets. The plots show the expected fragment and LCP regions. The fragments have a high Bragg value but low relative Bragg position, whereas the LCP have lower Bragg values but relative positions closer to the end of the track, near 1. There is a cluster of points with a Bragg position near 0. These vertices may be more likely to be due to ternary fission than the ones with relative Bragg position at larger values.

This can be explained using the diagrams shown in Figure 19. On the left is an illustration of a ternary fission event in which the starting locations of the three tracks completely overlap each other. For true ternary vertices, the track overlap makes it much more likely that some of the ionization energy loss belonging to one of the fragments gets assigned to the LCP. Since the LCPs have so much less energy overall, the extra mis-assigned energy from the fragment could skew the reconstructed Bragg position to the start of the track. For events in which the three tracks do not share any overlapping ionization, the chance of this occurring is much smaller, as shown in the right hand side of Figure 19. Good ternary events occur where all 3 tracks come from the same vertex. Misidentified ternary events have overlap regions where a binary fission event occurs near an unassociated alpha decay. The vertex finding code then ties the LCP track to the binary event, falsifying the LCP vertex, and creating a false ternary event. In the future, cuts to isolate the ternary events with LCP relative Bragg position near zero will be applied and these candidates will be studied in greater detail to better determine the ternary/binary fission ratios in
U-238 and U-235. In addition, vertex reconstruction, which was initially optimized to find binary fission events, will be re-optimized for ternary fission and the full analysis will be redone. Then the full 3D information will be used to characterize ternary fission events in greater detail.

Figure 18. Bragg value vs Bragg position plots for ternary vertex candidates.
SECTION 5

CONCLUSION

This analysis used data collected by the NIFFTE collaboration, which aims to improve the world’s data for fission cross-sections. The experiment uses a unique fissionTPC with a neutron beam aimed at P9/U5 and U8/U5 targets. The data for this experiment was placed under a series of cuts to obtain ternary fission candidates. Within the ternary candidate data, we found the ternary to binary fission ratios for a P9/U5 target to be 6.21% for Pu-239 and 0.88% for U-235, and 0.60% for U-238 and 0.59% for U-235 in the U8/U5 target. Comparing U8/U5 measurements to the 14 MeV results from Ref [59], 0.0373% at 0 degrees and 0.0309% at 90 degrees for U8 and 0.0296% at 0 degrees and 0.0233% at 90 degrees for U5, the U8/U5 measurements presented here are much greater. This difference will be investigated further in subsequent analysis. Additionally, the LvsADC plots for P9/U5 found vertex contamination, and a region of uncontained tracks for U8/U5. The contamination was further investigated in the Bragg Value vs Bragg Position plots. An unknown region was found that will need more analysis that will most likely lead to a new series of cuts on the data. Further investigations of ternary fission with the NIFFTE fissionTPC will be better constrained by the work presented here.

REFERENCES:


[8] F. Karpeshin. Ternary Fission of Nuclei into Comparable Fragments. DI. Mendeleev Institute for Metrology (VNIIM), Moskovsky pr. 19, St. Petersburg, 190005 Russia


[10] H. Diehl and W. Greiner. Ternary Fission in the Liquid Drop Model. Institut fuer Theoretische Physik der Universitaet Frankfurt, Frankfurt am Main, Germany


Received 16 April 1992, in final form 22 July 1992


[16] D.L. Smith and N. Otuka. Experimental Nuclear Reaction Data Uncertainties: basic Concepts and Documentation; Argonne National Laboratory, 1710 Avenida Del Mundo #1506, Coronado, CA 92118, USA Nuclear Data Section, International Atomic Energy Agency, Wagramerstraße 5, A-1400 Wien, Austria (Received 23 January 2012; revised received 10 June 2012; accepted 18 July 2012

[17] P. B. Vitta. Angular and Energy Distributions of alpha-Particles in LRA Fission. Department of Physics, Emory University, Atlanta, Georgia 30322

[18] Herbet Diehl and Walter Greiner. Theory of Ternary Fission in the Liquid Drop Model. Institut fuer Theoretische Physik der Universitaet Frankfurt, Frankfurt am Main, Germany


[24] W. Loveland and J. King, Total kinetic energy release in the fast neutron induced fission of 232-Thorium and 235 Uranium; Chemistry Department, Oregon State University Corvallis, OR 97331, USA


[27] R.B. Tashkhodjaev, A.K. Nasirov, and W. Scheid. Collinear cluster tripartition as sequential binary fission in the 235-U(nth,f) reaction. Institute of Nuclear Physics, 100214 Tashkent, Uzbekistan Joint Institute for Nuclear Research, 141980 Dubna, Russia Institut für Theoretische Physik der Justus-Liebig-Universität, 35392, Giessen, Germany


[29] C. Wagemans and A.J. Deruytter. Ratio of the Ternary to Binary Fission Cross Sections Induced by Resonance Neutrons in 241-Pu


[35] S. Vermote, C. Wagemans, O. Serot, J. Heyse, J. Van Gils, T. Soldner, P. Geltenbort. Ternary alpha and triton Emission in the Spontaneous Fission of 244-Cm, 246-Cm, and 248-Cm and in the Neutron Induced Fission of 243-Cm, 245-Cm, and 247-Cm. Nuclear Physics A806 (2008) 1-14


[37] N. Feather. Q Values in alpha-Particle-Accompanied Ternary Fission. Department of Natural Philosophy, University of Edinburgh, Edinburgh, Scotland


[40] P. Fong. Alpha-Particle Trajectories in Ternary Fission. Physics Department, Emory University, Atlanta, Georgia 30322.


[47] K.P. Santhosh, Sreejith Krishnan, and B. Priyanka. Light charged particle accompanied ternary fission of 242-Cm using the Coulomb and proximity potential. Received: 8 December 2013 / Revised: 12 February 2014 Published online: 2 April 2014 –Societ`a Italiana di Fisica / Springer-Verlag 2014 Communicated by F. Nunes

[48] A.K. Nasirov, R.B. Tashkhodjaev, and W. von Oertzen. Pre-scission configuration of the tri-nuclear system at spontaneous ternary fission of 252-Cf. BLTP, Joint Institute for Nuclear Research, Joliot-Curie 6, 141980 Dubna, Russia Institute of Nuclear Physics, Ulugbek, 100214, Tashkent, Uzbekistan, Inha University in Tashkent, 100170, Tashkent, Uzbekistan, Helmholtz-Zentrum Berlin, 14109 Berlin, Germany, Fachbereich Physik, Freie Universit “at, Berlin, Germany. Received: 9 February 2016 / Revised: 1 April 2016 Published online: 23 May 2016 –Societ`a Italiana di Fisica / Springer-Verlag 2016 Communicated by D. Blaschke


