Finding and analyzing U235 and U238 ternary fission events in the NIFFTE fissionTPC

A Senior Project

By

Gabriel Oman

Advisor J.L. Klay

Department of Physics

California Polytechnic State University San Luis Obispo

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Author: Gabriel Oman

Date Submitted: June 12, 2019

Senior Project Advisor: J.L. Klay

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Signature
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Date
Abstract

In this analysis the differences between ternary and binary fission were explored using data from the NIFFTE Collaboration’s fission time projection chamber (TPC). The ratio of binary-to-ternary events for U-235 and U-238 as a function of neutron kinetic energy in the range of 1-30 MeV is presented. The typical value of the ratio is approximately $10^5$ binary fissions per ternary fission, in agreement with previously published measurements. Future work will involve distinguishing the fissions of the two isotopes to provide more insight into this rare process.
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1. Introduction

The purpose of this analysis is to investigate the differences between binary and ternary fission induced by neutrons in the range from 0.1 to 30 MeV. Most research into ternary fission occurred during the Cold War era using older, less powerful accelerators that rarely went above a few hundred keV [1]. Because of that there’s a dearth of information about ternary fission available at higher neutron energies.

Binary fission occurs when the nucleus of an atom undergoes fission and produces two daughter particles. These daughter particles are nuclei in their own right, with one daughter particle being more massive than the other. For this analysis a daughter particle may also be referred to as a “fragment.” Binary fission is the most common type of fission and typically produces photons and neutrons of varying energy alongside the daughter particles.

There are several theories as to how exactly a nucleus undergoes fission [2]. The first hypothesis, theorized in 1935 by George Gamow, posited that the nucleus of an atom could be approximated as a droplet of incompressible liquid. It was further developed by Niels Bohr and John Archibald Wheeler. While this model effectively describes the collective behavior of the nucleons, especially at higher energy levels, it predicts a symmetric distribution of mass amongst daughter particles after fission. That has been observed to be false [3]. Nor does the model account for the angular momentum or parity of the nucleons.

Many modifications have been made to this model over the past 80 years, but the asymmetric mass distribution remains an issue. The nuclear shell model does a better job of predicting fission fragment size. It does this by describing the nucleus in terms of energy levels according to the Pauli Exclusion Principle[4]. It was originally developed prior to the liquid drop model of fission, but later expanded and modified to better describe fission events.

Fission can either be naturally occurring through the decay of the parent atom or induced through outside means. The fission events researched here aren’t natural events; that is, they aren’t due to the natural decay of the radioactive isotope. Rather, they are neutron induced fission events. The term comes from the fact that the experiment involves bombarding a target with neutrons. When one of those neutrons hits a nucleus it transfers energy to that nucleus. Given that the nuclei in these isotopes are already unstable, this added energy tips them over the edge and a fission event results.
Ternary fission is similar to binary fission, but produces three daughter particles rather than two [6]. The third daughter particle is most commonly an alpha particle, as shown in thermal neutron induced fission of U-233 in Figure 2 from [7]. This third daughter particle will be referred to as a Light Charged Particle (LCP). The other two daughter particles are smaller than what would emerge from binary fission. Like binary fission, ternary fission also produces photons and neutrons of various energies.

Exactly how these ternary particles are emitted from the scission point is unknown, but the liquid drop model offers three separate options [8]. Two theories are accepted as being most likely. In one case, known as direct fission, the LCP is produced at the scission point alongside the larger fragments. This happens through one of two processes. In the direct oblate fission model the three particles form the points of an equilateral triangle before splitting. In direct prolate ternary fission, the three particles form along the same axis before splitting apart. The third possibility suggested by the liquid drop model resembles binary fission. First, the parent atom undergoes binary fission into two fragments. One of those fragments would then undergo another fission event to split off the LCP. Figure 3 illustrates these possibilities.
Figure 2: Yield per fission of various third daughter particles in ternary and quaternary thermal neutron induced fission of U-233 [7].

Figure 3: Three proposed modes of ternary fission described by the liquid drop model [8].

This analysis is particularly focused on the ternary-to-binary fission ratio. That is, how many ternary fission events occur compared to how many binary fission events, as a function of bombarding neutron energy. Ternary fission is rare when compared to binary fission, as seen in Figure 2. Previous experiments determined the ratio at approximately one ternary event per one thousand binary events [2]. Others reported ratios of one ternary to ten thousand binary events
The goal of this analysis is to determine the same ratio for the neutron energy range accessible by the Neutron Induced Fission Fragment Tracking Experiment (NIFFTE).

2. Experimental Design

In this experiment fission is induced through the impact of energetic neutrons on a uranium target. The decay rate of uranium in this experiment is fairly low, so the vast majority of fission events recorded are of the neutron induced variety.

The NIFFTE project itself is located on the 90L beamline of the Weapons Neutron Research area of the Los Alamos Neutron Science Center at Los Alamos National Laboratory (LANL). It uses a time projection chamber (TPC) to track particles that result from neutron induced fission events originating from the fissionable target.

2.1 Neutron beam

The neutron beam for this experiment starts out as a beam of protons generated at the Los Alamos Neutron Science Center (LANSCE). The TPC is Target 4 on Flight Path 90L at the Weapons Neutron Research (WNR) facility, where the flight path is approximately 7 to 15 meters long. To convert the beam to neutrons, it’s directed at a tungsten block. Neutrons are produced through spallation when they are struck from the target by incoming protons. Those neutrons are then collimated into another beam before they strike the actinide target at the center of the TPC.

The energy for each neutron comes from the energy of the proton that produced it and is measured by the neutron time of flight (NTOF). The faster the neutron, the higher its energy. The proton pulse produces a wide range of energies, typically in the fast neutron (5-14 MeV) range. The NTOF is the difference in time between the accelerator start signal and a reaction in the TPC. Figure 4 shows the distribution of NTOF values for the neutron beam used in this experiment. This is very important to distinguishing between one fission event and the next, as is the relatively short drift time of the particles and fragments in the chamber. Overlapping events means more tracks in one event than there should be and complicates the analysis.

The TPC is typically mounted 6 to 8 meters away from the spallation target, which requires an NTOF resolution of about one nanosecond. This is easily attainable, and makes overlapping events a rarity. More common, but still rarely, the timing of a fragment will be such that it is detected in more than one event. This is an issue when trying to find an event with more than two tracks, as determining between a ternary event with three tracks and a binary event with an extra track left over from the previous event can be difficult. Vertexing can help reduce these
misidentifications. Vertexing is the process of analyzing a track by its vertex, where it originated on the target.

![NTOF plot](image)

**Figure 4:** An NTOF plot for the NIFFTE TPC. The red highlight is the photofission peak.

Immediately to the left of the main NTOF peak on Figure 4 there’s a smaller peak at about 29 ns. That’s the photofission peak. It’s created by the photons emitted by the spallation of the tungsten target. Because photons have a uniform velocity irrespective of their energy, we can use the time it takes for them to travel between the target and the detector to precisely measure the distance between those two points.

### 2.2 NIFFTE fission TPC

The core of the NIFFTE experiment is the MICROMEGAS (MICRO MEsh Gaseous Structure) fission Time Projection Chamber (TPC) that allows us to examine the cross sections of major actinides undergoing fission [10]. The TPC is an approximately 2-liter volume that consists of 5952 2-mm pads and contains an argon-isobutane gas mixture operating at 550 Torr. The pads record the ionized paths left by fission fragments and particles as tracks. This ionization also gives a method to determine energy loss, as the kinetic energy of the particle is transferred into the surrounding gas to ionize it. Figure 5 shows an example of a binary fission recorded in the TPC. The actual method will be described later.
The TPC itself is a $4\pi$ recorder with 100% acceptance to the first order. The one exception to this is when fragments travel parallel to the target itself. They lose so much energy traveling through the target that they’re nearly impossible to detect. To address that issue, cuts can be made to only accept data from an angular region away from target. This restricted angle only examines tracks that pass through a minimal amount of the backing and thus lose the least energy.

The target is 20 mm across and composed of 50-200 $\mu$g/cm$^2$ U-235 and U-238 deposits on a carbon backing. It’s located between the two drift chambers that make up the TPC. For the data collected in this analysis, Chamber one (also referred to as Volume 1) is “up-stream” of the target, meaning it is on the same side of the target as the entering beam. Chamber zero (also referred to as Volume 0) is “down-stream,” meaning that it’s the chamber on the side of the target plane opposite the beam entry. The side of the target with the actinide deposits faces Volume 0. Both chambers are 15 cm in diameter with the pads located 5.4 cm away from the target. The typical track length of a fragment in the TPC is about 50 mm.

Figure 6 shows an example of a ternary fission event from spontaneous fission of Cf-252. One fragment is present in each volume with an LCP track running almost parallel to the target. Planes one and zero recorded the ADC (a unitless measure of particle/fragment energy), which can be seen near the bottom of the image. As can be seen in the visualization, the fragment tracks are nearly perpendicular to the target and appear as high-intensity dots on the ADC plot. The LCP track, by contrast, appears as a lighter streak on the plane zero plot.
Figure 6: An example of spontaneous ternary fission of Cf-252 observed in the TPC.

Figure 7: A cross-section of the actinide target in the TPC [11]. The black outline shows where measurements are taken to produce the binary/ternary ratio estimate.

Figure 7 shows the origin of fragments in all neutron-induced fission events for the U-235/U-238 target used in this analysis. The more active actinide, U-235, is on the bottom. The highest concentration of tracks originate from near the center of the target where the neutron
beam is aimed. The number of tracks drops off as a function of radial distance from the center after that. There are a number of pixels that didn’t record any data and are therefore “dead.” That’s expected and doesn’t meaningfully impact the experiment, as a cut is applied to remove them from the analysis.

Tracks are created when there are 20 or more recorded readings in a row. That means that the fragment or particle has activated twenty or more of the small 2-mm hexagonal ionization detectors. The TPC then compares the ADC of each of these voxel measurements and fits them with a straight-line function. That function determines the length, start, and end points of the track. The ionization profile depends on the type of track. For alpha particles, the end of the track has the largest ionization, while for heavier fragments the start of the track has the highest ionization. The ADC of each point is added together to make the total ADC of the track. Figure 8 shows the distribution of length versus ADC for fission events in the TPC, including labels to identify the different particles, from [11].

Figure 8: Length v. ADC for fission events with labels describing the different particles, from [11].
3. Analysis

The data from the NIFFTE experiment is stored first as runs. These are 22 minutes long and contain all of the data collected inside the TPC during that time. Within runs come the fission events recorded by the TPC. Within each event fragments and LCPs are recorded as tracks. These tracks are the key to determining whether or not a given event was binary or ternary fission. The number of tracks per event is recorded, but not every event with three tracks is necessarily a ternary event.

The data used in this paper was filtered prior to the application of the analysis described by the author. Specifically; for each event there must be a fission fragment with ADC greater than or equal to 10,000 in Volume 0, there must be an NTOF value greater than zero, all tracks must have ADC greater than 50, length greater than 0.5 cm, and all tracks must be the highest quality fit from the TPC’s fitting algorithms. The tagging fragment from Volume 0 is referred to as “FF0” in the following discussion.

To start identifying ternary fission events the analysis program first restricts its analysis to fragment tracks that start within 1 cm of the target’s center on the xy-plane. Any tracks that begin further out couldn’t have come from the target. Figure 9 shows that the fragment tracks always start very near to the target on the z-axis. Fragments come from all radii within the target but as the distance from the center grows, the number of observed fragments grows, as can be seen in Figure 10. This is because the area of a ring of radius R and width ΔR grows with R. The absolute distance (x-y-z combined) from the target center can be seen in Figure 11.
Figure 9: Distance from the target center on the z-axis for FF0.

Figure 10: Distance from the target center on the xy-plane for FF0.
The second major restriction on the analysis looks at ADC value. As seen in Figure 8, fission fragments are expected to have higher ADC and shorter length than other particles because of their larger mass, charge, and thus, ionization potential, and so the program defines fragments as those with ADC greater than or equal to 10,000. The energy for a fragment is far higher than an LCP. When looking for the LCP only tracks with an ADC less than 10,000 are considered.

Due to the target facing Volume 0, the ADC for FF1 is expected to be lower than the ADC for FF0 because of its travel through the carbon backing of the target. That can be seen in a comparison of the two distributions in Figure 12, which shows the ADC values of FF0 (red) and FF1 (blue), respectively. Note the expected double-bump feature which is a characteristic of fission, with one fragment more massive than the other. Also note that the ADC distribution for FF1 is shifted to lower values compared to FF0. Sometimes the larger fragment travels into volume zero and leaves a larger energy reading, and sometimes the smaller fragment travels into volume zero and leaves a smaller reading.

Figure 11: Absolute distance from the target center for FF0.
An event is considered a ternary candidate event if it has two fragments and an LCP falling within the restrictions above. That’s one fragment in volume zero with 10,000 or more ADC, one fragment in volume one with 10,000 or more ADC, one LCP with less than 10,000 ADC, and the initial fragment track starting within 1 cm of the target center on the xy-plane and the other two tracks start within one centimeter of FF0 on the xy-plane. From Figures 13 and 14, it is clear that a cut of 0.2 cm for the distance between FF0 and FF1 is appropriate. The absolute distance between the start points of FF0 and the LCP is shown in Figure 15. The start of the LCP is required to be within 1 cm of FF0.
Figure 13: The distance between FF0 and FF1 on the z-axis.

Figure 14: The distance between FF0 and FF1 on the xy-plane.
Figure 15: The absolute distance between FF0 and LCP start.

Furthermore, all LCP candidate tracks are expected to be longer than or equal to five centimeters. This is due to the nature of the particles. As most of the LCP candidates are expected to be energetic alphas, they have a substantially longer track in comparison to other particles. Previous experiments on ternary fission have dubbed them “Long Range Alpha” (LRA) particles [12].

The most effective means of actually identifying which events are ternary is to find the events that contain an LCP and still meet all of the conditions and cuts listed previously. LCP candidates that meet the cuts can be seen on the length versus ADC distribution shown in Figure 8 and Figure 16. There’s a sharp line at the 10,000 ADC mark on Figure 16 from the restriction in this analysis that only events with a fragment in Volume 0 with ADC > 10,000 were considered.
Figure 16: Length versus ADC for all tracks. Fragments have large ADC and short length (lower right) compared to alphas (the rising band near the center), and protons (the yellow patch at low ADC).

Figure 17: Length versus ADC for LCP candidates. LCP candidates are to the right of the vertical black line at 300 ADC.
The most promising LCP candidates are located in the horizontal band near 6 cm and an energy between 300 and ~1500 ADC. These candidates can be seen on both Figure 16 and Figure 17, though it’s clearer on the latter. Those are the particles that fit the requirements for both length and energy. The reason the band is horizontal is because these alphas are so long they often leave the detector before depositing all of their energy, thus only a portion of their energy is observed. Once the band merges with the proton region they cannot reliably be identified and must be removed from consideration.

4. Results

Figure 18 shows the ratio of binary to ternary fission events as a function of neutron kinetic energy. Given the small number of ternary events the ratios have been binned to improve their accuracy. The ratios above 1 MeV are all around $10^5:1$ binary to ternary, in agreement with previously published literature [13][14]. This result is for the combined values of U-238 and U-235 targets. Although there are some fission events for U-235 below the 1 MeV threshold, there shouldn’t be any for U-238 because it does not undergo fission for neutrons with less than 1.4 MeV. Future analysis could distinguish the events originating from the two different actinides.

![NKE Ternary v. NKE Binary](image)

Figure 18: The number of binary counts per ternary count as a function of neutron kinetic energy.
5. Discussion

The purpose of this analysis was to determine the binary-to-ternary ratio for U-235 and U-238 as a function of neutron kinetic energy in neutron-induced fission. As Figure 18 shows, the ratios, which average around $10^5:1$ binary-to-ternary fissions, agree with previously published literature [13][14].

While this analysis was effective in finding the binary/ternary ratio, there are issues with it. The first issue, and the one that should be immediately addressed in any further research, is that this analysis doesn’t differentiate between the two isotopes present in the sample. The target is made up of U-235 and U-238 with each isotope forming half of the target. The analysis up to this point treats the target as one homogeneous isotope rather than two separate ones.

As it is, the code used in this analysis doesn’t care about which isotope is which so long as it’s within a certain range of the target’s center. The code could be modified to differentiate between which half of the target the tracks came from, allowing the data to be separated into results for each isotope. Although this is a small change, there was not enough time to implement it and re-run the full analysis before the writing of this report. This would also enable the analysis to extend to energies lower than 1 MeV since U-235 experiences fission at and below that threshold, but U-238 doesn’t undergo fission until bombarded with neutrons of at least 1.4 MeV. Future work with this dataset would provide further information about this rare process.

6. Conclusion

For this paper the differences between ternary and binary fission in U-235 and U-238 were explored using data collected with a time projection chamber by the NIFFTE Collaboration. The analysis involved determining appropriate cuts to apply to reconstructed events to determine the ratio of binary-to-ternary events as a function of neutron kinetic energy in the range from 1 to 30 MeV. The typical value of the ratio was found to be $10^5:1$ binary to ternary events for the combined U-235 and U-238 isotopes above 1 MeV, which is in agreement with previously published measurements.

In the future, this analysis could be improved by examining data for both isotopes individually rather than as a single data set. In addition, other vertexing cuts and particle ID selections might be employed. The most obvious benefit from this research is a better understanding of the fission process. That understanding could be used in the creation of more efficient nuclear reactors or sensors that could more accurately identify nuclear isotopes.
References


