Precision Fission Cross Section Measurements using a Time Projection Chamber

Progress Report, March 2012

Dipl.-Ing. Verena Kleinrath

Institute for Atomic and Subatomic Physics, Vienna UT, Austria

Department of Nuclear Engineering, Idaho State University, USA

Zusammenfassung

Das vorliegende Projekt arbeitet an der Implementierung eines revolutionären Messprogramms mit der Absicht Spaltquerschnitte in noch nie dagewesener Präzision zu liefern. Eine 4π Time Projection Chamber (TPC) soll alle Unsicherheiten aus bisherigen Messungen minimieren. Dieser Teilchendetektor, bekannt aus der Hochenergiephysik, ermöglicht eine präzise und vollständige Aufnahme von ionisierenden Teilchen aus neutroneninduzierten Spaltvorgängen. Eine Herausforderung an das Projekt ist die komplette Miniaturisierung dieses klassischen Instruments um es für die Aufnahme von Teilchen aus der Kernspaltung zu optimieren. Die dafür entwickelte Infrastruktur wird schlussendlich auch Informationen über die Ladungsverteilung zum Zeitpunkt der Kernspaltung liefern, worauf der Fokus der Dissertation der Autorin liegen wird.

Abstract

A fission cross section measurement program is envisioned with the purpose of providing neutron-induced fission cross section data with unprecedented precision and accuracy. A 4π time projection chamber (TPC) is being considered to minimize uncertainties associated with previous measurements. This instrument, successfully used in the field of high energy physics for over 25 years, provides detailed tracking of charged particles emitted in neutron-induced fission events. The key challenge in such an experiment is the miniaturization of the instrument to record complete tracking information from the highly ionizing particles in an event by event manner. The infrastructure needed to meet this challenge will then also provide insights on the nuclear charge configuration at the point of scission. This is going to be the focus of the author's PhD thesis.

Acknowledgment

The author thanks the Austrian Marshall Plan Foundation, whose generous support facilitated the research visit to the United States that will be the cornerstone of the author's PhD thesis.

Contents

1 Introduction **1**

2 Motivation **4**

2.1 The Time Projection Chamber Technique 4

2.2 A Fission Time Projection Chamber 7

2.3 Fission Cross Section Measurements 8

2.4 Potential Impact on Fission Physics 10

3 Progress on PhD Work **12**

3.1 Data Reconstruction Algorithms 12

3.2 Validation of Current Tracking Software 15

3.3 Towards a New Tracker 20

3.3.1 Crude Particle Tracking and Identification 20

3.3.2 Mapping xy Coordinates to Pad Plane 23

4 Summary and Outlook **25**

List of Figures

2.1 An overlay of simulated particle trajectories in a high data rate STAR TPC. 5

2.2 A schematic view of MICROMEGAS with the amplification gap between the micromesh and the anode. 6

3.1 A simulated waveform signal from a Cf252 source in the TPC. 13

3.2 The recursive prediction and filtering steps along a track and the smoothed estimate within the Kalman track fitter. 15

3.3 The polar angle reconstruction bias for 1000 simulated alpha particles. 17

3.4 The vertex reconstruction bias with varying polar angle for 1000 simulated alpha particles. 17

3.5 The track length reconstruction bias for 1000 simulated alpha particles using two different types of hit creation. 19

3.6 The slope of the total waveform (charge arrival parameter) versus track angle for 1000 simulated alpha particles. 21

3.7 Track length versus total charge for a simulated Cf252 source. 22

3.8 Typical Bragg curves for alphas (a) and fission fragments (b) produced using SRIM. 22

3.9 The simple specific ionization ratio calculated from the slopes of the total waveforms used for particle type distinction. . . . 23

Chapter 1

Introduction

A revolutionary measurement program for important fission cross sections is being considered. A time projection chamber (TPC), an instrument well-known in high-energy physics, is being studied for use for the detailed reconstruction of charged particles emitted from nuclei.

Fission cross section measurements have been typically carried out using parallel plate gaseous fission chambers. A number of systematic liabilities are associated with previous measurements, leading to inconsistencies in the results that have been used to prepare current nuclear data libraries, particularly for cross sections induced by fast (kinetic energies around 1 MeV) neutrons. Traditional fission chamber measurements typically employed a ratio technique to measure cross sections and are therefore limited by the accuracy of the cross sections standard, such as U235. A fission TPC can be filled with hydrogen gas and establish cross sections relative to the extremely well known H(n,n)H elastic scattering, thus removing the uncertainty liabilities associated with the U235 standard. Similar to the 3D visualization of charged particle emission during beam collisions in high energy physics, a fission TPC provides the same reconstruction strength. A fission TPC, however, can provide extended particle identification capabilities by containing the entire ionization history of charged particles within its active volume. The detector being studied will minimize all of the errors and uncertainties associated with traditional cross section measurements.

A fission TPC can measure fission cross sections to an unprecedented precision and accuracy for fast neutron-induced fission and provide new data to nuclear data evaluators. Furthermore, the experiment envisioned can be conducted in a high flux fast neutron beam, enabling the observation of more exotic phenomena, such as alpha accompanying fission, ternary and quaternary fission. The precise measurement and detailed reconstruction of the charged particles emitted in fission will also provide information on physics and specifically the charge configuration at the point of scission.

The current simulation study of a fission TPC assumes specially designed microelectronics to process extremely high bandwidth data, a precision gas handling system to control temperature and pressure in the TPC gas volume, a real time event builder, as well as an online control and monitoring interface. The software simulation as well as track reconstruction and particle identification. Chapter 3 gives an overview of the author's work in software validation and development.

The author's PhD thesis will focus on advanced simulation and reconstruction techniques to extend the physics reach of a fission TPC. Detailed simulation studies allow an understanding of the physics and detector response of the envisioned instrument. A fully informed track fitter will be developed for maximization of the information extracted from data in a highly segmented fission TPC. Advanced reconstruction will be needed to provide meaningful kinematic and particle identification quantities. Insights into nuclear charge kinematic details will provide information on the nuclear charge configuration at the point of scission.

Chapter 2

Motivation

Previous fission cross section measurements have been typically conducted using gaseous fission chambers. A number of systematic liabilities are associated with this technology, leading to large variations of nuclear cross section data in the current nuclear data libraries, especially for cross sections in the fast neutron energy range. The three dominating liabilities are believed to be particle identification, target and beam non-uniformities and uncertainties in the U235 standard. A fission TPC is an advancement over the traditional fission chamber and has superior particle identification capabilities and pointing resolution. The instrument can not only provide improved fission cross section measurements but also produce information on fission physics.

2.1 The Time Projection Chamber Technique

The TPC is an instrument that has frequently and successfully been used in high energy physics over the last 25 years, see [1], [2] and [3]. The TPC provides a complete three dimensional digital picture of the ionization in a gas volume. It allows for the complete reconstruction of ionizing particle trajectories and also provides detailed information on the specific ionization along the entire track as it ranges out in the drift gas. The TPC technology has been used in the past for precision and high data rate experiments, a famous example being the STAR detector at Brookhaven [4], which studies heavy ion collisions. Figure 2.1 is a rendering of the STAR TPC, including a high number of tracks with the one Helium particle of interest highlighted. Recent improvements in electronics and computation enable the use of TPCs for high resolution and zero-dead-time applications, like nuclear fission.

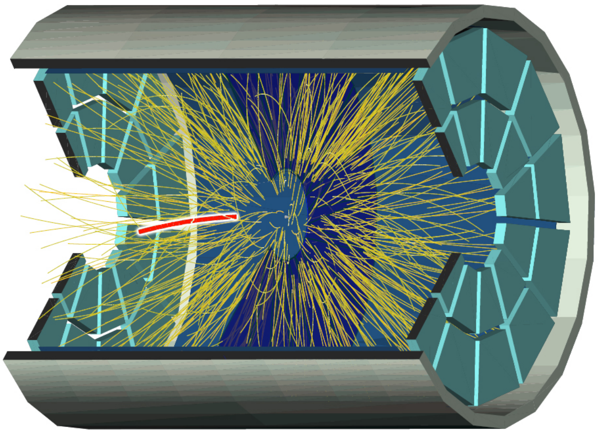


Figure 2.1: An overlay of simulated particle trajectories in a high data rate STAR TPC (figure 1 from [5]).

The TPC is an ionization detector, typically consisting of a pressurized chamber with a central cathode and two parallel anode detector planes on each end of the chamber. Each anode pad plane has a number of channels arranged on the pad for radial resolution. Ionizing particles emitted from an event ionize the filling gas. An applied electric field between the target and the readout anode pad planes accelerates the ionization electrons towards the pad planes and minimizes their recombination with positive ions. The measured electron drift time (knowing the drift speed in the gas) is used to calculate the z-coordinate of the ionization, while the channels on the anode pad plane provide the radial angle information for reconstructing the particle trajectories.

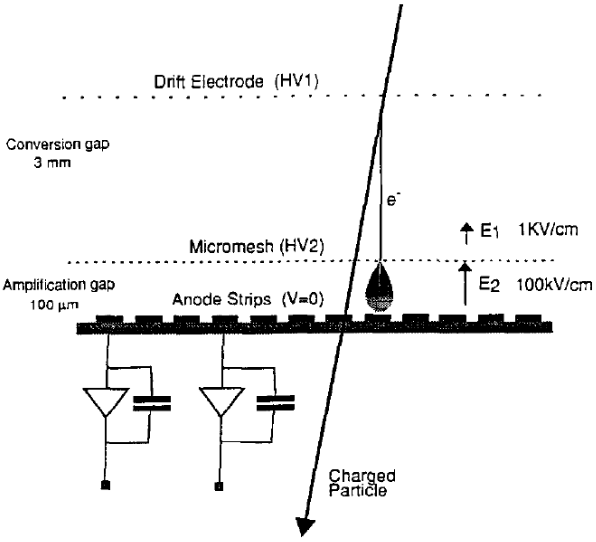


Figure 2.2: A schematic view of MICROMEGAS with the amplification gap between the micromesh and the anode (figure 1 of reference [6]).

The ionization electrons are multiplied and accelerated towards the anode using an avalanche amplification system. Wire amplification has been the most common method used in particle physics to produce this gas gain in the past. Recent developments have shifted the paradigm to better spacial resolution and less ion feedback into the TPC by the electron avalanche. The micromesh gaseous (MICROMEGAS) technology employs a fine grid of synthetic mesh wire kept in front of the pad plane, see [6] and [7]. Figure 2.2 shows the schematics for the MICROMEGAS avalanche system. The electrons are amplified by the high field between the micromesh and the pad plane.

2.2 A Fission Time Projection Chamber

A key challenge for a fission TPC experiment is the miniaturization of the classic TPC design from high energy physics. A fission TPC contains the entire ionization history of fission fragments and alpha particles within its active gas volume, maximizing particle identification.

The fission TPC design used for the Monte Carlo simulations in chapter 3.2 consists of a pressurized cylindrical chamber of about 11 cm length with a 7.5 cm radius. The vessel houses a central cathode and two parallel anode detector planes with nearly 3000 hexagonal detector pads arranged into sextants on a printed circuit board on each end of the cylinder. The radioactive target is placed into an axial opening in the central cathode plane. The vessel is assumed to be aluminum and operating at a pressure of 1.3 bar (chosen to stop both alpha particles and fission fragments within the active volume). The filling gas is assumed to be P-10 (90 % Ar + 10 % CH4).

The major hardware components of the envisioned experiment include the centerpiece - the pressure vessel with the electric field cage, the pad planes and the gas amplification; a complex data acquisition system, the gas handling and the radioactive targets. The infrastructure for this experiment will include specially designed microelectronics to process high bandwidth data, a real time event builder, an online control and monitoring interface, as well as the necessary software framework for complete reconstruction of experimental data and output from simulation packages.

The software for the fission TPC study is mainly built on C++ code arranged in modules using XML as configuration files. The package includes a complete simulation of the fission process in the target, the transport through the TPC volume based on GEANT4 [8], the detector response, as well as track reconstruction from digitized signals and data analysis based on ROOT [9]. There are currently different track finding and reconstruction algorithms under investigation.

2.3 Fission Cross Section Measurements

The available nuclear data libraries are primarily based on measurements using traditional fission chambers. The library evaluations are based on theory as well as measurements. The systematic uncertainties in the measurements propagate into the data in the evaluated databases, especially for the fast energy spectrum. Staples and Morley [10] give an overview of previous Pu239 cross section measurements and the available evaluated data. They report differences between the evaluated data and individual measurements of up to 20 percent, and around 3 percent between different evaluations. Individual measurements are often inconsistent with their reported errors, which suggests that there are some underestimated systematic errors involved.

It is assumed, that three factors have previously impeded the sub 1 percent accuracy measurement of fission cross sections. The three dominating uncertainties are believed to be missing particle identification (alpha separation), target and beam non-uniformities and the uncertainty in the U235 standard cross section. Unfolding a cross section from a ratio procedure is naturally burdened with the uncertainties of the U235 data itself. A fission TPC will be able to minimize or even eliminate all three of those liabilities.

Traditional cross section ratio experiments have include back to back fission chambers in the same neutron flux, measuring the cross section of the isotope interested in relative to the standard of U235. However, also the well-known U235 (n,f) cross section is only known to a precision in the 1 percent range. As it is the goal of the envisioned fission TPC project to determine cross sections with a sub percent precision, the ratio method with U235 will not be sufficient in the end. A fisson TPC experiment will measure with respect to the much better known H(n,n)H elastic cross section. The TPC volume would be filled with hydrogen gas, serving both as the ionization medium and the cross section standard.

The reasoning to conduct a ratio measurement in the first place is the possibility to eliminate effects from beam fluctuations in flux and energy. The envisioned fission TPC can eliminate the beam and also target non-uniformities because of its superior pointing resolution. The goal of the fission TPC project is to produce two highly segmented anode planes with around 6000 pads in total, which in conjunction with advanced particle track reconstruction, will lead to a pointing resolution in the range of 100 microns. This resolution allows the mapping of target non-uniformities using spontaneous radioactive decay of the target without beam and subsequently determining beam fluctuations with beam on.

The third main liability in cross section measurements is the particle identification capability. Fission chambers can only distinguish between fission fragments and lighter particles based on energy cuts, introducing an issue for fragments that undergo scattering and energy loss within the target. A fission TPC will not only provide energy information from the ionizing particles, but also include track length and specific ionization, as all ionizing particles can be contained within its active volume. This additional insight on particle properties leads to advanced particle identification capabilities.

2.4 Potential Impact on Fission Physics

Previous measurements of fission cross sections typically used parallel plating gaseous fission chambers. Those fission chamber have low bandwidth and can not provide accurate particle identification or insights into the dynamics of fission. A fission TPC is being designed to minimize the systematic errors associated with fission chamber measurements. However, the advanced instrument will also provide superior particle identification and information on fragment masses.

Fission theory can be considered the ultimate many-body quantum problem and shows characteristics of both quantum and classical mechanics. A purely classical representation of the number of nucleons is the liquid drop model, where one assumes the nucleons are bound in a fluid. Fission theory calculations based on this approximation lead to a single hump fission barrier potential. If one introduces quantum mechanical shell corrections to the system, a more accurate double hump potential is the result, see [11]. Fission modeling can describe the process of fission up to the point of scission. From there on, where the nucleus splits into a number of fragments and particles carrying charge, mass and energy, we rely on measurements. A fission TPC can provide information on the charge configuration at the point of scission to be used in theoretical fission models.

An example that will be observed in the fission TPC is alpha accompanied fission. In this process, a nucleus fissions into two large fragments and an accompanying alpha particle. The question theorists ask is 'Where does the alpha particle come from?'. Looking at the fission barrier and the potential phase space provides two possible answers. The classic liquid liquid drop model describes the elongation of the original nucleus until it forms a neck in the center, which then snaps at two points to produce two heavy fragments and an alpha. A quantum mechanical description involves the idea of different particle states existing in the original nucleus, including alpha states. The snap of the elongated nucleus then shifts the centers of mass of the two resulting fragments toward each other and the neck collapse enables the alpha state to reach its escape probability from the nucleus. At the point of scission, the fission TPC measurement comes into the picture. The accompanying alpha particle will function as a probe for the electric field at the scission point. The measurement will include information on the electronic configuration at the point of scission and therefore provide insight into the quantum mechanical description of the fission process itself.

The track reconstruction and particle identification capabilities of a fission TPC will have to be developed to maximum precision in order to get a glance at the point of nuclear scission. Even with a perfect TPC and highly precise algorithms, real world effects like multiple scattering of particles in the target itself will complicate this endeavor. Advanced reconstruction algorithms will therefore necessarily be a focus of the author's PhD work.

Chapter 3

Progress on PhD Work

The following pages shall describe the tasks accomplished at Idaho State University within the last six months. This chapter shall solely focus on the work that has been done by the author in simulation and software development. Efforts towards an advanced track finding and reconstruction have been undertaken.

3.1 Data Reconstruction Algorithms

A software package has been developed for the fission TPC studies. The software is mainly built on C++ code arranged in modules using XML as configuration files. The package includes a complete simulation of the fission process in the target, the transport through the TPC volume based on GEANT4 and the TPC detector response with effects like charge sharing and diffusion. The track finding and reconstruction from digitized TPC signals are also based on C++ modules, data analysis is using the ROOT software. There are currently different track finding and reconstruction algorithms under consideration, the most developed being a track finder and fitter based on Hough transform methods [12] and a Kalman filter [13].

The track reconstruction software transforms digitized waveform signals coming from the individual channels on the detector anode plane into a reconstructed track. The 2-dimensional (x,y) coordinates of the ionizing particle track comes from the position of each pad on the segmented anode plane, and the z-coordinate is based on the arrival time and shape of the signal from ionization electrons and is correlated to the drift speed of those electrons within the TPC. The height of the waveform signal correlates to the energy of the ionizing particle that left the track in the active volume of the TPC. The reconstruction software relies on the individual waveform signals, their channel location on the pad plane, their timestamp and the size of their rise. Figure 3.1 shows an example for those waveform signals arriving at different pads for a track.

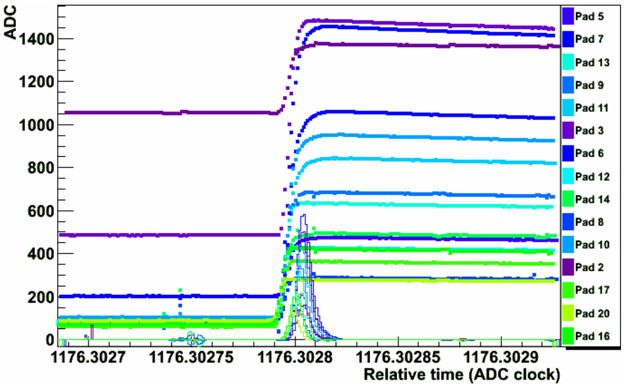


Figure 3.1: A simulated waveform signal from a Cf252 source in the TPC.

The first step in the reconstruction chain is the production of digits. Digit objects contain information on the channel, timestamp, rise time and size of the original waveform. This knowledge is extracted from the original waveform either fitting the signal or taking the derivative of the signal. The information is used to visualize data objects distributed in the 3-dimensional space (partitioned in hexagonal voxels from the geometry of the pad plane) within the TPC containing energy (or uncalibrated ADC) information. Those objects are then grouped to form clusters and hits by taking into account near neighbors and averaging over charge distribution. The next step in the reconstruction is identifying a track hypothesis for this collection of hits. A commonly used technique in high energy physics calculates probabilities for all possible tracks (Hough). A smoothing algorithm connects the individual hits, filters noise and outliers and also calculates the tracking uncertainties for the most probable hypothesis (Kalman).

The current reconstruction software assumes that the track trajectory is a straight line (there is no magnetic field in the current simulation). The Hough module calculates a track probability density by using all possible combinatorics of the available points in angle space using straight line hypotheses. The angle with the highest probability is the seed for a track fit, the process continues for all probabilities above threshold.

Once a group of hits have been identified as part of a track, the Kalman module connects them and calculates a smoothed track. The Kalman filter is a recursive track state estimator that determines the best fit for a set of points, adding one track point after another. In each step the state vector is predicted using the currently available information, then the propagation and error matrices are calculated. With each step the uncertainties become more refined as information is added. At the end of the track the filter is engaged once more to predict and filter the track in the opposite direction, which smooths the track and provides the best estimates of track parameters. Figure 3.2 shows the recursive Kalman filter process at the track points k-1 to k+1 with stepwise prediction and filtering along the track, the cones around the path estimates represent the uncertainties at that step. One can see that with each step the uncertainties are refined. The plot also includes the final track estimate after the smoothing in opposite direction and the true particle track. Both modules, Hough and Kalman, require some initial input parameters, the optimal values for those have been determined in the validation process of the reconstruction modules described in the following section.

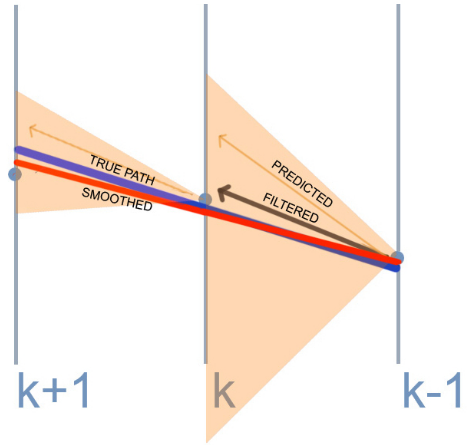


Figure 3.2: The recursive prediction and filtering steps along a track and the smoothed estimate within the Kalman track fitter.

3.2 Validation of Current Tracking Software

The tracking software is regularly tested and validated against a variety of simulations. The software contains an entire simulation package based on GEANT4, that simulates particle transport from the target through the TPC to the detector, a detector simulation modeling ionization of the gas, transporting the electrons through the drift gas, through the amplification and to digital waveform creation. The model takes into account a number of physical effects including diffusion of the electron cloud in the volume or charge sharing between neighboring channels. The package also contains a detailed account of the final digital processing, transforming original GEANT4 Monte Carlo (MC) truth particle tracks into ADC signals similar to those expected in such an experiment. In a validation study reconstructed track parameters are compared to the seed track parameters from the simulation. These comparisons provide invaluable feedback on the simulation and the reconstruction software used to optimize the algorithms and help refine an experiment.

The current software was validated and ideal values of input parameters for the reconstruction modules were found. The method of digit creation and algorithm initial values like the Hough radius (measure of how far digits or hits can be spread in space to be initially considered part of a track) were shown to have a large impact on the reconstruction quality. The quality of the reconstruction was determined by plotting the MC truth versus the values obtained from the reconstruction for track angles, track lengths and track vertex position. The vertex resolution versus track angles was also investigated, as varying track angles give different results due to the cylindrical geometry of the TPC. Figure 3.3 shows such a comparison for the MC generated polar angle versus the reconstructed polar angle for 1000 isotropically distributed simulated alpha particles. The vertex reconstruction bias with polar angle is plotted in figure 3.4, indicating greater uncertainty perpendicular to the cylinder axis of the TPC and incident beam direction (geometry).

The first parameter studied in this work was the hit creation. As mentioned previously, hits are created from ADC waveforms by either: fitting the waveforms with a Fermi function and using the fit parameters to produce a

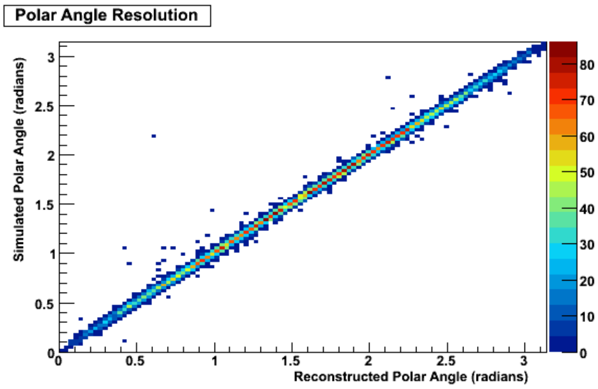


Figure 3.3: The polar angle reconstruction bias for 1000 simulated alpha particles.

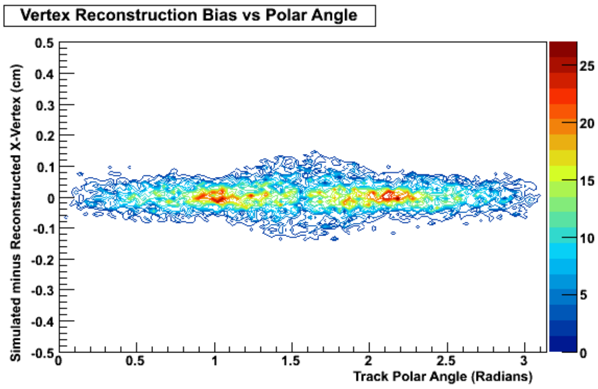
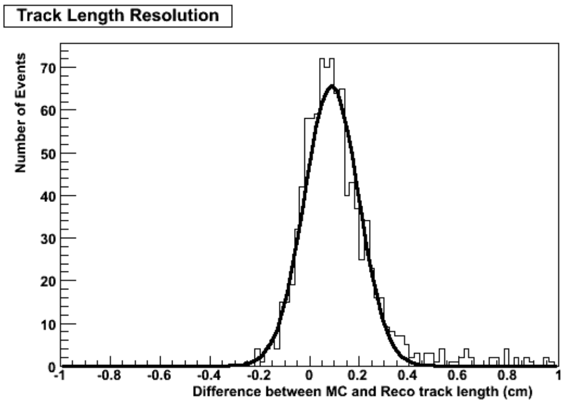


Figure 3.4: The vertex reconstruction bias with varying polar angle for 1000 simulated alpha particles.

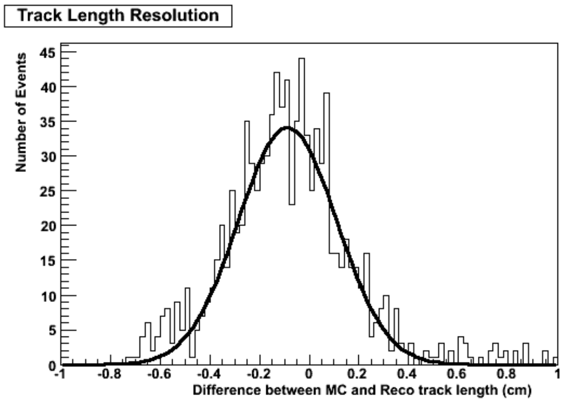
single track hit; or, calculating the derivative of the waveform with a variable number of points on the signal rise slope; or a hybrid of these two methods (merging some of the derivative information). Merging waveform information smooths out some detector effects like diffusion via averaging. Figure 3.5 shows an example of such an analysis plotting the difference between generated and reconstructed track length for 1000 isotropically emitted alpha particles for (a) derivative hits and (b) hybrid hits. In this case it appears that the derivative digits are a better choice for track length determination. Derivative digits also seemed to work best for both angles and track vertex, as similar plots to figure 3.5 showed that derivative digits give the smallest sigma for the Gaussian distribution in this configuration.

As a next step the number of points to form a derivative of the waveform signal was investigated. Possible candidates range from two (2 point difference) to nine (9 point least square). The investigation for this parameter indicated that a 5 or 7 point least square calculation gives the most optimal results, where one can see the least disturbance at a polar angle of 90 degrees, which is a sensitive spot for the tracker due to geometry reasons.

The Hough radius is an input parameter in the Hough track finder and has been studied using simulated alpha particles. The Hough radius is related to the expected length of a track and therefore rather specific to particle type and system variables like gas pressure. A look at the simulated alpha tracks with values ranging from 0.4 to 0.75 cm for the Hough radius appears to be optimized using a larger radius of 0.6 to 0.75 cm. Kalman parameters like the multiple scattering error and the ADC weighing for the track segments showed little sensitivity.



(a) derivative digits



(b) hybrid digits

Figure 3.5: The track length reconstruction bias for 1000 simulated alpha particles using two different types of hit creation.

3.3 Towards a New Tracker

The reconstruction software is being developed to take advantage of detailed tracking in a fission TPC. Due to the large amount of data to be processed, typically only minimal information from the original waveform signal is collected and used in reconstruction. A new tracker will use more information from the waveform from each channel. Recent work included investigations of signal waveform properties and issues of geometry mapping.

3.3.1 Crude Particle Tracking and Identification

Work is underway to understand and parameterize all features of the TPC digitized waveforms. Single waveform analyses of the simulation have been carried out and primitive tracking and particle identification algorithms have been developed in the process. The waveforms from individual channels were summed for each track to form one single waveform per track. The sum of signals for a track resembles treating the pad plane as a one channel detector. The shape of this total waveform is correlated to charge arrival time. A focus of study has been the direct correlation between the slope of the total waveform and the track angle. The charge arrival time at the anode pad is correlated to the z-distance between the occurred ionization and the pad plane and ergo track angle. The resulting summed waveform is driven directly by track angle, specific ionization, however, perturbs the one-to-one correspondence. This effect could be shown using simulated alpha particles and fission fragments.

The onset and completion of charge collection were found using a second derivative on the total waveform. A parameter for the difference in charge arrival time was found calculating the slope of the total waveform, hence considering the total charge collection time and total charge of the track. A clear correlation between the arrival parameter (slope of total waveform) and the angle of generated particles can be seen in figure 3.6 for 1000 simulated alpha particles. The effect could as well be demonstrated for simulated fission fragments.

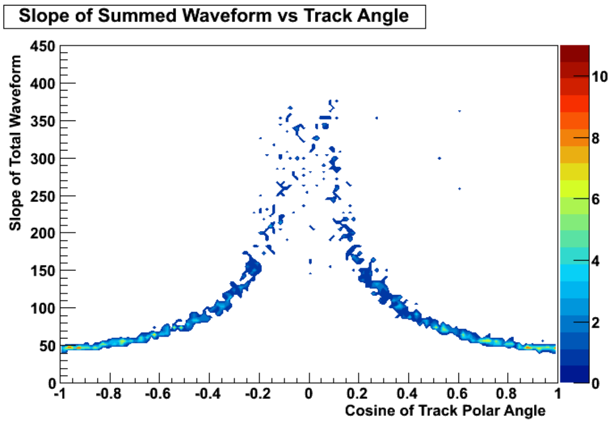


Figure 3.6: The slope of the total waveform (charge arrival parameter) versus track angle for 1000 simulated alpha particles.

This extremely crude tracking algorithm has also been used as an additional particle identification capability. A fission TPC provides particle identification by recording track length and energy deposition. Figure 3.7 shows a typical track length versus total track charge (ADC) plot for a simulated Cf252 source in a fission TPC. One can clearly distinguish between short length, high energy fission fragments and alpha particles with longer range and less energy.

The direct correlation between the slope of the total waveform and the track angle can be used as an additional simple particle distinction. The correlation is perturbed by the specific ionization. For alpha particles the

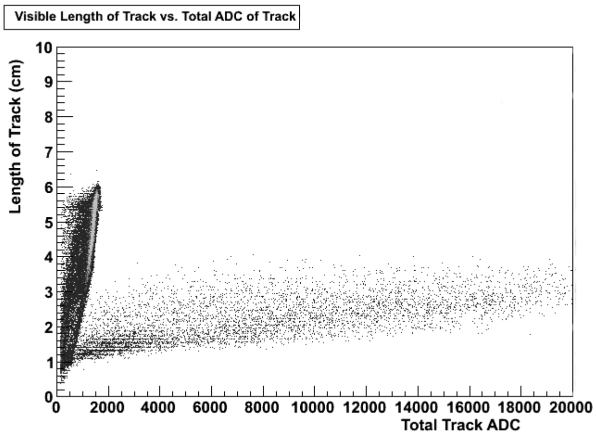
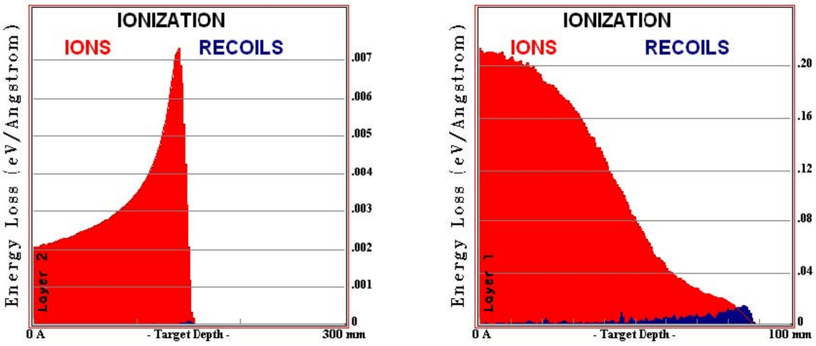


Figure 3.7: Track length versus total charge for a simulated Cf252 source.

slope is steeper at the beginning of the summed waveform (the track end closer to pad plane) because of the higher energy deposition at the end of the track. Typical Bragg curves for alpha particles and fission fragments as produced using the SRIM (Stopping and Range of Ions in Matter) software are shown in figure 3.8. Alpha particles are expected to deposit most of their charge at the end of their track, while fission fragments deposit most of their charge at the beginning of their track.



(a) alpha particles

(b) fission fragments

Figure 3.8: Typical Bragg curves for alphas (a) and fission fragments (b) produced using SRIM.

Establishing a ratio of the slopes in the first and second half of the total waveform gives particle discriminating results for fission events and alpha particles. This corresponds to a very rudimentary specific ionization ratio. Figure 3.9 shows this primitive particle ID for 1000 randomly distributed alphas and 1000 randomly distributed fission fragments. The resulting plot might be further improved using an extra variable (total ADC, track length) or using only the first and last quarter of the total waveform. This first investigation suggests that fission fragments and alpha particles can be distinguished and their angle estimated to relative precision considering only the signal waveform without the steps of hit creation.

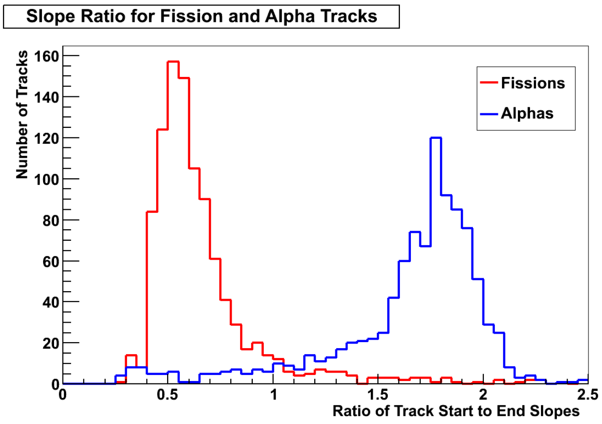


Figure 3.9: The simple specific ionization ratio calculated from the slopes of the total waveforms used for particle type distinction.

3.3.2 Mapping xy Coordinates to Pad Plane

As a first step towards a highly refined fitter, an algorithm to calculate the position of track segments with respect to the centers of the anode pads has been developed. The waveforms on those pads are then fit using a Fermi function and the information is parameterized. The mentioned algorithm could only be developed using a routine to map the xy coordinates of a track to the row column coordinates on the pad plane that consists of hexagonal tiles. An algorithm developed by game programmers Jahn and Loviscach [14] to map the relatively complex geometry was of much help. This lead to a preliminary mapping of the xy coordinates in the TPC to the hexagon pattern anode plane.

Chapter 4

Summary and Outlook

The author's focus has been heavily directed on supporting simulation and software development. It became obvious that for advanced cross section measurements as well analyses on fission kinematics, a very precise track reconstruction and particle identification capability is needed.

The PhD thesis will focus on a the potential impact of a TPC measurement on fission physics. To extend the physics reach of the fission TPC data towards information at the point of scission, angular information, particle mass, range and stopping power and a precise vertex are crucial. This necessity motivates a strong emphasis on improvement of track finding and reconstruction. As explained in the previous chapters, the experiment already has well-working algorithms in place that are a very good starting point for future analyses. However, work continues towards a more precise tracker. The basic waveform structure of ADC detector signals has been investigated in detail and the now deeper understanding of the physical information available from those signals will be used for an improved tracking package.

Analysis topics like the investigation of varying proton and mass numbers of the fission fragments with incoming neutron energy will provide information about charge configuration at the point of scission. To further deepen the understanding of the fission kinematics that will be necessary for the detailed analysis of physics data, fission theory will also be a big part of the author's upcoming work.

Bibliography

[1] J. N. Marx and D. R. Nygren, *The Time Projection Chamber*, Physics Today, 31 (1978).

[2] V. Lepeltier, *Review on TPCs*, Journal of Physics: Conference Series, 65 (2007).

[3] H. J. Hilke, *Time Projection Chambers*, Reports on Progress in Physics, 73 (2010), pp. 116–201.

[4] M. Anderson et al., *The STAR Time Projection Chamber: A Unique Tool for Studying High Multiplicity Events at RHIC*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 499 (2003), pp. 659–678.

[5] The STAR collaboration, *Observation of the Antimatter Helium-4 Nucleus*, Nature, 473 (2011), pp. 35–36.

[6] Y. Giomataris, P. Rebourgeard, J. Robert, and G. Charpak, *MICROMEGAS: A High-granularity Position-sensitive Gaseous Detector for High Particle-Flux Environments*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 376 (1996), pp. 29–35.

[7] G. Charpak, J. Derré, Y. Giomataris, and P. Rebourgeard, *Micromegas, a Multipurpose Gaseous Detector*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 478 (2002), pp. 26–36.

[8] S. Agostinelli, *GEANT4 A Simulation Toolkit*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 506 (2003), pp. 250–303.

[9] R. Brun and F. Rademakers, *ROOT An Object Oriented Data Analysis Framework*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 389 (1997), pp. 81–86.

[10] P. Staples and K. Morley, *Neutron-induced Fission Cross-section Ratios for 239Pu, 240Pu, 242Pu, and 244Pu Relative to 235U from 0.5 to 400 MeV*, Nuclear Science and Engineering, 129 (1998), pp. 149–163.

[11] C. Wagemans, *The Nuclear Fission Process*, CRC Press, 1991.

[12] J. Illingworth and J. Kittler, *A Survey of the Hough Transform*, Computer Vision, Graphics, and Image Processing, 44 (1988), pp. 87–116.

[13] G. Welch and G. Bishop, *An Introduction to the Kalman Filter*, Design, 7 (2001), pp. 1–16.

[14] T. Jahn and J. Loviscach, *For Bees and Gamers: How to Handle Hexagonal Tiles*, in Game Programming Gems 7, S. Jacobs, ed., Charles River Media, 2008, pp. 47–58.