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Innovative Fission Measurements with a Time Projection Chamber

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Abstract

This study explores a pioneering idea to utilize a Time Projection Chamber (TPC) to measure fission cross sections and other fission quantities. The TPC is inherently capable of measuring fragments from fission events, decay alphas, and beam-material scatters. This document explores whether the TPC can improve the precision of the $^{239}Pu(n,f)$ cross section and measure other new and significant fission quantities simultaneously. This work shows that the TPC can in fact deliver sub-1% cross section measurements and should provide breakthroughs in both the quality and quantity of information available from neutron-induced fission experiments.

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Executive Summary

This is a proposal to measure the ^{239}Pu(n,f) cross section to sub-percent accuracy, using a Time Projection Chamber (TPC). This measurement would support the goals of the Stockpile Stewardship Program. The current differences between evaluations of the data range from 2-3% below 14 MeV neutron energy to over 10% at higher energies. A true sub-percent measurement would therefore be a significant improvement over current measurements.

The current technology for fission cross section measurement is the fission chamber, which has been in use for a number of decades and may have reached its limit in accuracy. The proposal investigated here is to use a detector called a Time Projection Chamber that could provide a breakthrough technology to considerably improve the cross section measurements.

There are a number of known systematic errors that contribute to the total error of the fission measurements, dominated by these three: particle identification, target thickness, and the use of ^{235}U as a normalizing reference. These three alone have precluded sub-1% measurements with fission chambers. While all of the known, suspected and subsequently discovered systematic errors can be fully investigated in a TPC experiment, this report focuses on these three limiting uncertainties.

The **Particle Identification** uncertainty is the largest of the fission chamber errors and one where the TPC will have the most significant impact in reducing the error. Since deposited energy is the only information obtained from a fission chamber, events of different types which leave the same amount of energy in the chamber are indistinguishable. The most confounding situation is determining the difference between a high angle fission fragment, which loses most of its energy in passing though a relativity large amount of target material, and a neutron scattering on chamber materials, both of which can leave the same amount of energy in the fission chamber. This ambiguity is the largest component of the total systematic uncertainty in a fission chamber.

A simulation of this effect was carried out with the GEANT4 particle transport software.[1] The most significant effects have been included: alpha decay of the target, neutron scatters on chamber materials, and the fissions themselves. Figure 1 shows the results of the simulation. The horizontal axis is the energy deposited in ionization for each particle that enters the active gas volume. The green line is the contribution from the scatters and alphas, and the red line shows the fission fragments. Fission fragments leaving the

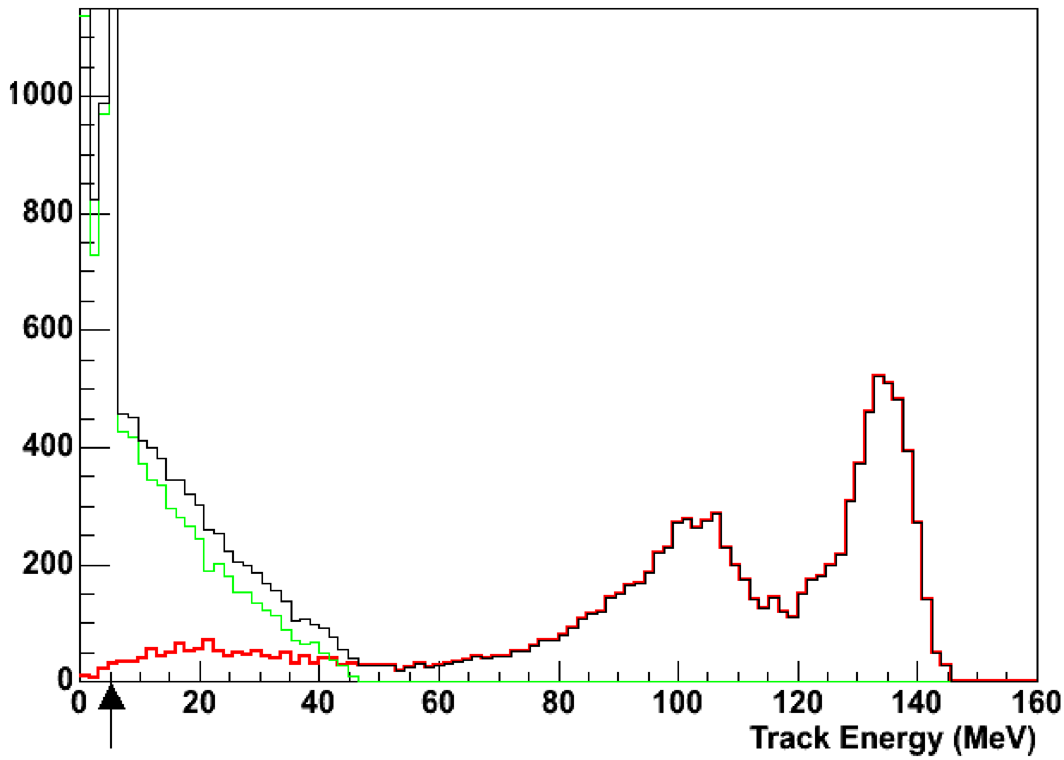

Figure 1: Simulation of particle identification in a fission chamber. The figure shows the energy spectrum for different event types. Beam-chamber interactions and alphas from the target are shown in green. Fission fragments are shown in red. The total distribution is in black. Fission fragments leaving the target at large angles lose a significant amount of energy, leading to the low-energy tail which overlaps the beam-chamber and alpha distributions.

target at large angles lose a significant amount of energy, which leads to the long low-energy tail to the fission fragment spectrum. Black is the net energy distribution one would measure. It is clear from this plot that the fragments overlap with the scatters. In a fission chamber measurement, this is addressed by setting a cut in energy to remove scatters, and then correcting for the fission fragments removed by the cut (and alpha particles and beam-gas scatters that were included).

Figure 2 demonstrates the improvement provided by the TPC, which is capable of measuring both the deposited energy and the track length (range). The specific energy loss differs for particles of different mass and charge, leading to different ranges for different particles of the same energy. The alphas are indicated in green, the neutron scatters are red, and the fission fragments are black. The fission fragments are well separated from the other particles to as low as 5 MeV in this conservative simulation. The power to discriminate is far greater in the TPC and reduces the particle identification error by at least a factor of 5.

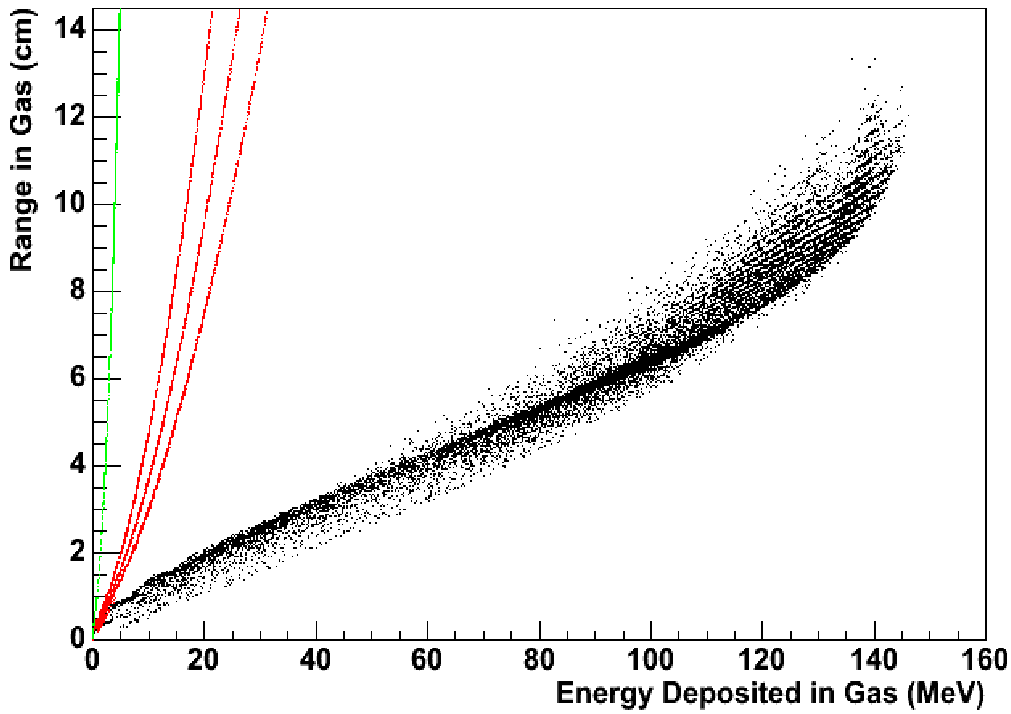

Figure 2: Simulated energy vs. range.
Alpha particles are shown in green, neutron-chamber interactions in red, and fission fragments in black. By measuring the particle range in addition to the total energy, a TPC can unambiguously distinguish fission fragments down to 5 MeV.

The **Target Thickness** error is the error in measuring the quantity of ^{239}Pu in the target. In preparation for a fission chamber measurement, the mass of the target can be determined by counting the spontaneous alphas. The thickness determination is limited by three systematic errors: uncertainties in the alpha counter calibration; averaging over variations across the full target; and alpha counting inefficiency due to high-angle alphas losing significant energy in the target itself, which depends on the thickness.

The TPC has the ability to significantly reduce all three of these systematic error terms by counting the alphas in situ. First, the TPC has 100% efficiency for tracks of a minimum length, so the calibration error is extremely small. Second, the TPC measures the point where the alpha track leaves the target to a resolution of a few 100 microns, and thereby measures the target uniformity directly. Finally, the TPC measures the angle that the alphas leave the target, allowing a direct determination of the flux lost due to large energy loss in the target. An additional cross check can be made by reducing the gas pressure, so that the high angle, low energy alpha tracks are long enough to be measured with high efficiency. The sum of these improvements from the TPC measurements will drive this target thickness error down by as much as a factor of 7.

The ^{235}**U Reference** error refers to the conventional method used to measure the beam flux. The neutron beam flux from the broad spectrum source at LANSCE is not known directly at the percent level. The conventional solution is to place a reference target of a known cross section in the beam simultaneously with the material under study. Given the cross section, the total number of events from the reference material is a measure of the flux. For fission measurements the reference is usually ^{235}U, which has the best measured (n,f) cross section, but even this cross section is only known to about 1%.

The most accurately known neutron cross section suitable as a reference is ^{1}H(n,n'), which is known to about 0.2%. The TPC can track interactions which occur both at the target and in the drift gas. Therefore, selecting ^{1}H as the drift gas will provide the highest accuracy reference target to reduce the absolute error on the cross section. This has the potential to enable us to make sub-percent measurements on ^{235}U as well as ^{239}Pu. In any case, a TPC will perform a high precision measurement of the ^{239}Pu/^{235}U cross section ratio, which should be a baseline goal. The potential of a ^{1}H reference should be explored to determine if a higher accuracy absolute measurement is possible.

In summary, application of a TPC to fission measurements will produce a far more detailed measurement than a fission chamber. This provides a large lever in understanding, reducing, and quantifying the dominant systematic errors in fission measurements. In addition, the richness of the data to come from a TPC, including species, energy, and angle correlations between emitted particles, would enable significant new theoretical work that could lead to dramatic improvements in our theoretical understanding of the fission process.

Introduction

This study explores a pioneering idea to utilize a Time Projection Chamber to measure fission cross sections and other fission quantities. An experiment to measure (n,f) cross sections at sub-percent accuracy would support the goals of the Stockpile Stewardship Program. The particular experiment put forward here would have the additional impact of measuring other fission quantities, some for the first time, that would be the catalyst to improve models of the fission process itself.[2] This document will describe the experiment, present simulations demonstrating the critical issues, analyze the dominant errors to show that a sub-percent measurement can be made, and make a first estimate of the cost and effort needed.

Present State of Fission Measurements

One of the more recent fission papers by Staples and Morley [3] has nicely summarized the state of the ^{239}Pu fission cross section (Figure 3). The variations between experiments are as large as 20%, although quoted statistical and systematics errors for individual experiments are far smaller. These large and inconsistent differences between experiments provide difficulty for the evaluators and are reflected in the different evaluations[4] of the same cross section, shown in Figure 4. Variations between evaluations are 2-3% below 14 MeV and much larger above that.

Clearly, some systematic errors are under estimated or unaccounted for. There have been many discussions among practitioners to understand what these errors could be and what might be done to reduce them. These discussions have produced a laundry list of possible unaccounted errors, and indicate that even the more modest goal of pinpointing what these unknown errors are would be worthwhile. The errors discussed in this document are derived from that laundry list and known systematic errors found in the literature.

The solution presented here is to introduce a much more powerful instrument to the problem than has been previously attempted. This instrument is called a Time Projection Chamber (TPC). It has the potential not only to identify additional sources of systematic uncertainty present in the traditional fission chamber measurements, but is also capable of sub-percent fission cross section measurements and will provide additional experimental handles to better understand the fission process.

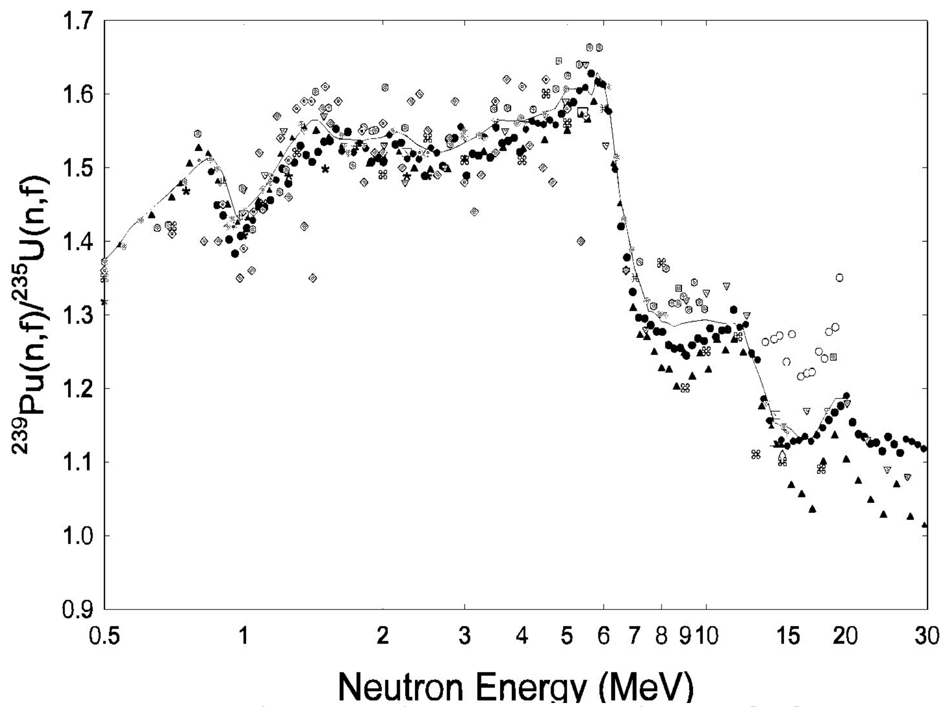

Figure 3: Summary of 239Pu(n,f) cross sections from multiple experiments, each noted by a different symbol type. The line is ENDF/B-VI. Plot from figure 3 of reference [3].

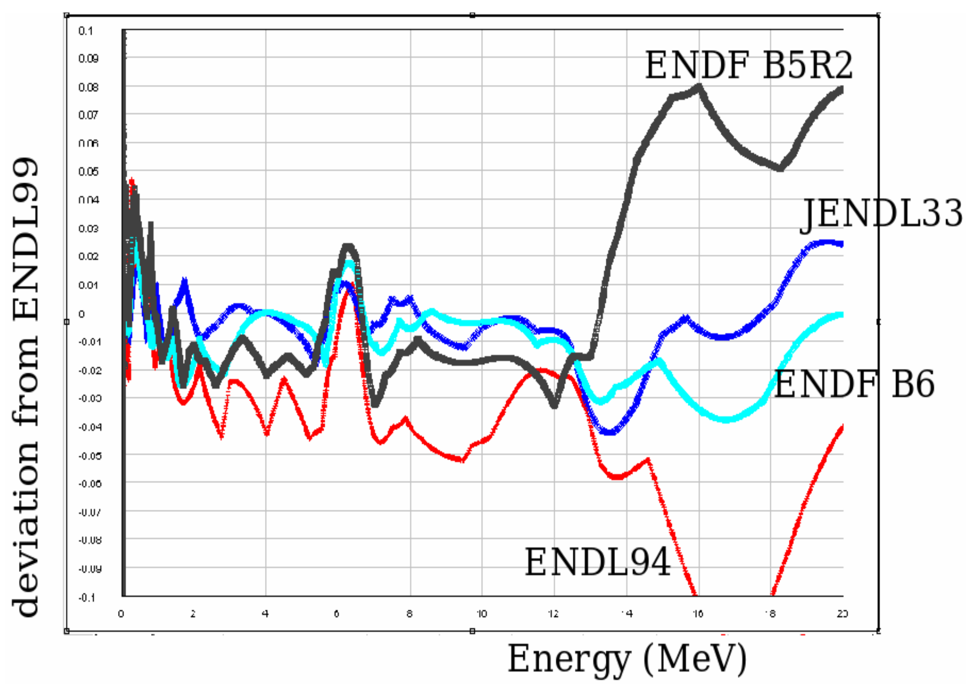

Figure 4: Comparison of different evaluations of the $^{239}Pu/^{235}U$ (n,f) cross section. Using the NADS[4] database, each evaluation is compared to the ENDL99. To get percent deviation multiply the vertical axis scale by 100.

How a Fission Chamber Works

The standard in fission cross section measurement is a fission chamber. A sketch of this relatively simple device is shown in Figure 5. It is basically just two parallel plates separated by a few centimeters of gas. A power supply connected to the plates sets up a moderate electric field. The target is deposited onto one of the plates. When a fission occurs, the fragment ionizes the gas and the electric field causes the produced electrons to drift to the opposite plate, which records the total energy deposited in the chamber.

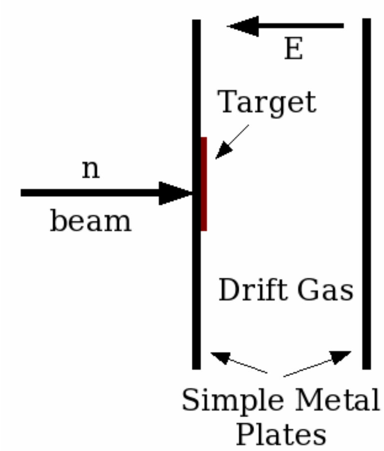

Figure 5: Schematic for a typical fision chamber.
Fission tracks leaving the target and entering the gas ionize the gas molecules. The ionization electrons drift to the second collecting plate. A charge-sensitive pre-amplifier measures the total ionization, which is proportional to the fragment energy. A fast signal from the target plate gives the neutron time-of-flight.

Modifications to the basic fission chamber can produce more information about the fission events. An improvement currently under development is the addition of a Frish grid to the fission chamber. The Frish grid is a screen or set of wires parallel to the readout plate. This screens the drifting charge until is passes though the grid and the resulting waveform then has information about the track angle. In some sense this is a very simple one channel TPC, but it is crude in comparison and is only an incremental improvement. The TPC described below will measure all that a Frish grid fission chamber can and much more.

Systematic Errors in (n,f) Cross Section Measurements

The quantity of interest is the cross section which can be simply written as,

$$\sigma = \frac{N_{fission}}{N_{atoms} N_{neutrons}} \quad (1)$$

The error on the cross section is the quadrature sum of the fractional errors to each of the measured components, $N_{fission}$ is the number of observed fissions, N_{atoms} is the number of atoms in the target, and $N_{neutron}$ is the number of neutrons aimed at the target.

Table 1 Summary of systematic errors to be studied with the TPC. The items in red have the largest effect on the final result. Total error estimated by a quadrature sum of the individual errors.

Effect	**Estimated Error**	
	Fission Chamber	**TPC**
Total	1.62%	0.48%
Neutron Beam		
Neutron energy (TOF)	0.10%	0.10%
Flux, using ^{235}U reference	1.00%	0.40%
Profile	?	very small
Energy position dependence	?	very small
Beam flux outside of target	0.01%	very small
Beam spreading and attenuation	0.30%	very small
Target		
Purity	0.10%	0.10%
Surface contamination	?	very small
Non-uniform surface density (target mass)	0.70%	0.10%
Energy loss in target		
Complete loss	0.10%	0.05%
Particle ID with energy loss: alpha knock ons, fission fragments	1.00%	0.20%
Fragments		
Partial containment of fragment track	0.00%	0.00%
Change of pulse height with beam energy	?	0.00%

Fourteen potential sources of systematic error have been identified that may contribute to the systematic error of previous experiments. Each of these errors have been considered (see Appendix A), and summarized in Table 1. All of the errors can be quantified in an experiment using a TPC. Quantifying the size of these systematic effects will provide a method to look for surprises -- errors that were overlooked or undetectable in simpler measurements. For this study, the currently known errors which prevent a sub percent error in the measurement of ^{239}Pu(n,f) have been investigated. The three that satisfy this criteria are: particle identification, that is, discriminating between fission fragments and scatters/alphas; target thickness and mass distribution; and the use of ^{235}U a normalizing reference. These three are highlighted in red in Table 1

A TPC for Fission Measurement

How a TPC works

A TPC is a gas ionization detector similar to a fission chamber. A TPC, however, measures charged particle trajectories in the active volume in three dimensions. In simple terms, the TPC can be thought of as a 3D digital camera which makes a 3D "picture" or "image" of the event. In reality it can do more than take pictures; it can read continuously, and can use the specific ionization information to look at the Bragg curves for the particles within an event. The specific ionization for each particle track enables the TPC to distinguish different particle types.

Figure 6 shows a conceptual design of a TPC for the proposed fission measurement. The isotope to be studied (i.e. ^{239}Pu) is located in the center of the TPC (shown as red in the figure). The neutron beam enters from the left through the end plate and induces fissions in the target. The resulting fission fragments exit either side of the target and ionize the gas, typically P10 (90%Ar +10%CH_4), or, in this case, hydrogen. As in a fission chamber, an electric field between the target plane and the readout planes (labeled "gain, pad, and readout" in the figure) prevents the ions and electrons from recombining and causes the electrons to drift, in a predictable way, to the readout plane. The transverse coordinates are determined by using a segmented readout plane. By timing the arrival of the charge and knowing the electron drift velocity in the gas, one can calculate the spatial coordinate of the ionization in the direction of the drift.

Figure 7 shows a close up section of the readout plane for a circa 1990 TPC. When the drifting electron cloud reaches the very high electric fields surrounding the anode wires, the accelerated electrons cause an avalanche, leading to gas gain. The image charge induced on the pads by this avalanche is integrated, amplified, digitized and written to disk. The segmentation of the readout plane provides the two dimensions perpendicular to the drift direction.

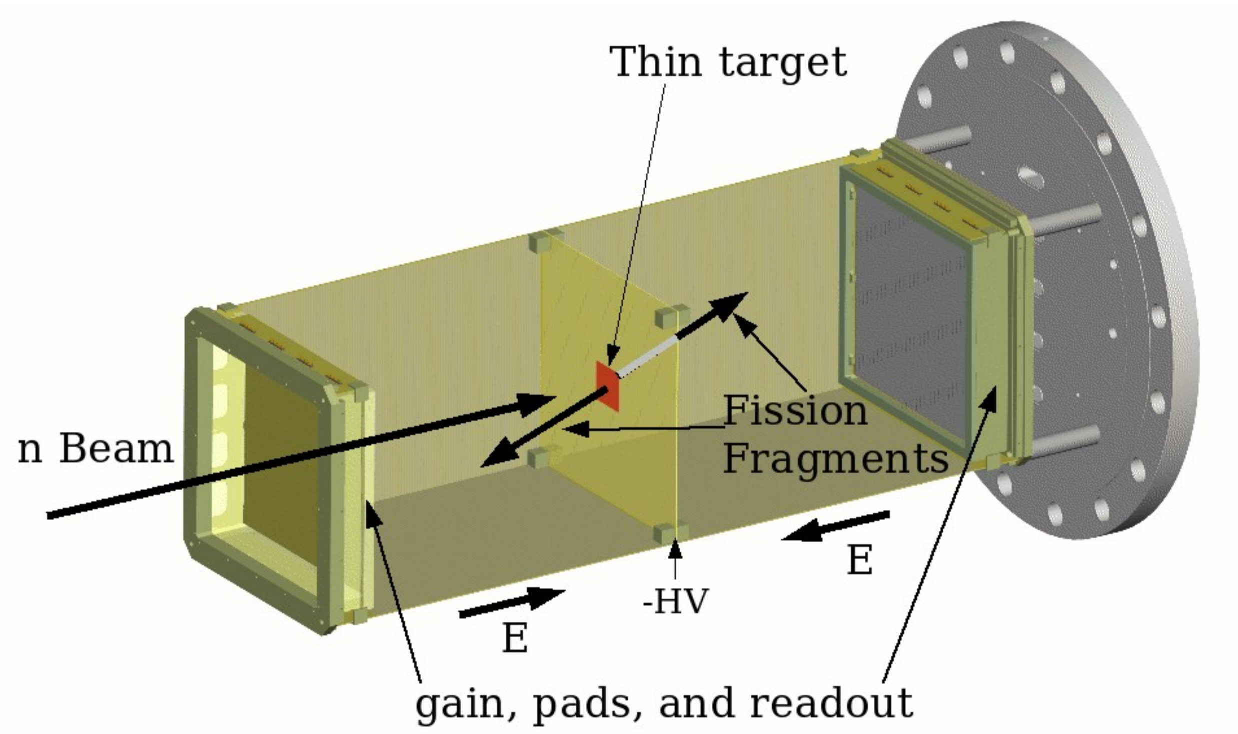

Figure 6 Schematic view of a two-sided TPC with a solid target at the cathode for fission measurements

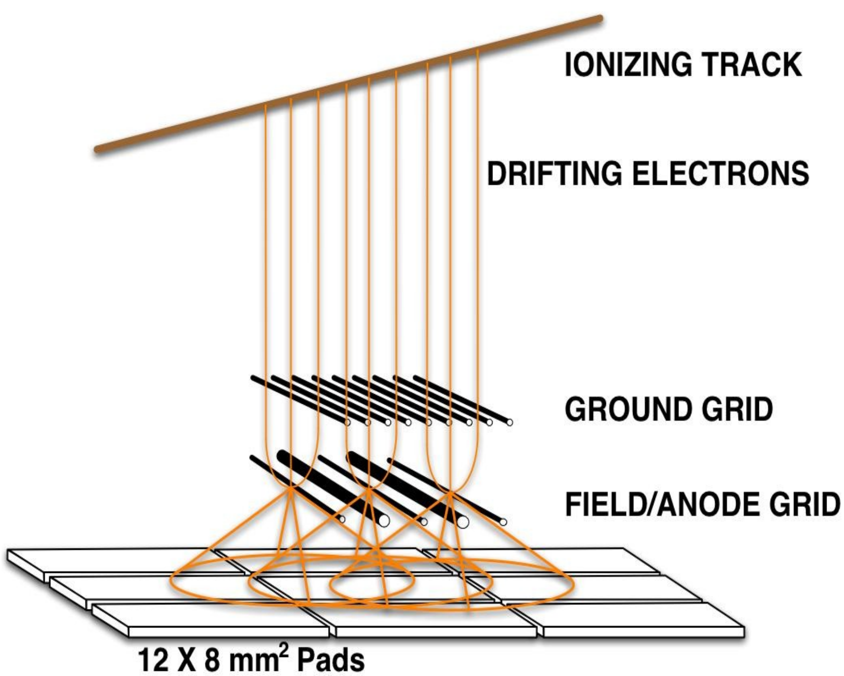

Figure 7 Close up view of a typical TPC pad plane, using an anode plane made of individual wires to generate gas gain.

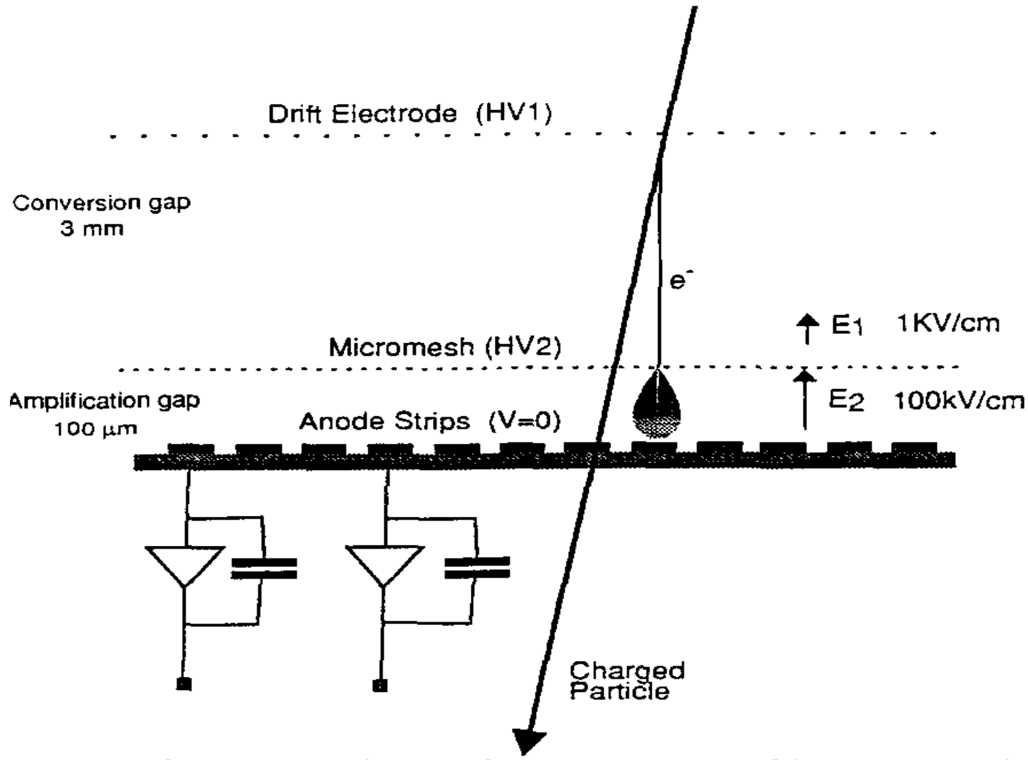

Figure 8 Close up view of a typical MICROMEGAS amplification system for a TPC. Figure 1 of reference[5]

Wire amplification has been the most common method used in Particle Physics to produce gas gain. Developments over the last 10 years have led to better solutions, such as MICROMEGAS,[5] which provide better spacial resolution, less ion feedback from the avalanche into the drift volume, are more robust, and should hold up well to radiation damage. Because of the nature of the fission fragments as highly ionizing short-range particles, the MICROMEGAS is most likely the best gas amplifier technology for this measurement. Figure 8 shows a close up of this avalanche system. The electrons are amplified by the high field between the micro mesh and the pad plane. The pad readout is the same as with the wire amplification scheme.

Measuring the fission rate of a thin ^{252}Cf source in the TPC and then in a simple fission chamber is an experimental method to verify that the complexity of the TPC has not introduced any subtle effects from the gas amplification, drift field shaping or segmentation of the readout plane.

In summary, the TPC has an active volume and electric field similar to the traditional fission chamber but with a significantly different readout and data acquisition.

Fission TPC Design Considerations

A TPC designed for fission measurements should have enough gas (pressure and path length) that the fission fragments range out, so that the full energy of the particle is measured. The gas gain and readout have to handle the very high specific ionization of the fission fragments. Finally, the measurement of fission neutrons is of interest in the fission measurements. Some of these requirements can be met in a two-sided TPC using a solid target at the cathode, as sketched in Figure 9. This concept is the baseline detector considered in this report.

The baseline detector, however, is not the best that can be done using a TPC. Though the baseline detector will be a huge improvement over a fission chamber, the use of a solid target will likely still be the source of the limiting systematic errors, in measuring the target mass and the acceptance for high angle fission fragments and alphas. To remove the issues related to the

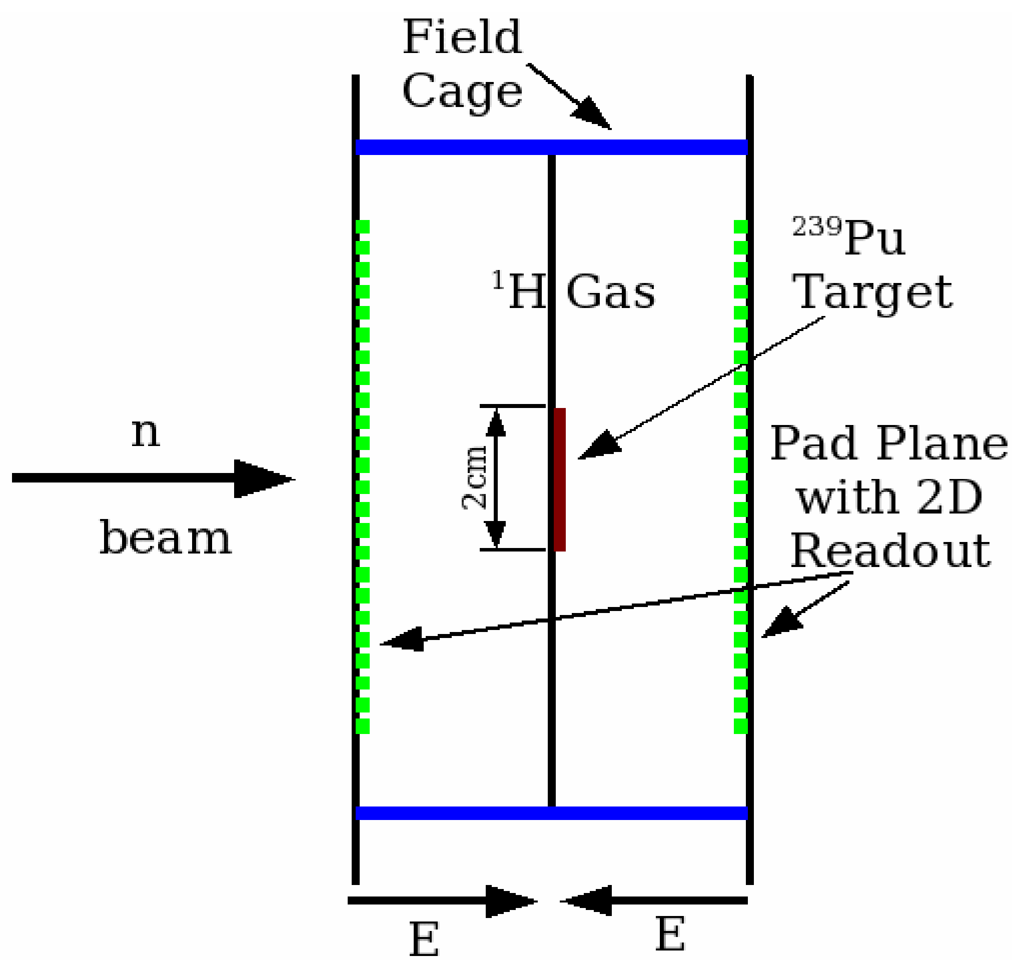

Figure 9: Side view of solid target design. The active volume is to scale and actual size.

target, ideally one would use a gaseous target, and measure the fission events free in the drift gas.

The following sections describe and give operating parameters for the baseline detector using a solid target. Also described is how to use a gaseous target. Finally, two approaches to measure the fission neutrons simultaneously are discussed.

Baseline Solid Target TPC

The baseline design is sketched in Figure 6 and drawn to scale in Figure 9. The design goal of this TPC is to make the best measurement of ^{239}Pu(n,f) using proven techniques, that is, minimizing technical risk. This TPC will also be capable of measuring fragment energy and fragment mass distributions. Fission neutrons will be very poorly measured without auxiliary detectors. In this design two identical TPCs are placed in the beam simultaneously, one with the target material of interest, the other with a ^{235}U target to use as a flux monitor, similar to what is done with fission chambers. This same design will be used with ^{1}H drift gas to explore the feasibility of using this as a high precision reference target.

Baseline TPC Design Parameters

The optimum design parameters are a trade-off between competing effects and depend on the properties of the neutron beam. For this design the beam requirements are, less than 2cm spot size on the target, less than 1500 neutrons/cm^2 per pulse and pulse spacing no closer than 1.8μs. These requirements can be met by the LANSCE facility.

The design evolved though an iterative process that resulted in the parameters in Table 2. A simple step by step post design description of the design process is outlined below.

- The working gas in the TPC should be light to reduce the multiple scattering of the fission fragments and allow for a good measurement of the fragment trajectories from the target. H and He are the two candidates as they have both been used in TPC and are the lightest atoms. ^{4}He is not a good gas since neutron scatters on the gas would be difficult to distinguish from alphas from the target. In addition, the ^{1}H gas is a better choice since the cross section is well known and can be used as the reference target to determine the beam flux.
- In pure hydrogen gas the electron drift speed is basically monotonic function of the electric field over pressure (for reasonable values of E and P). In a high flux environment the higher drift speeds are desired to clear the chamber as fast as possible. The limit to a very high

electric field is break down of the gas, and at high pressures the surface breakdown along the field cage. Extrapolating from other TPCs a field of 1kV/cm/bar was selected.

Table 2 Baseline Detector Design Parameters.
All pressure-dependent parameters are given at the 5 bar nominal operating pressure.

Parameter	**Value**
Drift gases	^{1}H ^{3}He (neutron measurement) P10 (as in fission chambers)
Gas pressure	5 bar, nominal (0–10 bar range)
Typical fragment track length	18 mm
Magnetic field	None
Beam diameter	20 mm
Readout structure	0.9 mm X 0.9 mm square pads
Typical samples per track	20
Target diameter	20 mm
Fiducial area guard radius	9 mm, (50% of track length)
Drift length, including fiducial guard radius	27 mm = 18 mm + 9 mm
Pad plane diameter	74 mm = 20 mm + 2 x 27 mm
Number of pads per side	5300 = $(74\text{ mm}/0.9\text{ mm})^2\ \pi/4$
Gas amplification	MICROMEGAS or GEM, conductive pad coating to spread signal charge
Drift field	5 kV/cm
Maximum field	27 kV @ 10 bar
Drift velocity	11.5 mm/μs
Drift time	2.35 μs
Sampling rate	13 MHz

- With a gas and a drift field the electron drift speed is calculated. Combining this with the desired drift time (from the beam pulse spacing) the drift distance is selected.
- Next the pressure is selected to set the track lengths to fit within the drift distance. The pressure is a knob that will be used to fine tune the TPC during the experiment to get the best tracking and particle identification. Lowering the pressure in special runs also provide a means to investigate the very high angle tracks that loose a lot of energy in the target.
- With the basic dimensions of the drift, the readout segmentation is selected such that a typical track has about 20 points. This is the empirical minimum number of points to get a good particle identification. The result is pad sizes of 0.9mm, and the number of points can be varied to some extent by changing the gas pressure (which changes the track length). The small pad size then also drives the gas amplification to the MICROMEGAS which are well suited for the pad size.

Gaseous Target TPC Design

The systematic errors in a fission measurement are dominated by effects due to the use of a solid target. The best experiment design would use a gaseous ^{239}Pu target mixed with ^{1}H, for use as the beam flux reference, with Ne or Ar as the bulk drift gas. The most challenging part of this concept is the manufacture of the gaseous ^{239}Pu. It has been suggested that perhaps a carbonyl could be formed that would have good properties, but this has not been synthesized to date. Exploring the feasibility of synthesizing this gas, or another Pu-containing gas, is a very high leverage R&D item that should be undertaken at the earliest opportunity.

The bulk drift gas would be Ne or Ar, with a controlled admixture ^{1}H. Beam neutron interactions with the ^{1}H give a very high precision flux monitor. The Pu gas concentration would also be controlled to achieve the desired target mass, while limiting the alpha rate. The TPC design differs from the baseline in that it would be single-sided and oriented with the pad plane parallel to the beam, with the ionization electrons drifting perpendicular to the beam. The beam would enter through windows in the field cage at the ends of the TPC.(see Figure 10). Although the Pu gas could be introduced into the two-sided baseline design and measured in that configuration, the optimum TPC design would most likely need more column depth of gas (depending on the properties of the Pu gas which are not known), and the requirement for two-sided readout is removed which reduces electronics cost.

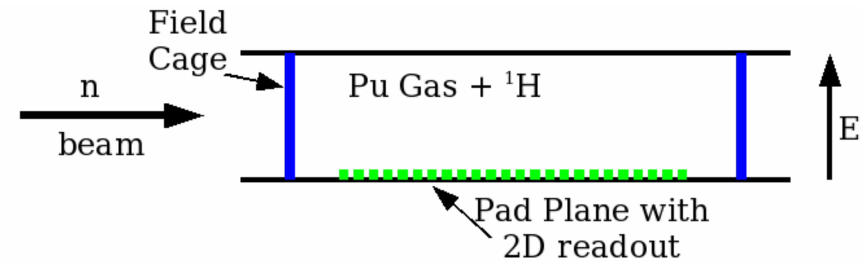

Figure 10: Side view of gaseous Pu TPC.
The beam enters through the field cage at the end. Ionization electrons drift down to the pad plane, which is parallel to the beam.

Projected Performance

This section covers some of the basic performance expectations of the baseline TPC with a solid target. The performance parameters are listed in Table 3 and discussed in detail below.

Table 3: Baseline TPC performance parameters at the nominal 5 bar operating pressure.

Performance Parameter	Value
Single track pointing resolution	379 μm (worst case)
Track angle resolution	37 mRad (worst case)
Occupancy	11%
Beam Gas Interactions	10/pulse/TPC side
Fission Rate	<1/pulse
Target Thickness	200 μg/cm^2

Pointing Accuracy

The single point spatial resolution is the worst when a small ionization cluster falls on only one pad, which gives a resolution equal to the width of the pad. The average cluster, spread over 2 to 3 pads, should have an accuracy 3 to 10 times better than this. The tracking precision can be estimated using the worst case error. Since there is no magnetic field the tracks can be described by a straight line parameterized by an offset, a, and slope, b:

$$y = a + bx \quad (2)$$

The offset a represents the coordinate where the track exited the target. The uncertainty on this parameter can be estimated, as shown in [6], by

$$\sigma_a = \frac{\epsilon}{\sqrt{(N+1)}} \left(\frac{12r^2 + 1 + \frac{2}{N}}{1 + \frac{2}{N}} \right)^{1/2} \tag{3}$$

A typical track will have N = 20 points measured. The parameter r is related to the detector geometry; for our baseline design it is 1/2. With the worst case single point accuracy ϵ = 0.9 mm the resolution is,

$$\sigma_a \approx 379 \mu m \tag{4}$$

This is the limiting resolution for which variations of the target and beam non uniformities could be inspected. For most tracks the resolution will be much better than this.

The error on the slope b, which is related to the angle of the track by the tangent, can also be estimated:

$$\sigma_b = \frac{\epsilon}{x_n} \frac{1}{\sqrt{(N+1)}} \sqrt{\left(\frac{12N}{N+2}\right)} \tag{5}$$

The variable X_n is the track length, typically 17 mm. So the typical angle error would be:

$$\sigma_b \approx 0.037 \tag{6}$$

For angles near zero, b=tan(θ)~θ, so the angular error (using the worst case single point error) is about 37 mRad for shallow angle tracks.

Discriminating Fission Fragments from Alphas and Scatters

The largest systematic error in the cross section measurement comes from the inability of fission chambers to distinguish clearly between fission fragments, alpha particles, and nuclear recoils from neutron scatters on target holder materials or chamber gas. This problem is illustrated in Figure 11, taken from reference [7]. The fission fragment peak is evident near channel 70 and spontaneous alpha decays and scatters form the peak close to zero. Because of energy loss in the target material, some fission fragments lose enough energy that the tails of the two peaks overlap, filling in the valley around channel 40, as shown. To determine the number of fissions in this data one makes a cut between the peaks, then applies corrections for the number of fission fragments not counted because they fall below the cut, and the number of alphas and scatters that are included above the cut. In the figure this cut is shown by the vertical line near channel 30.

Independent runs without the target in place are used to assess the scatter distributions (see Figure 12), which can be subtracted from the fragment distribution above the cut. Even with this information the quoted systematic error on this correction is of order 1% at low neutron energy, rising to 2% at higher energies.

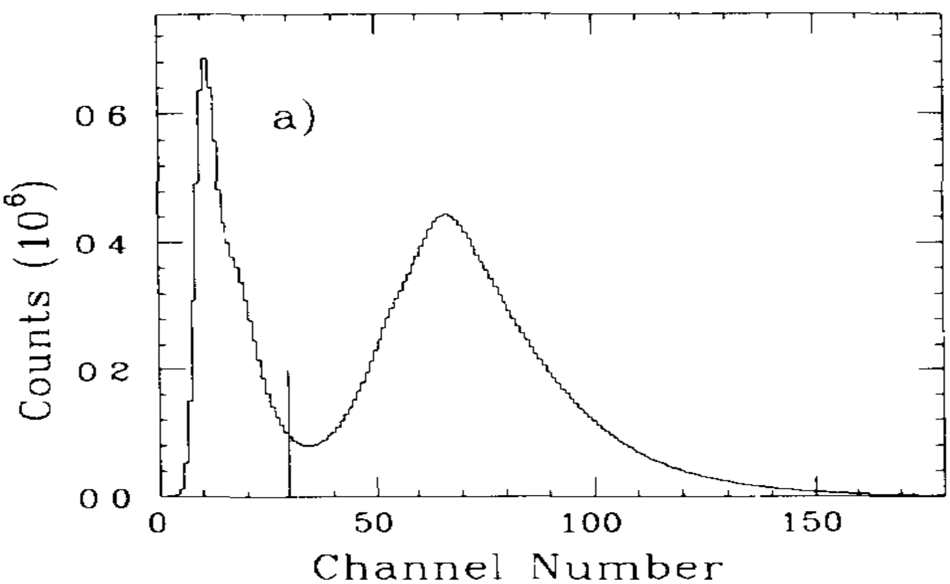

Figure 11 Energy spectrum measured in a fission chamber. The horizontal axis is the fragment energy in arbitrary units. Plot from taken from reference [7]

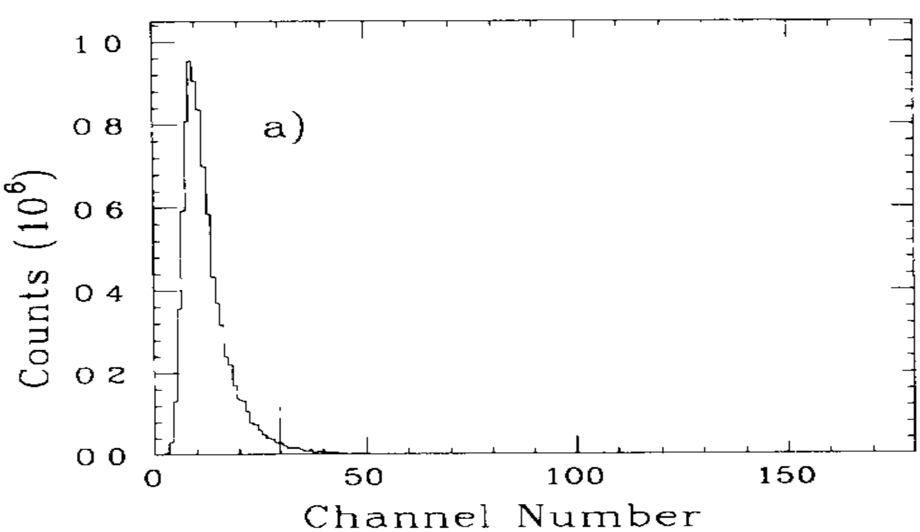

Figure 12 Fission chamber energy distribution for target out run. Plot from [7]

In order to quantify this same effect for a TPC measurement, simulations using the GEANT4 software package have been run and evaluated.[1] The following items were included in the simulation:

- Spontaneous alpha decays at 5.1 MeV.
- S-wave (in the CM boosted to the lab) neutron scatters on ,C, N, O, and Pu, for 1–200 MeV incident neutron energies, with a flat energy distribution.
- Fission fragments distributed in atomic mass and energy as observed in fissions induced by 0.5 MeV neutrons.
- 200 $\mu g/cm^2$ target with backing material.

Figure 13 (the same as Figure 1) shows the energy distribution from the simulation. Although this is not an exact simulation of the fission chamber experiment that produced the data in Figure 11, the simulation reproduces the essential features. The fission fragments and scatters overlap down to the lowest simulated energies.

With the TPC there is additional information, the range of the fragments in the gas. Figure 14 (the same as Figure 2) shows a scatter plot of fragment range vs. energy. (The projection of this figure onto the energy axis is the same as Figure 13) The correlations between range and energy can be used to separate the alphas and scatters from the fission fragments by placing a cut in this 2D space. In this simulation the scatter and fission fragments overlap below 5 MeV. The 5 MeV limit is indicated in Figure 13 with an arrow, illustrating just how small the fraction of lost fission fragments would be with a TPC. In fact only 40 of 10,000 fission fragments are below 5 MeV in the forward region, and 70 of 10,000 are lost in the target (no energy deposited in the gas). Range/energy cuts alone can reduce the fraction of fragments which overlap with scatters to 0.4%. Extrapolating from the well measured scatters to the small confusion region, target out runs could be used to reduced the uncertainty by at least a factor of 2, resulting in a total error of better than 0.2%. This is a conservative estimate. Using the simulation code SRIM,[8] similar results are obtained over the full energy range, with the exception that SRIM predicts no over lap at energies below 5 MeV. The least favorable estimate is presented here to be conservative.

This discussion has only used one additional piece of information available from the TPC. Yet more information is available. Typically there are two fragments, either one of which can tag the event as a fission. The Bragg curve can be measured for each track, giving yet another means to separate fragments from alphas or gas recoils. Both of these additional sources of information would further reduce the already acceptable estimated error of 0.2%.

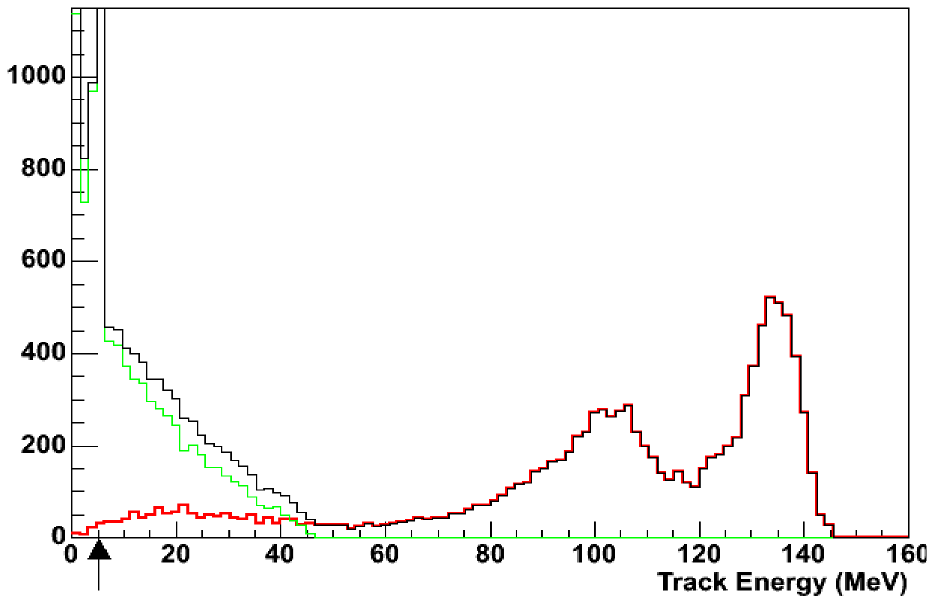

Figure 13 Simulation of particle identification in a fission chamber. The figure shows the energy spectrum for different event types. Beam-chamber interactions and alphas from the target are shown in green. Fission fragments are shown in red. The total distribution is in black.

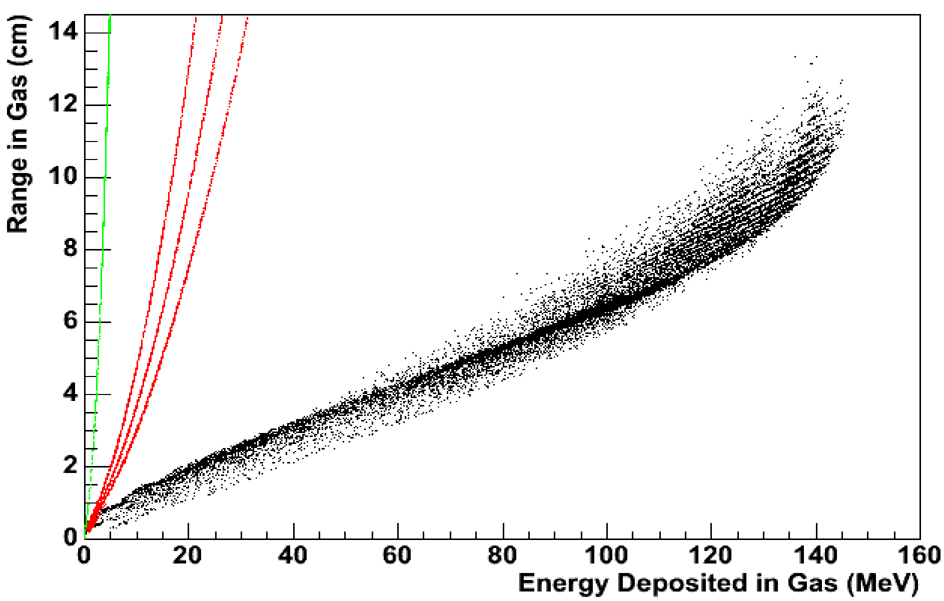

Figure 14 Simulated energy vs. range.
Alpha particles are shown in green, neutron-gas interactions in red, and fission fragments in black. By measuring the particle range in addition to the total energy, a TPC can unambiguously distinguish fission fragments down to 5 MeV.

Measuring the Target Mass and Uniformity

The target mass will be measured by alpha counting. In the past this has been accomplished with a non-directional alpha counter calibrated with a known source. This introduces three systematic errors. First, the reference source has a systematic error in flux. Second, the alpha counter has a finite efficiency, especially for high-angle alpha tracks. Third, the targets are known to be nonuniform at the 5% level.

There are at least three ways in which a TPC will improve this measurement. First, the TPC measures the location on the target where each alpha was emitted. This provides a map of the target thickness over the entire surface. The target can then be thought of as several hundred micro-targets, each with its own well-determined thickness. In addition, the target will be measured in situ in the TPC. Consequently, the target thickness map and the beam profile (which is also measured in the TPC) can be used directly to compute the cross section.

The second improvement is that the TPC does not need an alpha calibration source since it is 100% efficient for tracks longer than a minimum length. One possible remaining source of inefficiency could be two track merging effects, but these are estimated to contribute far less than one percent. There are additional methods which can be used to reduce the uncertainty from tracks that are shorter than the minimum length, which leads to the third improvement.

The two target mass measurement errors discussed above have relatively little contribution to the total error. The limiting component for the TPC measurement of target mass is from alphas that exit the target at large angles to the normal and suffer large energy loss in the target. This is a small effect (affecting less than about 2% of all alphas), and can be almost completely corrected for with a TPC, yielding a final error of less than 0.1%.

The 2% effect that has to be corrected is conservatively estimated in the following way. The range of an alpha in the target is 8.56 μm with 0.63 μm straggling. To be measured without any loss an alpha needs to have 2 MeV on exiting the target Consider a 5 MeV alpha emitted at the far side of a 200 ug/cm^2 target. Assuming constant specific energy loss the alpha will have 2 MeV on entering the gas if it is emitted at 1.27 degrees. This corresponds to 2.2% of the solid angle.

The correction for the 2.2% of alphas that are poorly measured is derived by extrapolating from the measured 97.8%. This extrapolation will be highly accurate since the alpha decay is isotropic, and such a large fraction of the alphas are well measured. A 5% error is estimated for this extrapolation. A 5% statistical error on a 2% correction results in a 0.1% systematic error.

Reference Targets and *n* Flux Measurement

The beam flux error is the error associated with using ^{235}U as the reference to determine the total beam flux. Although ^{235}U has the best known fission cross section, it is only known to about 1%. The most promising alternative is the reaction $^{1}H(n,n')$, which is known to 0.2%. The interactions of the beam neutrons with the gas is understood and discussed below. The remaining technical issue, which will be understood in the first year of the project, is the size of the cathode signal from the recoil protons in the gas. This signal has to be large enough (compared to the noise) to use as the neutron time-of-flight measurement, to determine the incident neutron energy, as is done for the fission fragments. If the signal is too small, the baseline plan will measure $^{239}Pu(n,f)$ in one TPC, and the beam flux using $^{235}U(n,f)$ in a second identical TPC. This will result in a sub-percent measure of the ratio of the cross sections, which would be very useful in its own right.

Neutron Measurements

Although TPCs only detect charged particles, through the ionization trail they leave in the gas, there are also methods to detect the fission neutrons. The two methods considered here are the $^{3}He(n,p)^{3}H$ reaction and scattering on ^{1}H gas. Both of these methods produce a charged particle that can then be tracked in the TPC. The ^{3}He reaction cross section is smaller and, more importantly, not so accurately known as the ^{1}H reaction particularly at high neutron energy. The ^{3}He would be best used for detecting the fission neutrons because of the better energy and angle measurement. The ^{1}H has a much better known cross section that would be better for beam flux measurement. Either can be used in any TPC configuration. Following is an example using ^{1}H. The cross section for (n,p) scattering near 1 MeV is approximately 5 barns. From this a calculation is made of the probability of beam neutrons interacting in a hypothetical TPC filled with ^{1}H at 10 bar with a 4.5 cm drift and 15 cm radius.

Fission neutrons will interact with 2.0% probability in traversing the 15 cm transverse radius. Beam neutrons will interact with the gas along the drift direction with 0.6% probability.

From these numbers the number of neutrons detected in the TPC from beam-gas scatters and from fission are calculated. Each pulse of neutrons from the WNR at LANSCE produces about 1440 n/cm^2. This results in about 35 beam-gas scatters across a 4 cm^2 beam size. There is less than one fission per pulse. Because of the low detection efficiency, most fission events will have either zero or one fission neutrons detected. The number of fission neutrons measured in the TPC is quite small in comparison to the beam neutrons which scatter in the gas. Attempts to increase the fission neutron efficiency with increased pressure or longer drift also increase the number of beam neutrons. The number of beam neutrons in this design is already large and could start to degrade the performance. The conclusion is that the baseline TPC design is ill-suited to measure fission neutrons by itself. Two ideas to improve the neutron detection performance are described below.

Measurements of Other Fission Properties

The focus of this report is the accurate measurement of the ^{239}Pu cross section. However, the TPC is capable of measuring other fission properties. This information is acquired simultaneously with the cross section, resulting in a many-dimensional data set, allowing exploration of a number of correlations and differential cross-sections. The first section discusses fission properties that will be measured in the baseline detector. As indicated above, any parameters involving neutrons will require changes from the baseline.

Fission Fragment Spectrum and Mass Distributions

The **energy of the fission fragments** are recorded. The fission fragments in the TPC are easily separated from alphas and neutron-chamber scatters, so fragment energy measurement is simple. The simulations show energy resolution better than 10% for most fission fragments.

The **mass distribution of the fission fragments** is also measured by looking at the Bragg curve of each particle. The A resolution is not spectacular (approximately 10% of A) but it is sufficient to study correlations with the cross section, fission fragment energy, beam neutron energy or any other parameter.

Photons from Fission

Fission gammas may be measurable by placing the TPC inside existing hermetic photon detectors at LANSCE. The active volume of the baseline detector is quite small. Efforts will be made to keep the overall structure compatible with such auxiliary photon detectors.

Neutron Measurements

As estimated above, the measurement of fission neutrons is complicated by the much larger rate of beam-gas scatters. The accommodations needed to measure the neutrons in one TPC would cause a degradation to the fission cross section measurement. There are two approaches to designing additional TPCs for this measurement.

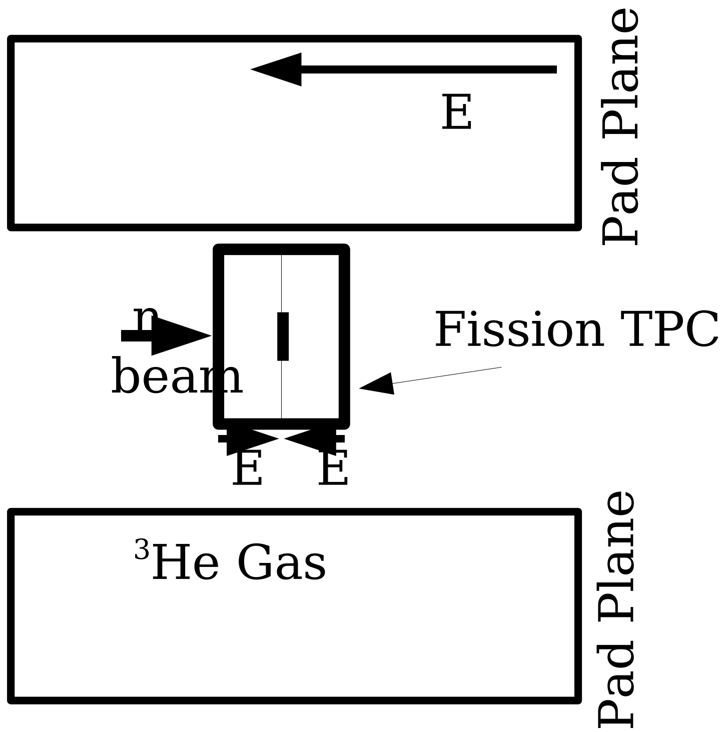

Figure 15 Side view of annular neutron TPC.

One obvious solution is to build a barrel TPC to surround the baseline TPC. A sketch of this arrangement is shown in Figure 15. This has the advantage that the fission measurements are still well measured, but the disadvantage that the walls of the two TPCs introduce material for the neutrons to scatter from, potentially degrading the neutron measurement. Due to the low occupancy, the readout would consist of a set of strips in two or three directions, which will use many fewer DAQ channels, helping to control the cost.

The second solution is to make an asymmetric TPC, as shown in Figure 16. This design is also considerably wider than the baseline detector. In this TPC the down-stream side will have a lot of confusion along the beam due to beam-gas scatters; this central column would have to be ignored. As a result, only one side of the fission will be observed, in the upstream side. However, the longer down stream side and greater width increase the fission neutron interaction probability significantly. Outside the central beam column, the occupancy will be low, so a strip readout in the barrel TPC would be appropriate.

The **fission neutron spectrum**, dN_n/dE, could be measured with either of the two neutron TPC upgrades.

The **fission neutron angular distribution**, $dN/d\Omega$, could also be measured with either of the two neutron TPC upgrades.

The **number of neutrons per fission**, ν, could be measured with the relatively simple upgrade of adding a scintillator barrel. This would be a segmented liquid scintillator surrounding the TPC to capture the fission neutrons. It would be designed to have a high efficiency so it could determine the number of fission neutrons in each event. The ability of a device like this to determine the direction or energy of the neutrons is limited so this would only be a neutron counting detector.

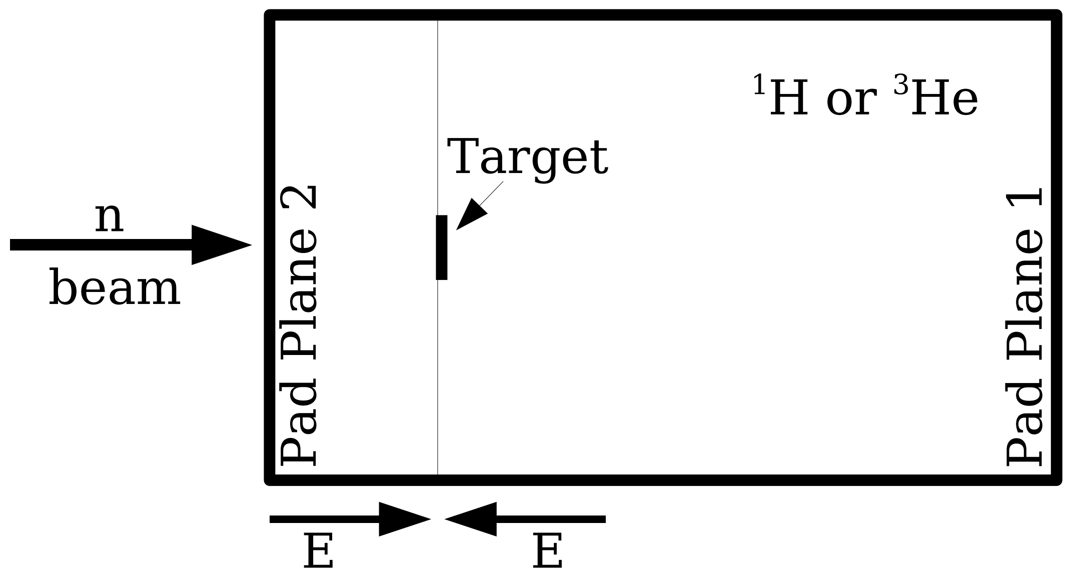

Figure 16 Asymmetric TPC for neutron measurement

Collaboration and Project Plan

Collaboration

This project has been discussed with potential collaborators at LANL and NIST. Dr. Tony Hill, LANL, is actively working on fission experiments. He is very eager to collaborate, and is actively seeking funding from LANL. This experiment offers the possibility of several graduate student thesis topics, and opportunities for at least two post-doctoral researchers. Dr. Hill has contacted at least one university potentially interested in collaborating.

Cost and Schedule Plan

A first draft project plan has been developed for the development, construction, and operation of the baseline design.[9] The plan covers: design, fabrication, testing, and installation of a pair of small, double-sided

TPCs; design and fabrication of ^{239}Pu, ^{238}U, and ^{235}U solid targets; design, fabrication, testing, and installation of detector digitizing and readout electronics; development of an accurate and complete simulation for the experiment; operation of the experiment at the LANSCE WNR neutron beam facility; analysis of the data and publication of the (n,f) cross sections; and project management.

The fission data will be taken at the WNR facility of the LANSCE accelerator, at LANL.[10] This facility delivers approximately 100 macro pulses per second each 625µs long with 1.8 µs micro pulse structure. Each micro pulse contains ~1440 neutrons per cm^2. This will result in 30–50 fissions/s in a 200 µg/cm2 sample.[11] To obtain 0.1% statistical errors in 100 neutron energy bins, we need to measure 10^8 fission events. At 50 fissions/s, this will take ~23 days of running.

The Level 1 summary is shown in Table 4. The Fission TPC Experiment will cost $6.0 M, and take 5.5 years to complete.

Because of the very limited level of detail available at this early stage in the design, the confidence interval on the cost estimate must be somewhat broad. Certainly any contingency estimate less than 35–50% is unjustified at this stage. The largest uncertainties come from the open system-level design decisions, and technology options: solid or gaseous targets, neutron detection, and electronics design. A major deliverable for the first year must be a much more detailed project plan, based largely on bottoms-up estimates, which will have a much reduced contingency estimate. At that point the project will be re-baselined.

Table 4 WBS rollup to Level 1.

WBS	Task	Labor	M&S	Total
	Fission TPC Experiment	$ 4,638 K	$ 1,338 K	$ 5,976 K
1	TPC	$ 900 K	$ 395 K	$ 1,295 K
2	Electronics and DAQ	$ 708 K	$ 797 K	$ 1,505 K
3	Online Software	$ 362 K	$ 6 K	$ 368 K
4	Offline Software	$ 480 K	$ 0 K	$ 480 K
5	Simulation	$ 428 K	$ 0 K	$ 428 K
6	Operations	$ 1,161 K	$ 140 K	$ 1,301 K
7	Project Management	$ 600 K	$ 0 K	$ 600 K

Finally, this is a complete project plan. No “credit” has been taken for possible contributions by non-LLNL collaborators except for beam time and floor space at LANSCE.

First Year Design Development Activities

In the first year, the focus will be on conceptual design and development tasks that directly reduce the cost and schedule risk to the project. Based on that work, a complete bottoms-up project plan will be developed. The tasks to be addressed are: conceptual design of the TPC hardware, basic simulation development, constructing and testing prototypes for the pad plane and preamplifier/shaper amplifier, system block diagram for the data acquisition, and investigating the feasibility of using a Pu gas target. These tasks are discussed below.

First year activities require $850K. A lower funding level will delay some development and risk reduction tasks to Year 2. The schedule impact will be larger than just the amount of delayed work, since the associated cost and schedule risks won't be known at the end of Year 1, when, presumably, a decision will have to be made on whether to go forward, based on the revised project plan,.

Conceptional Design of the TPC Hardware

The only technical challenge in the TPC structure itself is the field cage, which maintains a uniform drift field at the edges of the fiducial volume. There are several options which need to be investigated for manufacturability and performance. A certain amount of basic mechanical design (pressure vessel size, wall thickness, flange sizes; location of feedthrus; etc.) remains to be completed as input to the revised project plan, and to provide baseline geometry for the simulation.

Simulation

In order to evaluate properly various design trade offs, a fairly accurate simulation is needed as soon as possible. The simulation needs an accurate geometrical model, and will use the known particle interactions on all materials. The simulation will also incorporate a detector response model. This is essential for simplified analyses of simulated data to evaluate the impact of various design options. Implementation of the final online and offline software will occur in later years, so the simulation output at this stage will be a simple N-tuple.

Front-end Electronics Prototype

The front-end electronics will be a new implementation, using modern components, of a fairly conventional chain (preamplifier, shaper amplifier, digitizer, pedestal subtraction, zero suppression). As in existing implementations, the main technical concerns are the noise and cross-talk in the pad plane and preamplifier and the dynamic range. A secondary concern is freezing the system-level block diagram, specifying the number of channels per board and the interconnects. To understand the noise and cross talk issues, a prototype pad plane with MICROMEGAS gas amplification will be built, and a small number of channels instrumented with preamplifiers/shaper amplifiers.

Feasibility of a ^{239}Pu Gas Target

A gaseous target would eliminate most of the large systematic errors, and open the way to better fission measurements. There have been limited discussions with experts about the possibility of making a Pu-containing gas, such as a carbonyl ($Pu(CO)_6$). Other heavy metal carbonyls, such as tungsten, are easy to make and are sold in industrial quantities. At least one reference indicates that uranium carbonyl has been made, although details have not been investigated for this purpose. Because of the dramatic reduction in systematic error made possible by a gaseous target, it is very important to investigate this possibility further, and as early in the project as possible. The specific task for Year 1 is to design, and if possible, execute, an experiment to make $Pu(CO)_6$, or other Pu gas. Most likely this would be done in collaboration with rad-chemists. If the synthesis experiment appears feasible then the manufacture of a ^{239}Pu gas would be attempted at the end of Year 1 or beginning of Year 2.

Appendix A. Systematic Errors in Fission Measurements

Name	**Neutron Beam Energy**
Description	The energies of the beam neutrons are determined by a time-of-flight (TOF) measurement. The stop time for this measurement is the signal on the actinide target plane. The target plane signal is generated by the primary ionization of the gas in the chamber caused by the fission fragment.
Fission Chamber Error	0.1%, from reference [3] and Dr. Tony Hill, LANL (private communication).
TPC Error	0.1%, same as for a fission chamber, since the same stop signal will be used.
Summary	Error is well understood and small. No improvement is necessary.

Name	**Neutron Beam Flux**
Description	The cross section is the number of signal events per target nucleus divided by the incident beam flux. For broad spectrum sources like LANSCE the number of neutrons is determined by placing a material with known cross section in the same beam. The number of signal events from the reference target is an indirect measure of the beam flux. This error does not enter, to first order, in a measurement of the ^{239}Pu to ^{235}U cross section ratio.
Fission Chamber Error	~1%, using ^{235}U(n,f) as the reference target, from the quoted errors in the ^{235}U(n,f) cross section.
TPC Error	0.4%, using ^{1}H as the reference target. The error on the ^{1}H(n,n´)p cross section is 0.2%. Measuring the recoil proton in the TPC is strait-forward. A technical issue that remains is the measurement of the beam neutron time-of-flight, since the signal induced in the cathode by the recoil proton will be small. The total error estimate is 0.4%.

Name	Neutron Beam Flux
Summary	Need to evaluate the cathode signal to noise ratio from a proton recoil in the gas, then simulate the accuracy obtainable using the hydrogen reference.

Name	Beam Profile
Description	Non-uniformities in the beam couple with non-uniformities in the target thickness and reference target to introduce a systematic error.
Fission Chamber Error	0.5% non-uniformity of the beam, from reference [3], based on scanning a fiber scintillator though the beam. Unknown quantitative effect on fission measurement, but should be small.
TPC Error	Very small. A TPC will measure the beam profile at a typical few hundred micron resolution, using the recoil protons from the $^{1}H(n,n')p$ interactions. Beam profile variations larger than this scale will be measured directly. This error is essentially absent from the TPC measurement.
Summary	A TPC will measure the beam profile directly, and significantly improve our understanding of this error in fission chamber measurements.

Name	Position Dependence of Neutron Beam Spectrum
Description	In principle the beam spectrum can depend on position, due to source or collimator effects. Since the reference target cross section is energy dependent, spectral variations couple to target non-uniformities to introduce a systematic error.
Fission Chamber Error	Unknown.
TPC Error	Very small. Using the $^{1}H(n,n')p$ reaction, the beam spectrum will be measured on a few hundred micron spatial scales.
Summary	A TPC will directly measure the beam spectrum as a function of position, and significantly improve our understanding of this error in fission chambers.

Name	**Beam Outside of Target**
Description	If the neutron beam is larger than the target some portion will miss the target. If the two targets are not the same size, or not positioned equivalently in the beam, they see different beams.
Fission Chamber Error	0.01%, based scanning a fiber scintillator.
TPC Error	Very, very small. All beam, including beam outside the fiducial volume or completely missing the target, will be measured using the $^{1}H(n,n')p$ reaction.
Summary	Very small effect; can be studied in the TPC.

Name	**Beam Spreading and Attenuation**
Description	When a separate reference target is used, the beam seen at each detector is not exactly identical because of the opening angle of the beam profile, and attenuation in the detectors themselves.
Fission Chamber Error	0.3%, from [3]. Determined by simulation and comparison of several reference targets.
TPC Error	Very small. The $^{1}H(n,n')p$ reaction measures the beam flux directly at the experimental target. The reference target is not in a separate detector. For the $^{239}Pu/^{235}U$ ratio measurement, each detector has its own beam normalization. To put it another way, any spreading or attenuation between the two detectors will be measured.
Summary	A TPC will significantly improve our understanding of this error in fission chambers.

Name	**Target Purity**
Description	Error associated with the chemical and isotopic purity of the target.
Fission Chamber Error	0.1%, quoted in [3], from alpha spectroscopy and chemical analysis.
TPC Error	0.1%, as for a fission chamber.

Name	Target Purity
Summary	Error is well understood and small; no improvement is necessary.

Name	Target Surface Contamination
Description	Contamination of the target surface can cause non-uniform energy loss for fission fragments.
Fission Chamber Error	Unknown. The surface can be inspected before installation to help reduce this error.
TPC Error	Very small. A position-dependent energy loss will be easy to measure in a TPC on the target in situ.
Summary	Error is expected to be very small, and can be measured with a TPC.

Name	Non-Uniform Target Areal Density or Thickness
Description	Target density variations of at least 5% are known to exist.
Fission Chamber Error	0.7%, from [3]. This error is a result of three factors: calibration of the alpha counter, averaging over the whole target surface, and alpha counter inefficiency for alpha particles emitted at high angles.
TPC Error	0.1%. A TPC will measure the target thickness on a few hundred micron scales by directly tracking the alpha particles, in essence performing an auto-radiograph of the target. No separate alpha counter is required. For alphas emitted at up to ~98°, a TPC will be 100% efficient. The correction for emission beyond this angle is essentially geometrical, and can be checked by lowering the operating pressure to enable detection of these low-energy alphas.
Summary	A TPC will make a large improvement in this error.

Name	Complete Energy Loss in the Target
Description	Fission fragments emitted at large angles to the target surface can be completely stopped in the target, leading to an undercount of the number of fissions. At higher neutron energies the incident neutron momentum tends to push the

Name	Complete Energy Loss in the Target
	fragments into the forward region, so that the downstream fragment is no longer at high angles, reducing the error.
Fission Chamber Error	0.1%, from [3].
TPC Error	0.05%. A fragment is more likely to be “lost” if the fission occurs near the opposite surface of the target. Because a TPC measures both fragments, when one fragment is “lost,” the other is likely to be seen. This increases the net acceptance above what a fission chamber can measure.
Summary	The fission chamber error is acceptably small; the TPC error will be smaller.

Name	Partial Energy Loss in the Target/Particle Identification
Description	Fission fragments emitted at large angles to the target surface can lose sufficient energy that they give the same signal as an alpha particle or a beam-chamber scatter.
Fission Chamber Error	1% at low beam energies, rising to 2% at higher beam energies, from [3]. In a fission chamber it is impossible to distinguish alpha particles, beam-chamber scatters, and fission fragments of the same energy. In the overlap region, one makes a cut, then corrects for fission fragments removed, and alpha particles and beam-gas scatters that were included.
TPC Error	0.2%. A TPC measures the particle range and specific ionization, as well as the particle energy. A cut in the range-energy plane and target-out runs will reduce this error to 0.2%.
Summary	A TPC will significantly reduce this error.

Name	Fiducial Volume
Description	Fission fragment tracks that are absorbed or escape the detector will not be detected, or appear as low energy events in a fission chamber.
Fission Chamber	Unknown; should be zero if the chamber is large enough. Since the tracks are not detected directly, however, there is

Name	**Fiducial Volume**
Error	no way to verify that they are not being lost somehow.
TPC Error	Zero. In a TPC all tracks can be reconstructed. Tracks exiting the active volume are very easy to detect.
Summary	Though this error should be zero in both cases, a TPC can measure it directly.

Name	**Pulse Height Dependence on Beam Energy**
Description	It is observed that the pulse height in a fission chamber depends on the beam energy. The reason for this is unknown.
Fission Chamber Error	Unknown. In principle one could correct for effect with a proper analysis.
TPC Error	Unknown. A TPC measures the specific ionization along every track, which help tremendously in understanding the origin of this effect.
Summary	Probably not a significant error for either detector. A TPC can explore this issue.

Name	**Space Charge**
Description	Accumulation of charged ions in the chamber gas or on surfaces can distort tracks in the active volume.
Fission Chamber Error	Unknown, probably very small.
TPC Error	Unknown. This could affect the tracking somewhat, but it is also measurable, and actions can be taken to reduce the source and effects.
Summary	Probably not a large effect, and can be measured in a TPC.

Bibliography

1. GEANT4 Home Page, http://wwwinfo.cern.ch/asd/geant4/geant4.html.
2. W. Younes, et. al, Phys. Rew. C, **64**, (2001) See paper intro
3. P. Staples, K. Morley, Nuc. Sci. Eng., **129**, (1998)
4. Nuclear and Atomic Data Systems, http://nuclear.llnl.gov/CNP/nads.
5. Y.Giomataris, et al., NIM A, **376**, (1996)
6. Blum, Rolandi "Particle Detection with Drift Chambers"
7. S.A. Wender, et al., NIM A, **336**, (1993)
8. SRIM & TRIM, http://www.srim.org/.
9. P. D. Barnes, Jr., M. D. Heffner, "Fission TPC Draft Project Plan," Lawrence Livermore National Laboratory, UCRL-AR-217390 (2005).
10. Weapons Neutron Research, http://lansce.lanl.gov/WNR/index.html.
11. Tony Hill, personal communication (2005).