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A Time Projection Chamber for precision $^{239}\text{Pu}(n,f)$ cross section measurement

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A Time Projection Chamber for Precision $^{239}\text{Pu}(n,f)$ Cross Section Measurement

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Abstract.

High precision measurements of the $^{239}\text{Pu}(n,f)$ cross section have been identified as important for the Global Nuclear Energy Partnership (GNEP) and other programs. Currently the uncertainty on this cross section is of the order 2-3% for neutron energies below 14 MeV and the goal is to reduce this to less than 1%. The Time Projection Chamber (TPC) has been identified as a possible tool to make this high precision measurement.

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INTRODUCTION

The measurement of the $^{239}\text{Pu}(n,f)$ cross section has been carried out many times over the last 50 years [1]. Despite this large effort, the uncertainty on this cross section remains in the range of 2-3%. Individual experiments quote smaller errors, but when a collection of experiments are considered, it is clear that some systematic error remains in the 2-3% range [1]. Although the precise origin of the remaining error has yet to be discovered, many possible sources have been enumerated and it is the goal of the fission TPC project to uncover the sources of error and to drive down the uncertainty of the $^{239}\text{Pu}(n,f)$ cross section to 1%.

The GNEP program was designed to aid in the deployment of more nuclear power reactors world wide [2]. This program has a number of goals such as reducing cost, increasing safety, reducing proliferation, and reducing radioactive waste. A part of the program is to develop fast spectrum fission reactors to reduce generation of waste though increased burn-up and burning of transuranics. These new Gen IV reactors are in the design stage and it has been recognized that improved nuclear data is needed to achieve the required accuracy in the simulation of these reactors [3, 4]. A number of cross sections have been identified for each of the designs, and the requirements vary from design to design. In particular, $^{239}\text{Pu}(n,f)$ has very strict requirements, demanding errors less than about 1%.

Most $^{239}\text{Pu}(n,f)$ cross section measurements have been conducted with a fission chamber. This simple parallel plate chamber is easy to construct and has been effective in many cross section measurements. Studying $^{239}\text{Pu}(n,f)$ experiments, in detail, reveals that the error achievable with the fission chamber is reaching a limit. This is understandable given the very simple nature of the device.

The fission chamber measures only the total energy of the fission fragment¹.

TIME PROJECTION CHAMBER (TPC)

The TPC is a sophisticated drift chamber detector that was revolutionary in the expansion of detailed tracking information that could be collected in one gas volume. It was invented in the late 1970s by David Nygren at LBL [5]. The TPC has found many application in the accelerator physics, dark matter searches, neutrinoless double beta decay, and even homeland security projects.

Applying the TPC to low energy nuclear physics problems is a natural extension of the fission chamber work. The TPC shares major features with the fission chamber such as the active gas volume and electron drift, but deviates in the complexity of the readout. The fission chamber has one channel to readout per fission, where the fission TPC will have about 12,000. This large increase in channels results in a very powerful detector that will enable the experimenter to address the remaining errors in the cross section measurement. The key improvement is that the fission chamber returns only the energy deposited in the active gas volume, while the TPC returns a full 3D reconstruction of the event. Figure 1 shows an example event in the EOS TPC.

¹ In the case of a white neutron source the time-of-flight of the neutron is also measured

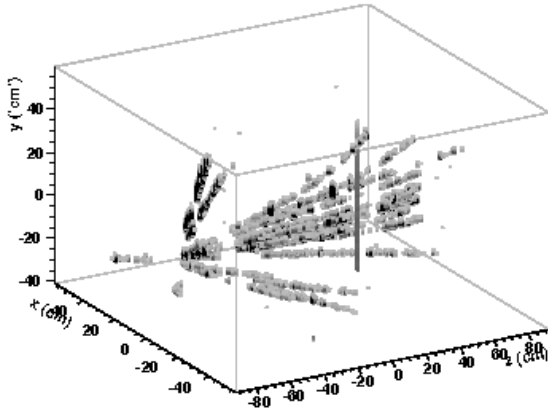


FIGURE 1. Event in the EOS TPC. The individual tracks within one event are clearly distinguishable by eye.

How the 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 "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 distinguish the different particle species within an event.

Figure 2 shows a conceptual design of a TPC for the proposed fission measurement. The isotope to be studied (*e.g.* ^{239}Pu) is located in the center of the TPC. 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% CH₄), 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.

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 [7], GEMs and LEMs [8], 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

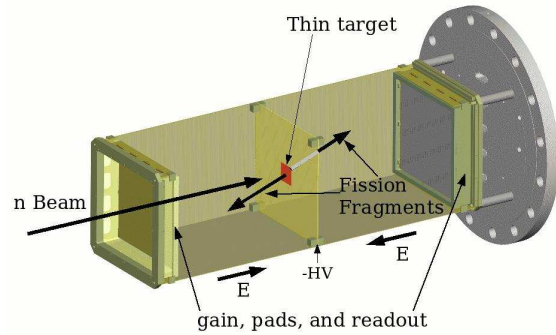


FIGURE 2. Schematic view of a two-sided TPC with a solid target at the cathode for fission measurements

short-range particles, these new methods are most likely the best gas amplifier technology for this measurement.

SYSTEMATIC ERRORS

There are a number of known systematic errors that contribute to the total error of the fission measurements. The three dominate errors are related to, particle identification, target thickness, and the use of ^{235}U as a normalizing reference. These three alone have precluded sub-1% measurements with standard fission chambers. While all of the known, suspected and subsequently discovered systematic errors can be fully investigated and addressed in a TPC experiment, the focus here is 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 error reduction. The amount of ionization from a charged particle traversing the active gas volume is proportional to the total energy of the charged particle. Fission fragments are highly charged and have typical energies around 100 MeV, therefore, they typically leave a large signature in the gas volume. Spontaneous decay backgrounds from the sample or sample contaminants typically have energies around 5 MeV and are not highly charged - their signature is small in comparison. However, multiple scattering of the fission fragments through the sample itself and the support backing can cause extreme straggling, particularly for the lower energy, higher Z fragments that have trajectories at large angles from the target normal. At low measured energies, the two signatures overlap and result in one of the largest systematics associated with these types of measurements because assumptions have to be made about the shape of the straggling fission fragments energy distribution. The problem is exacerbated by (n,n α) and other scattering reactions on the target backing, chamber entrance window material and the drift

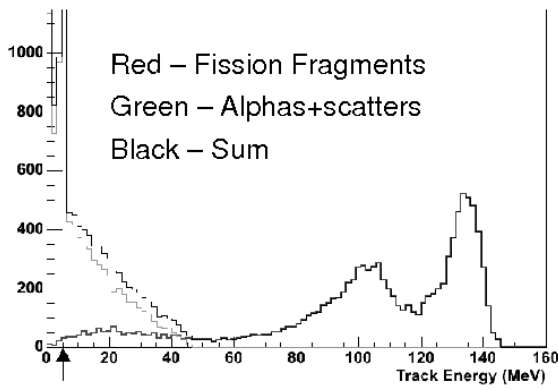


FIGURE 3. : Simulation of particle identification in a fission chamber. The top line is what would be measured in an experiment. The lines below show the components: alphas, scatters, and fission fragments.

gas itself. These particles can have even larger energies than the decay α s and further increase the systematic errors.

A simulation of this effect was carried out with the GEANT4 particle transport software. [6] The most significant effects have been included: alpha decay of the target, neutron scatters on chamber materials, and the fissions themselves. Figure 3 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 top line is the net energy distribution one would measure. The lines below show the contribution from the scatters and alphas, and the fission fragments. Fission fragments leaving the target at large angles lose a significant amount of energy, which leads to the long low-energy tail of the fission fragment spectrum. 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).

The situation is considerably different in a TPC. Figure 4 show the same simulation in a TPC. The horizontal axis is the same as in figure 3, but the TPC also measures the track length which is now plotted on the y-axis. The fission fragments are the right most bands, and the bands to the left are alphas and scatters on the chamber materials. It is clear from this plot that separating the particles is much easier in the TPC.

The **Target Thickness** error is the error in assaying the quantity of isotopes in the target sample and determining the homogeneity. In preparation for a fission chamber measurement, the mass of the target is usually determined by counting the spontaneous alphas. The total

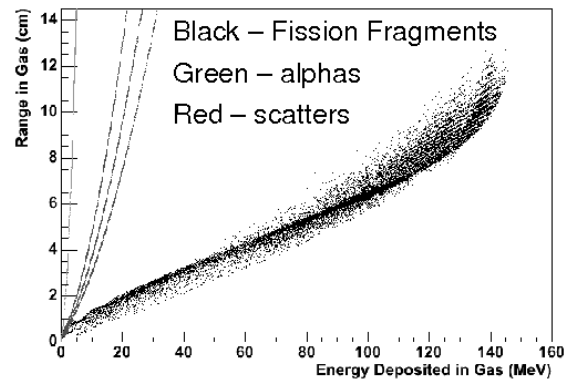


FIGURE 4. Simulation of particle identification in the TPC. The right most band is the fission fragments. The alphas and scatters are on the left.

mass is usually measured by viewing the entire sample. The thickness and homogeneity determination is usually carried out using a masked detector. 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 will measure the alphas produced from the target and use this to produce an in situ autoradiograph of the target. This can then be used to determine the homogeneity of the target. There is no mask to confuse the measurement, the TPC is 100% efficient in measuring the alphas and the detailed tracking removes the need to average over the target.

The **^{235}U Reference** error refers to the conventional method used to measure the beam flux in fission experiments. The beam flux from a typical neutron source 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, optimistically, to about 1% in some incident energy regions. Measuring a fission cross section ratio in this way minimizes all the beam related uncertainties since they will nearly cancel in the ratio.

An improvement would be to use hydrogen as a reference since the (n,p) cross section is known much better than ^{235}U . In some portions of the phase space the (n,p) is known to 0.2%. A prime candidate for the drift gas of the fission TPC is hydrogen for the low multiple scattering and decent properties as a drift gas. The drift gas also

experiences the neutron beam, so if the density was well controlled it could also serve as the reference target. This has a number of advantages such as the simplicity, and no target straggling.

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, and the dynamic range to simultaneously measure protons. 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 2. This detector, however, is not the best that can be done using a TPC. Though this 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 target, ideally one would use a gaseous target, and measure the fission events free in the drift gas.

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/cm² per pulse and pulse spacing no closer than 1.8ms. These requirements can be met by the LANSCE facility.

PROJECT STATUS

The fission TPC concept entered a feasibility study in Feb 2004, and has received substantial money starting in fiscal year 2008. The projection is that the TPC will be built and the ²³⁹Pu(n,f) measurement made in 5.5 years.

We have started detailed design of both the TPC chamber and the electronics. Figure 5 shows the current 3D model of the TPC. The center is a pressure vessel that holds the hydrogen working gas with pressures from 0 to 5bar. The fan like structure is an extension of the pad plane and the fins are the readout cards that plug in to the pad plane. Each readout card sends data from 64 pads on a standard Ethernet cable to the event builder computers for event reconstruction.

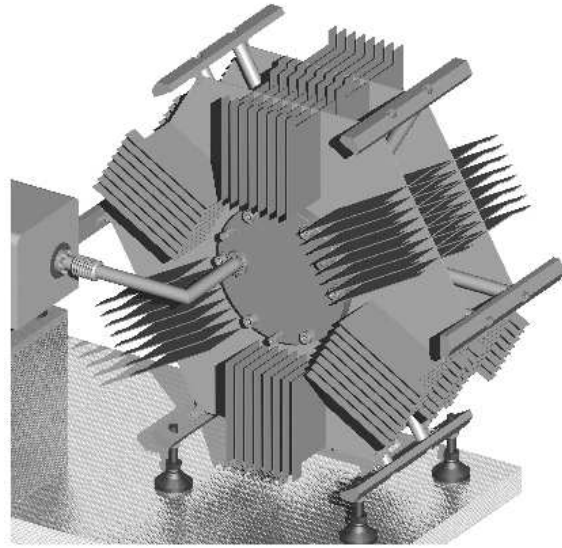


FIGURE 5. Model of the fission TPC.

CONCLUSION

There is a need for precision measurement of the ²³⁹Pu(n,f) cross section and the TPC has been selected to make this measurement. The utility of the TPC should extend beyond this measurement to the basic physics of fission and it is expected that the TPC should make significant contributions to the understanding of fission in the near future.

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