Fission Experiments

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1 Introduction

The history of fission is many ways the history of the applications that make use of this complex nuclear reaction. The enormous amount of energy release in fission and its potential for creating chain reactions was successfully explored both for military and civil purposes in the early days of its discovery, and those technologies continues to have important impact on society today. However, there is also a fascinating history of the physics experiments that shaped our understanding of the fission process with its many-faceted aspects. Lise Meitner and Otto Frisch explained the experimental results obtained by Hahn and Strassmann as the result of a new and previously unknown reaction, nuclear fission, in late 1938. Within a few months Otto Frisch was able to irradiate a uranium-lined ionization chamber with neutrons and observe signals from fission fragments being stopped in the gas volume of the detector. This technique, with some improvement, continues to be used in fission research today in parallel with together with new and advanced instruments and methods.

More than 75 years after fission was first discovered one might think that enough research had been performed to where we essentially understand most aspects of the fission process.   And indeed, most general properties of fission have been studied in one way or another by now. We have studied the phenomena of spontaneous fission, which occur in heavy element that are instable with respect to fission. We have measure the reaction probability, or cross section, for inducing fission in different nuclei using neutrons, protons, gamma-rays, light ions such as alphas and tritons, and various heavier projectiles. We have also measured the fission fragments that are formed, the prompt radiation in the form of neutrons and gamma-rays emitted as the neutron-rich fission fragment de-excite, and delayed radiation such beta-decay and beta-delayed neutron emission. There are highly successful fission models that describe the general features of fission in terms of mass, charge and kinetic energy of the fission fragments, as well as total energy and energy spectrum in neutron and gamma ray emission.

There are, however, many aspects of fission that are not well understood. While fission models describe many experimentally observed features there is still no general theory that successfully predicts the behavior of systems where data is unavailable. Furthermore, sensitivity studies of existing nuclear reactor types have shown that while the current data correctly predicts their performance, it is often for the wrong reasons: many compensating errors in the microscopic data gives the right macroscopic answer. Those types of issues with the underlying science of nuclear technologies lead to large systematic uncertainties when designing new and advance reactors.

The good news is that we are at a unique time in history for advancing our understanding of the fission process; new detector types provide higher accuracy and precision than ever before and new experiment facilities allows us study fission over a wider spectrum of excitation energies that were accessible a few decades ago. With more experimental studies the missing pieces in the puzzle that is fission could be found; careful studies of how fission observables change as a function of excitation energy and more measurement of their correlations would provide a more complete picture of the fission processes.

2 Fission process

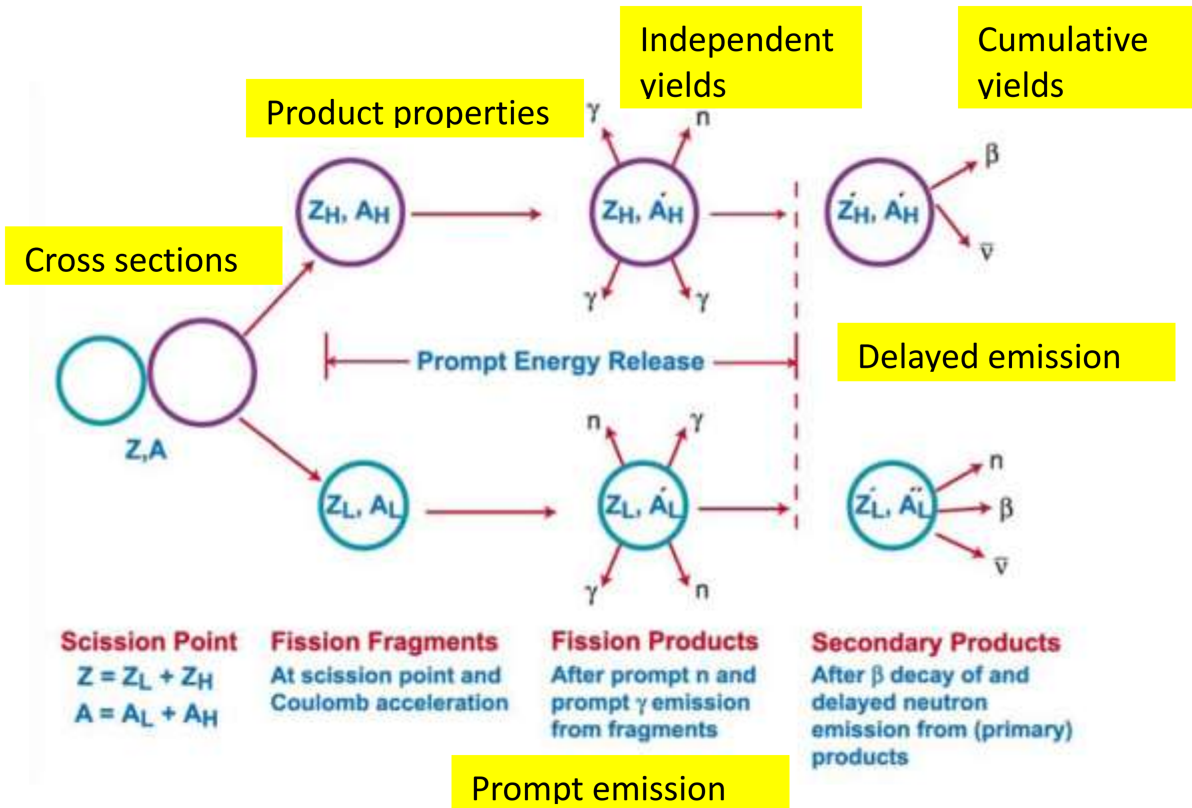

Figure 1: Schematic view of the fission process and the different steps from formation of the fissioning system to the final products.

Induced fission starts with a target nucleus absorbing a projectile, resulting in an excited compound system. The compound nucleus will undergo shape deformation which eventually leads to a split into two fission fragments. The fragments are highly excited and decay initially by neutron evaporation, and when the excitation is less than the neutron separation energy the remaining energy is emitted as gamma-radiation. Prompt emission happens on a very short time scale, so in most experiments one measures the properties of the fission products rather than the fission fragments. After prompt emission the neutron-rich products tend to beta-decay, and sometimes undergo delayed neutron emission. There are several classes of physics experiments that studies different aspects of the fission process.

2.1 Fission cross sections

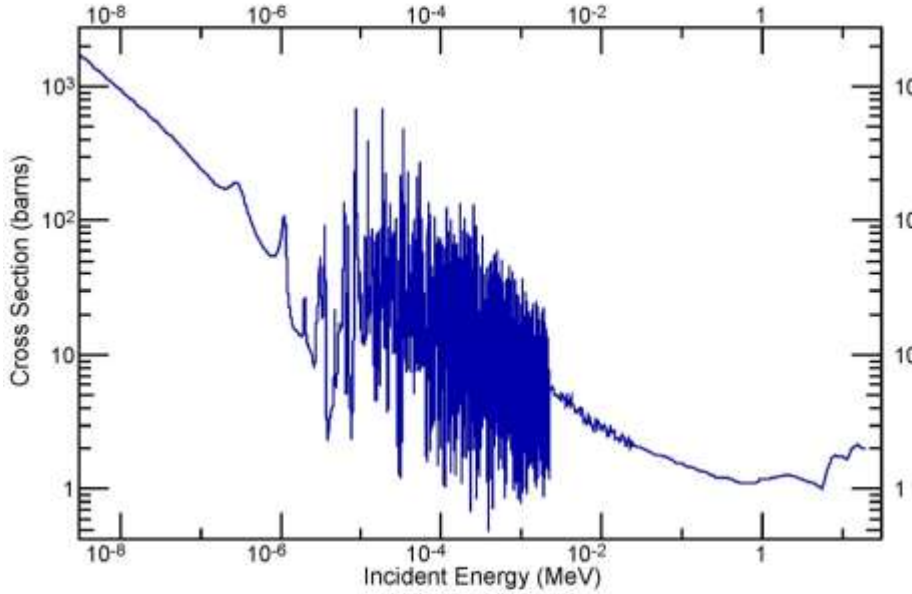

Figure 2: En evaluation (ENDF/B-VII.1) of the U-235 neutron induced fission cross section as a function of incident neutron energy.

In cross section measurements one measures the probability of fission to occur when irradiating a target nucleus with some type of projectiles. These measurements are usually performed by irradiating a thin target foil and count the number of fissions by detecting the fission products emitted from the material. In order to determine the cross section one needs to measure the number of reactions, the number of target nuclei, and the projectile flux. The total number of target nuclei is typically obtained by alpha- or gamma spectroscopy, while the flux can be obtained from some other standard cross section. Figure 2 shows an example of neutron-induced fission of uranium-235 as a function of incident neutron energy. There are several distinct energy regions of the cross section that stands out in this figure. At the low end of the spectrum we have the thermal region where the cross section changes smoothly proportional to the inverse of the neutron energy. The region between 0.1 eV and 1 keV is the resolved resonance region, where nuclear levels in the target nucleus lead to enhanced cross sections at well-defined energies. Above 1 keV is the unresolved region, where nuclear levels are wider than their separation energy, leading to structure in the cross section that is different than what is observed in the resolved region. From 0.1 to 6 MeV a smooth behavior of the cross section is observed, and then at 6 MeV a new reaction channel opens up: neutron evaporation followed by fission. This new channel is called second-chance fission and leads to a sudden increase in the cross section. At higher energies third-chance fission, fourth-chance fission, and so on, is observed.

2.2 Mass yields

In fission of actinides at low excitation energies we typically observe asymmetric mass distributions. There is a well-defined light and heavy peak and almost no yield in the valley between them. The position of the heavy peak changes very little from one actinide to the next, and the difference in total mass of the fissioning system is observed as a change in the light peak position. As excitation is increased a symmetric component of the mass distribution becomes evident, and starts filling in the valley region between the asymmetric peaks. Measurement of the mass distributions for many different systems at many excitation energies is important for validating modern fission models; the potential energy landscape and how the system proceeds through this landscapes is evident in the observed mass yields and is therefore helpful in understanding the process better. Many different approaches to measuring mass yields have been used in the past and will be discussed in the detector section.

2.3 Charge yields

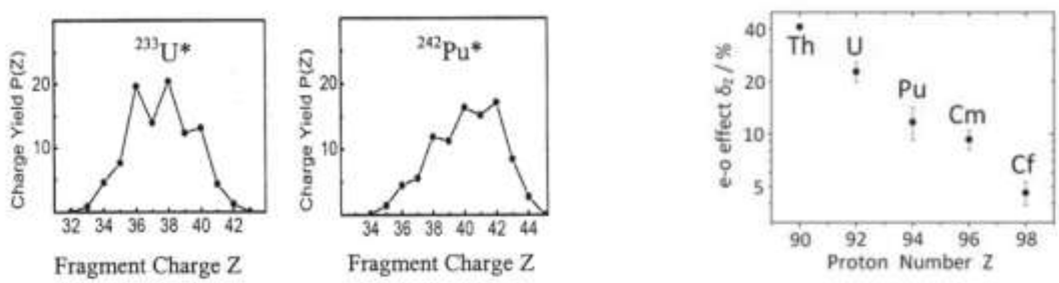

Fig. 1: Charge distribution in (n_{th},f) of ^{232}U and ^{239}Pu   Fig. 2: Even-odd effect δ_Z vs Z of CN nucleus

Figure 3: from F. Gönnenwein, Physics Procedia 47, 107 (2013)

For any given fragment mass there are some 3-5 possible proton numbers. The charge yields exhibits strong odd-even effects which tend to decrease with increasing excitation energy as well as increasing mass of the fissioning system (Fig. on slide 7). The charge of fission fragments can be obtained experimentally by measuring their specific energy loss in some way. One such approach is two let a fission fragment pass thought one detector where it losses some of its kinetic energy, and then have a second detector that stops the fragment and measures the remaining kinetic energy. The ratio between the energy lost in the first detector and the sum of the energy lost in both detectors provide a measure of the nuclear charge. This technique can separate neighboring charges when the ion has a kinetic energy of at least 1 MeV/amu, and is therefore only really effective for light fragments.

2.4 Kinetic energy release

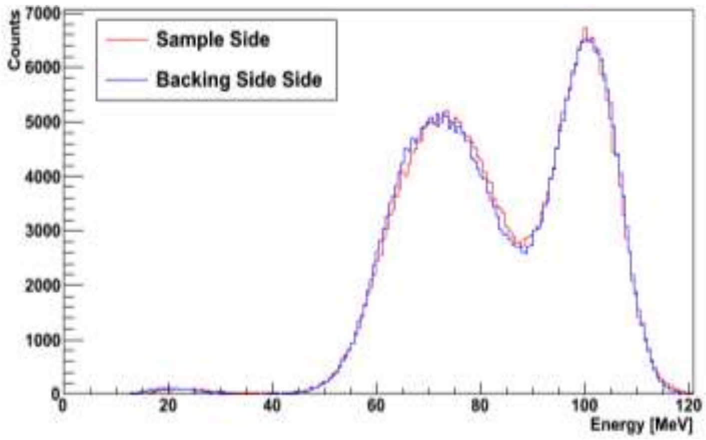

Figure 4: The kinetic energy spectra for fission fragment on the deposit side of a target (red line) and the side of the backing material (blue line).

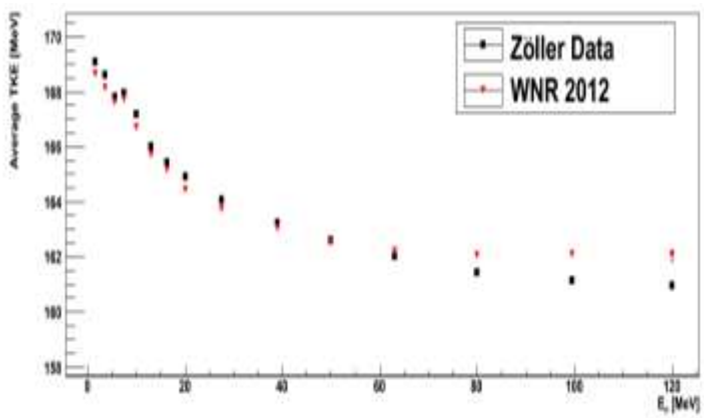

Figure 5: Total kinetic energy release in neutron-induced fission of U-235 as afunction of incident neutron energy.

The kinetic energy release in fission is partitioned between the two fragments; one observe a high energy peak in single-particle spectrum corresponding to light fragments, and a wider low energy peak corresponding to heavy fragments (Figure 4). The sum of kinetic energy of the two fragments in a fission reaction is referred to as the total kinetic energy (TKE). Most of the energy release in fission is in the form of TKE, and corresponds to 160-180 MeV on average. TKE in fission follows a distribution that is well described by a Gaussian function with a width of about 25 MeV. The partitioning of energy release in fission changes with excitation energy, and the average TKE is known to decrease with increasing excitation energy (Figure 5). The change in TKE as a function of excitation energy has only been measured for a small number of actinides, and in most cases only for energies below 10 MeV. The 14 MeV value is important for applications, so more research is need to determine this TKE value with high accuracy.

2.5 Angular distributions

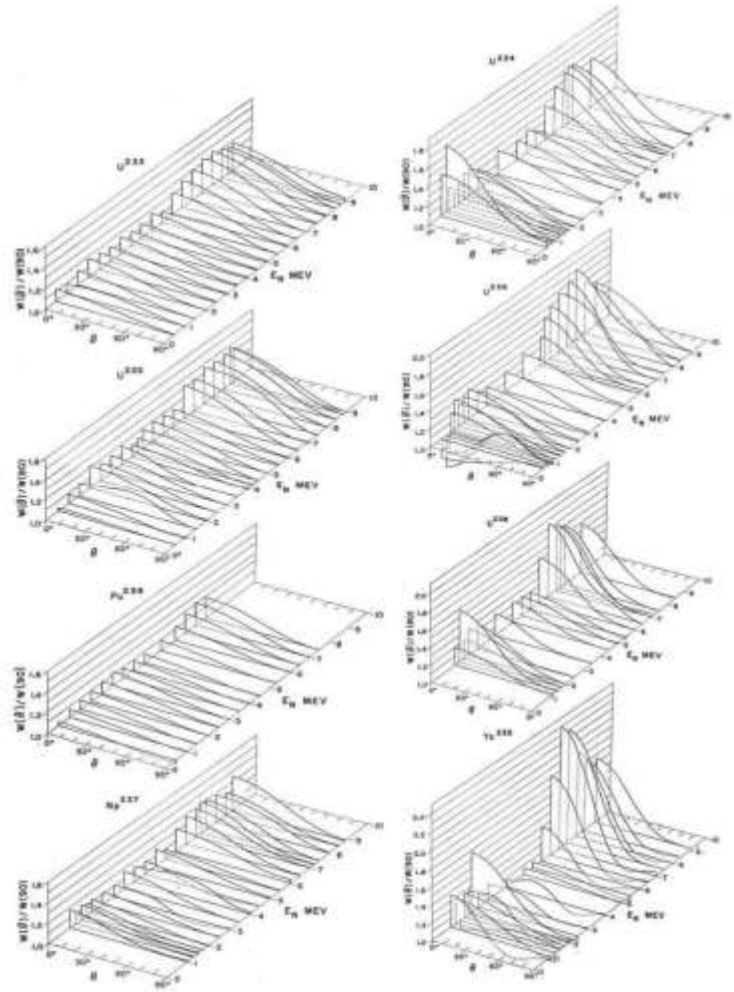

Figure 6: Anisotropy in fission of different isotopes in the incident neutron energy range from 0-9 MeV. From J. E. Simmons et al., Phys. Rev. 120, 198 (1960)

To first order fission is isotropic in the center-of-mass frame, but there are slight deviations from this that have been observed experimentally. Simmons et al measured this for many actinides between 1 and 10 MeV in the 1950's and 60's, and convincingly demonstrated that the angular distributions vary as a function of excitation energy and fissioning system. The anisotropy of fragments is usually presented as the ratio of the yield at 0 degrees and 90 degrees, relative to the incident beam axis. There have been recent measurements of anisotropy in fission, most notably for Th-232.

2.6 Prompt neutron emission

There are on average about 2.5 neutrons emitted in low excitation energy of U-235. This fact is what makes a fission chain reaction possible; if those neutrons on average induce at least one fission reaction you have a self-sustained chain reaction. This makes it important to know the specific of the neutrons emitted as changes in the energy spectrum or total number of neutrons emitted will directly impact that chain reaction.

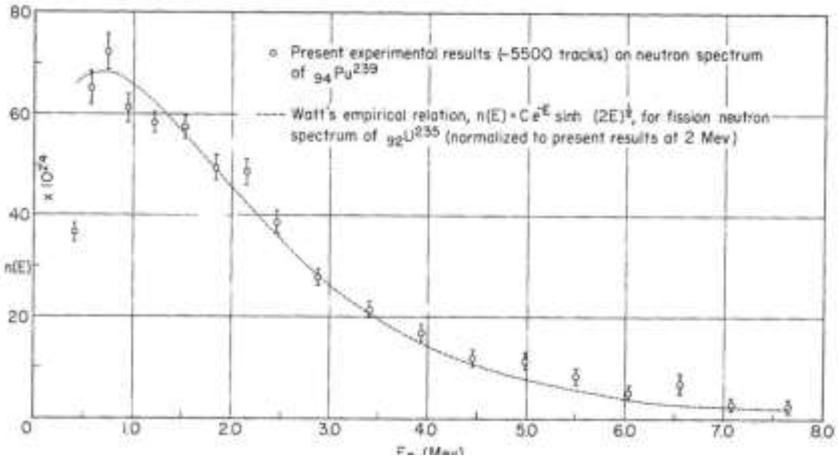

Figure 7: from N. Nereson, Los Alamos Sci. Lab. Report #LA-1078 (1950)

The energy spectrum of fission neutrons are rather well described by a Watt function, with an average of approximately 2 MeV. The spectrum is slightly different for different systems, which has been observed experimentally for e.g. U-235 and Pu-239.

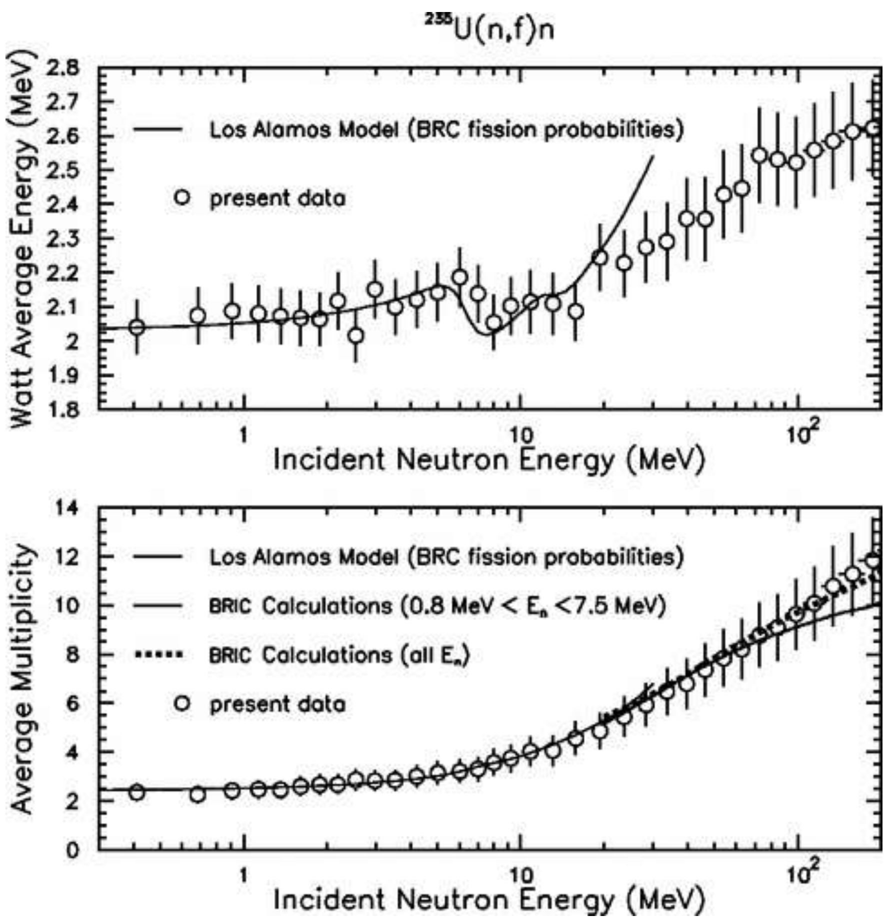

Figure 8: From T. Ethvignot et al., Phys. Rev. Lett. 94, 31 (2005).

The fission neutron average energies have been shown increase as a function of incident neutron energy, the opposite trends observed for TKE. The average number of neutrons also increases with increasing excitation energy, from about 2.5 at 1 MeV to about 10 at 200 MeV.

2.7 Prompt gamma emission

The multiplicity of gamma-rays in fission is rather high, 7-8 on average for low excitation energies. The average energy released in the form of gamma-ray emission in fission is about 6-7 MeV. Some noteworthy studies of fission gamma rays have been performed recently at Los Alamos with the DANCE array (Chyzh et al., Physical Review C 85, 021601 (2012)) and at the IRMM in Geel, Blegium).

3 Neutron sources

Most fission experiments are performed by inducing fission using neutrons. There are several types of neutron sources commonly used, each with different properties and advantages.

3.1 Reactors

Nuclear reactors are intense sources of neutrons. As the fuel fissions a large number of neutrons are emitted, initially with the energy spectrum described in section 2.6. The neutrons are then flowed down in some moderator material. As a result neutrons in a reactor range in energy from thermal up to several MeV. The thermal flux is significantly more intense than other neutron energies, and reactors are therefore most commonly used to study thermal neutron induced fission. In fact, nuclear reactors are the most intense sources of thermal neutrons available for experiments. Some experiments that require very high neutron flux can only be performed at reactors. The disadvantage with reactor experiments is that they provide limited options for study neutron energy dependence in fission. The high flux reactor (HFR) at Institut Laue-Langevin (ILL) is the most intense reactor neutron source in the world with 10^{15} neutron per cm^2 and second in the moderator region.

3.2 Mono-energetic sources

Mono energetic neutrons can be made using various nuclear reactions such as

- Li(p,n)
- $^{2}H(d,n)^{3}He$
- $^{3}H(p,n)^{3}He$
- $^{3}H(d,n)^{4}He$

A common method to use these reactions is to accelerate protons or deuterons with a Van de Graaff accelerator onto a gas- or solid target. An example of such an installation is the 7 MV accelerator at IRMM in Geel, Belgium. By using the various reactions and locating experiments at various angles relative to the primary beam one can get neutrons at any energy between 0.1 and 24 MeV. Other accelerators, such as cyclotrons, are also used to produce mono-energetic neutrons. An example of that is The Svedberg Laboratory at Uppsala University in Sweden where high energy mono-energetic neutrons made through the Li(p,n) reaction. The neutrons can be produced with energies up to 200 MeV in this case.

3.3 White spectrum sources

An alternative to mono-energetic sources is to produce a white spectrum of neutrons with a pulsed beam, and then determine the energy of incident neutrons by measuring the neutron time-of-flight (TOF) over some flight path. In this approach it is possible to determine the energy of the neutron that caused fission in each event by measuring the time difference between the accelerator pulse hitting the neutron producing target and the fission reaction in the detector. This allows the experimenter to measure the energy dependences in fission in a single experiment.

One type of neutron TOF sources is electron beam facilities. One such facility is the GELINA Linear electron accelerator that produces 100 MeV electrons in pulses with 800 Hz repetition rate and 10 ns pulse widths. This neutron source uses a uranium target, and when the electron beam hits the target it produces bremsstrahlung, which in turn produces neutrons through photonuclear reactions. Flight path with lengths of 10, 30, 50, 60, 100, 200, 300 and 400 meters has direct view of the neutron source, and depending on the length of the flight path the incident neutron energy can be resolved with higher or lower resolution.

Another class of TOF neutron sources is spallation facilities. In spallation neutrons are produced when high energy ion beam hits some high-Z material, and the neutron spectrum in this case extends up to the energy of the ion beam which typically is in excess of 500 MeV. The Weapons Neutron Research (WNR) facility at LANL is a spallation source with an 800 MeV proton beam that hits an un-moderated tungsten target. The flight paths in this case are between 6 and 25 meters long, and the proton pulse spacing is 1.8 us, which set s to lower neutron energy limit in the TOF measurements to about 100 keV. Another more recently constructed spallation source is the N_TOF at CERN in Geneva, Switzerland. This source uses a 20 GeV proton beam hitting a lead target, and has two flight paths at 20 and 200 meters. The repetition rate for the beam in this facility is 0.5 Hz, which makes it possible to study thermal neutron energies all the way up to several hundreds of MeV.

4 Detectors

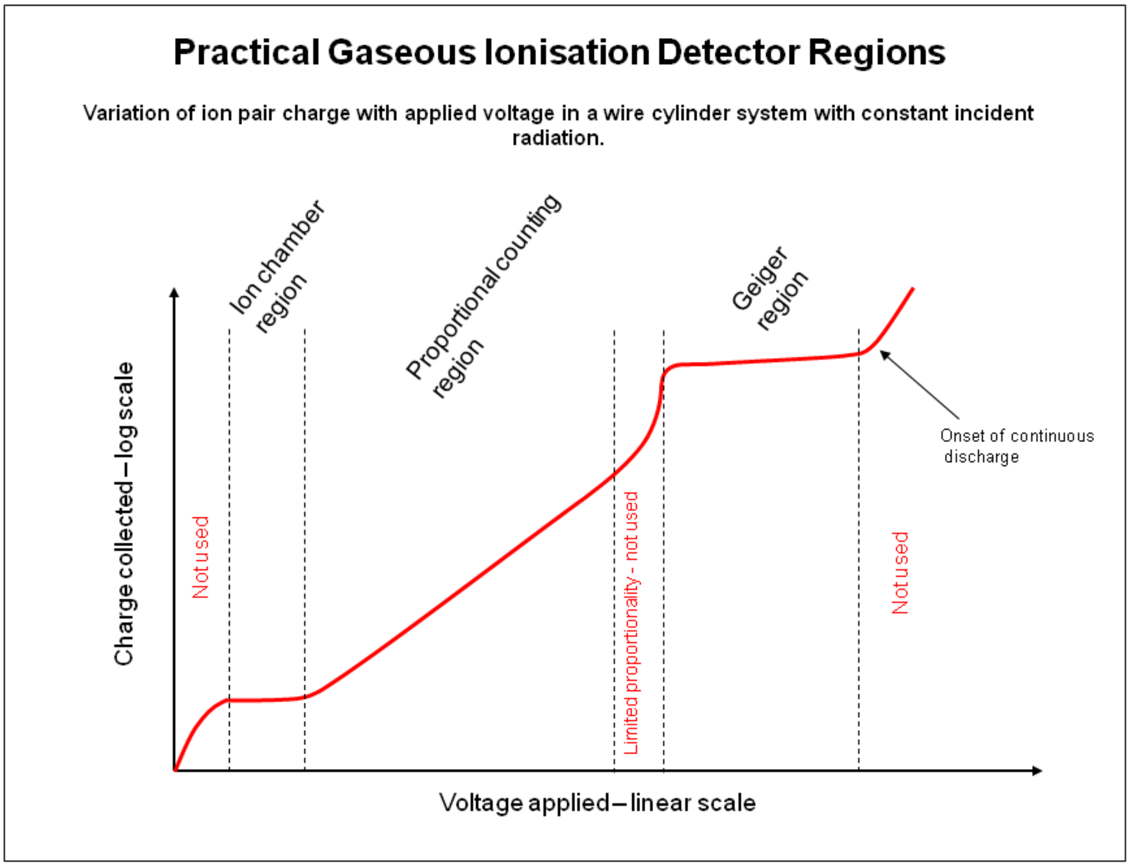

Figure 9: Different regions used for gas ionization detectors.

4.1 Gaseous detectors

Gaseous ionization chambers are the most commonly used type of detectors for fission fragments. The basic concept for these detectors is that fragments pass thought the gas and lose energy mainly through ionizing interactions with the gas. An electric field separates the positive ions from the electrons and results in charge drifting through the gas, which results in a voltage drop on the readout electrodes. Depending on the magnitude of the applied voltage you will have different responses, as illustrated in Figure 9. The two regions typically used for fission studies are the ionization chamber region and the proportional counting region. The ionization chambers are operated in a region where the charge collected is rather insensitive to the voltage applied. The voltage applied is high enough to where there is very little ion-electron recombination, but low enough where there no secondary ion pairs are created. Ionization chambers can provide excellent energy resolution for fission fragment, and has achieved better than 0.5% energy resolution for light fragments (ref). Proportional counters operate at a higher voltage where the charge produced by ionizing radiation creates secondary ion pairs, resulting in a gas gain effect. The charge collection in this region changes with the applied voltage, making it possible to vary the gain by changing the voltage. The energy resolution is much lower in this region compared to the ionization chamber region, and is about 30% for fission fragments.

4.2 Surface Barrier detectors

Solid state detectors are alternatives to ionization chambers for measuring the kinetic energy of fission fragments. The most common type for fission studies are silicon surface barrier detectors (SSBD) which consists of doped silicon that behave as diodes with reversed biasing. Particles that hit the detector create electron-hole pairs, and the result is a signal proportional to the ionization created. SSBDs have slightly lower energy resolution than ionization chambers: around 2% for typical fission fragments.

4.3 Fragment timing detectors

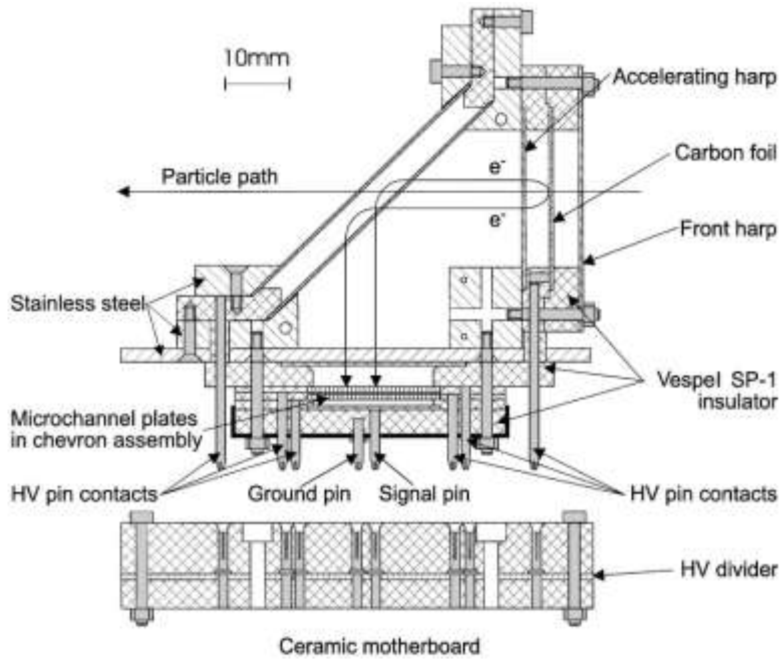

Figure 10: Drawing of a fission fragment time pick-off detector. From A.V. Kuznetsov, Nucl. Inst. Meth. A 452, 525 (2000).

In certain applications one might need to measure the velocity of fission fragments without stopping them or introducing significant energy loss. This can be achieved by letting the fragment pass through a thin film and detecting the secondary electrons created on the surface of the conversion material. One such arrangement is illustrated in Figure 10. In this case the fragments pass thought a thin carbon foil, from which the secondary electrons are emitted. An electrostatic potential accelerate the electrons towards another potential oriented 45 degrees relative to the carbon foil, which bends them out of the path of the fission fragment. The secondary electrons are detected by a micro channel plate, which provide a fast timing signal. By placing two of these detectors in the path of a fission fragment beam one can measure the velocity distribution.

5 Future of fission experiments

The last few years have seen a renaissance in fission experiments with several new facilities and instruments being developed for fission research. In this section we will describe some of the experiments that are state-of-the-art in the field.

5.1 Fragment spectrometers

There are different types of spectrometers that have been used to study fission, including magnetic spectrometers. Recently there are several fission fragment spectrometers being developed that measures fragment time-of-flight and kinetic energy in order to determine their mass. This technique has been used to achieve one unit resolution for light fission fragments, while covering more of the solid angle compared to magnetic mass spectrometers. The mass is calculated as (in the non-relativistic limit):

$$M = \frac{2Et^2}{l^2},$$

where E is the kinetic energy, t is the measured time-of-flight (TOF), and l is the flight path length for the fragments. The mass resolution is thus given by

$$\frac{\delta M}{M} = \sqrt{\left(\frac{\delta E}{E}\right)^2 + \left(2\frac{\delta t}{t}\right)^2 + \left(2\frac{\delta l}{l}\right)^2}.$$

In order to resolve light fission fragments one need a 1% mass resolution, so the individual contributions need to be smaller than that. The energy resolution is a combination of inherent detector resolution and energy straggling in material in the spectrometer, the TOF resolution depends on the inherent time resolution of the detector, and the uncertainty of the flight path length is the variation in distance travelled by individual fragments between the timing detectors. The velocity of fission fragments is about 1 cm/ns, so with a 50 cm flight length the TOF is about 50 ns. Hence the coincidence timing resolution needs to be better than 250 ps to stay within 1% contribution. The type of fragment TOF detectors described in 4.3 can achieve about 150 ps resolution. The energy inherent energy resolution of an ionization chamber is about 0.5% for fission fragments, and the energy straggling trough a thin chamber entrance window is about the same. The uncertainty of the flight path length is typically much smaller than the other two contributions, so all taken together it is possible to achieve 1% mass resolution in this approach.

5.2 Fission studies in inverse kinematics

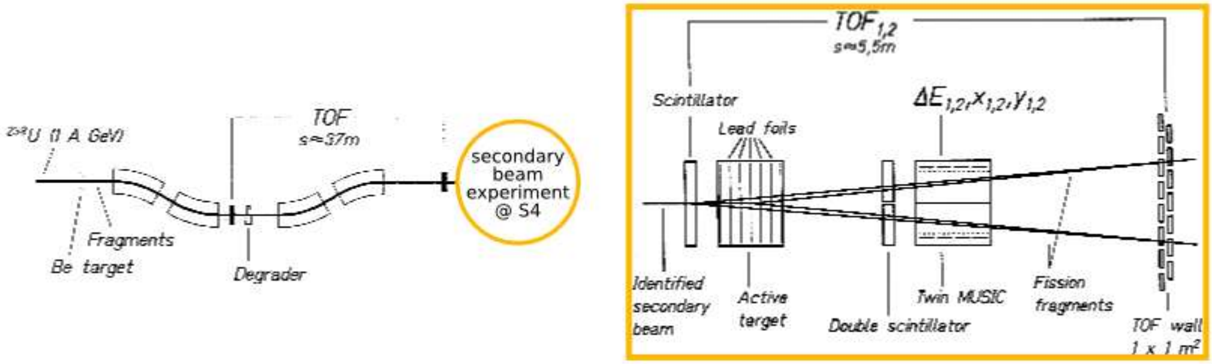

Figure 11: Schematic view of an inverse kinematic fission experiment at GSI (from K.H. Schmidt et al., NPA 665, 221 (2000)).

Fission spectrometers have a difficult time resolving mass and charge due to the relatively low kinetic energy of the fragments. In addition the efficiency is low, since the spectrometers usually only cover a tiny fraction of the solid angle around the fissioning sample. Another approach to that solves some of these issues is to study fission in inverse kinematics. A fissionable isotope such as U-238 is used as a projectile and hits a target that induces fission. While the fission fragments are emitted almost isotropic in the center-of-mass frame, in the lab frame they are focused along the primary beam axis. This make it easier to detect all the fission products compared to normal kinematic experiments. The kinematic boost of the fragments also increases the resolution to which their mass and charge can be resolved. The disadvantage of inverse kinematic studies is that the excitation energy of the fissioning system is typically not well defined. So while the reaction products are measured with high accuracy the initial conditions of the reaction mechanism are not.

5.3 Fission Time Projection Chamber (TPC)

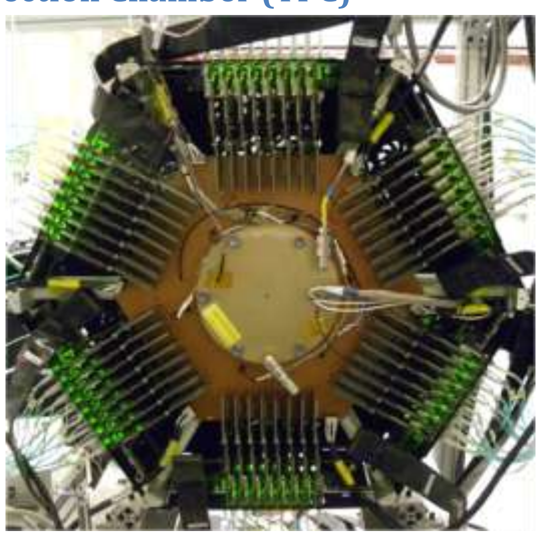

Figure 12: The fission TPC.

Time projection chambers are a type of tracking detectors that have been in use in high energy physics since the late 1970's. These detectors allows for 3D particle tracking by combining drift time and segmentation, and are thus ideal for tracking particles in for example beam collision experiments.

In the last decade people had the idea of using a Time Projection Chamber to measure fission cross sections. In traditional cross section measurements the accuracy to which fission reactions could be counted was limited by limited detector efficiency, challenges in separating fission from other types of reactions, and other effects. A tracking detector can address those issues and reduce the uncertainties associated with them; the efficiency can be measured directly by observing event rate versus emission angle, fission fragments can be identified using specific energy loss along the track and beam and target uniformity can be determined.

The Neutron Induced Fission Fragment Tracking Experiment (NIFFTE) collaboration between 3 US national laboratories and 6 universities has developed a TPC specifically for high accuracy fission cross section measurements. The goal of this project is to reach 1% uncertainty in fission cross section measurements between 0.5 and 20 MeV,