# The Performance of Thick Gaseous Electron Multiplier Preamplifiers (THGEM) as a Neutron Sensitive Detector.

Authors
Haitham Abdel Majid
Dr.Tony Forest

## Introduction

I propose to construct and measure the performance of a fission chamber instrumented with preamplifiers known a Thick Gas Electron Multipliers (THGEM). This fission chamber is a chamber filled with an inert gas enclosing a fissionable target material, like Uranium or Thorium. A neutron of sufficient energy has the potential to interact with fissionable material producing heavy ions known as fission fragments. The fission fragments within 5 micron of the target's surface may escape the target as ions and ionize the gas in the chamber. Electrons freed from the ionization gas can enter the THGEM preamplifier producing secondary electrons and directed to collectors using strong electric fields.

A THGEM preamplifier is a perforated fiberglass board (PC board) clad with a conducting material. The design is based upon the Gas Electron Multiplier (GEM) invented by Fabio Sauli in 1997.[1] The GEM preamplifier is a 50 micron sheet of kapton that is coated on each side with 5 micron of copper. The copper clad kapton is perforated with 50-100 micron diameter holes separated by 100-200 micron in a staggered array . The THGEM preamplifier is a more macroscopic version of GEM that uses a 2 mm thick fiberglass sheet perforated with holes that are 2 mm in diameter.

Strong electric fields are established by supplying a potential difference between the two sides of the kapton, or in the THGEM , the fiberglass. The electric field lines transport liberated electrons through the preamplifier holes. For the GEM foils, the smaller diameter of the hole can provide sufficient amplification using a potential difference of 350 V between the two sides. On the other hand, the THGEM with the larger hole diameter requires a higher potential difference of about 2000 Volts to achieve similar amplifications.

The objective of this work will be to construct a THGEM based ionization chamber. The THGEM will follow a proven design[2] and use a resistive paste to reduce discharge events. The detector may be made sensitive to neutrons by doping the resistive paste with a fissionable material. The doping step will take place once a working THGEM equipped detector has been demonstrated. This fission chamber-like device will have the advantage of measuring the location of the incident neutrons that induced a fission event within the chamber by measuring the ionization signal using a segmented charge collector.

## Gas Electron Multiplication

An electron from a primary ionization event needs to liberate more charge in order to create a detectable signal. One method to accomplish this amplification uses strong electric fields to accelerate the primary electron until it has sufficient energy to liberate more electrons from the chamber gas. In a traditional drift chamber, an electric field is established between two or more conducting wires. As an electron is accelerated towards a wire, it may obtain sufficient energy to ionize the chamber gas producing secondary freed electrons. The secondary electrons produced may themselves also be accelerated along the electric field lines and cause further ionization in a process commonly referred to as an avalanche.

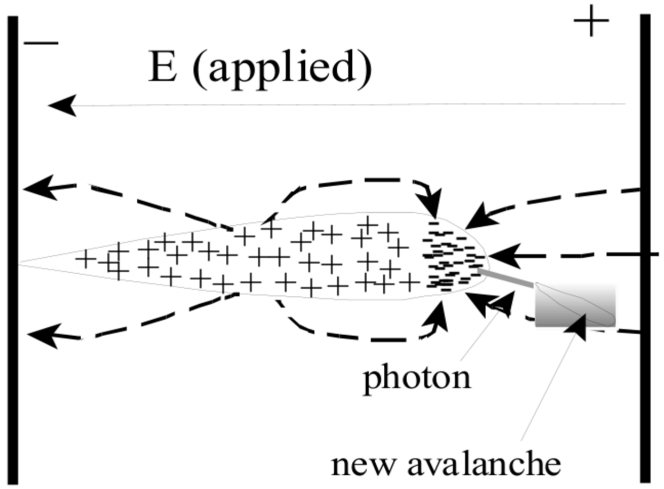


Figure 1: More than one avalanche in a streamer.[3]

### The Gas Electron Multiplier (GEM)

The Gas Electron Multiplier (GEM), invented by Fabio Sauli[1] in 1997, is a modern method using electric fields to create an avalanche condition. A GEM is a 50 micron thick kapton foil clad on both sides with 5 micron of copper. A staggered pattern of 50 micron diameter holes, equally spaced by distances comparable to the hole diameter, is etched into the copper clad foil. The small size facilitates the use of low voltages (300 Volts) to generate an electric field for amplification. By comparison, the typical drift chamber, operating on the same principle, would need more than 1 kV to establish a similar electric field.

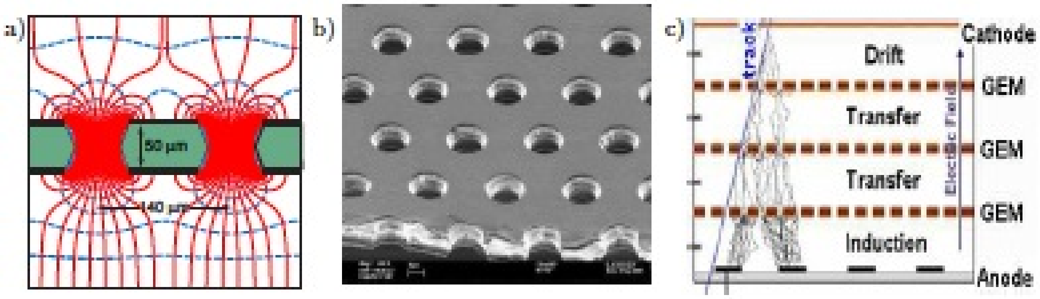
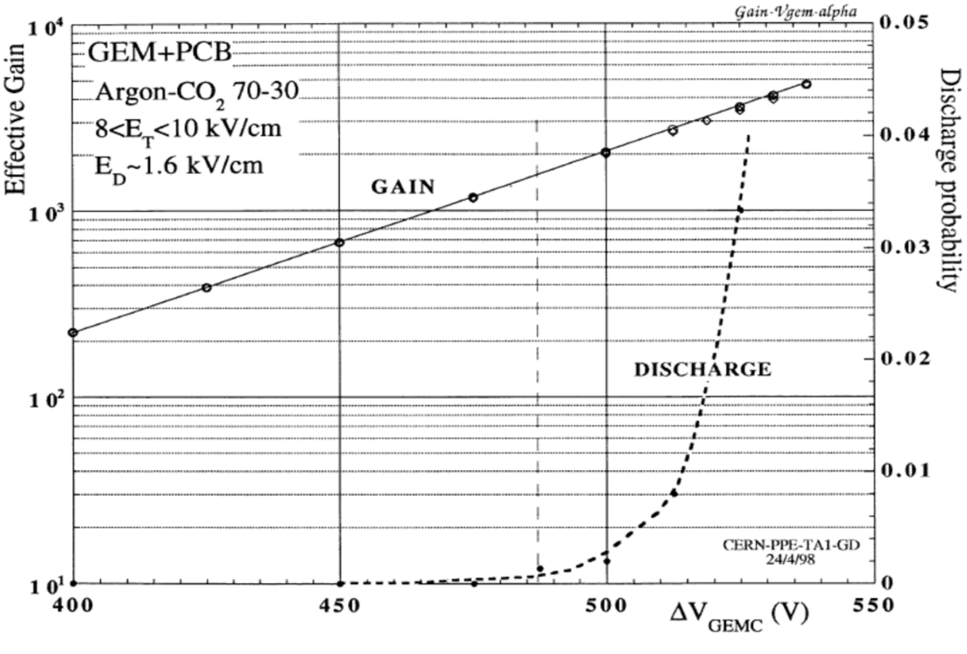


Figure 2: a)Electric field lines distribution in GEM holes. b) GEM card holes pattern. c)Electron amplification process as GEM in operation.

Some noteworthy advantages and disadvantages of the GEM are given below. The GEM foil is flexible enough to be curved, allowing cylindrically shaped ionization chambers with larger active areas. Unfortunately, the micrometer scale of a GEM foil makes it susceptible to damage from sparking at high amplification voltages. When the voltage increases from 525V to 600V (regardless of the card's pattern or the hole's geometry), the operating voltage range decreases to about 450 V or less as shown in Figure 3.[4] GEM has a low noise signal because of the relatively low operating voltage, also the micrometer scale hole diameter increases the electric field flux through the holes, so a relatively high gain is obtained in the range of the operating voltage.



Effective gain and discharge probability on the internal α source obtained with the GEM detector with an argon–CO$_2$ gas filling.

Figure 3: GEM gain and discharge as function of voltage.[4]

## The Thick Gas Electron Multiplier (THGEM).

A Thick Gas Electron Multiplier (THGEM) is basically a GEM foil which has been scaled from micrometer to millimeter. A THGEM card is made from FR4/G10 clad on both sides with copper. The THGEM cards for this work are 12x12 cm square plate that is a 1 mm thick and coated with 17 um thick copper cladding.[2] Each card is chemically etched to leave a copper trace around the perimeter of the card as a border for a square area of a side length of 10 cm as shown in Figure 4. A thin layer (around 5 micron) of resistive paste (ED-7100) is applied to allow potential difference between the top and bottom layers and provide some spark protection by limiting the current flow along the surface. The card is machined to have 0.5 mm diameter holes. The resistive paste near the hole is machined away to form a 0.2 mm thick rim around the hole. The holes are formed in a staggered array with a pitch of 0.8 mm.

Figure 4: A copper frame on FR4.

Figure 5: A layer of ED-7100 on FR4.

The THGEM cards are fixed in place to have the holes of each THGEM card is aligned by the holders and separators in each corner. The cards are separated from each other by a vertical distance of approximately 2.6 mm. A drift voltage card, cathode, made of copper paper is placed at the top of the cards at a distance of 2.6 - 4 mm from the closest THGEM card. The THGEM cards are placed inside a chamber made of two sheets of machined ertalyte (plastic), with a kapton window on the upper piece as shown in Figure 6.

The gas chamber is constructed using two 29.5 X 29.5 X 1.25 cm sheet of ertalyte plastic and are bolted together by a number of M3 plastic screws located around the detector window to form a well closed cavity around the THGEM cards away from the surrounding atmosphere. The ionization gas is a 90/10 percent Ar/CO2 gas flowing the cavity with a pressure of 1 atm.

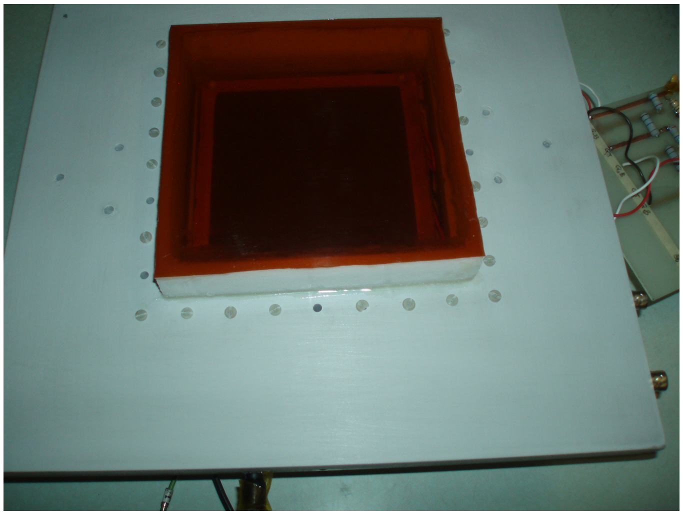


Figure 6: THGEM gas chamber.

A read out plane exists on the bottom the detector. It consists of different width copper strips that are organized to have the same pitch such that the upper strip width is 50 micron and lower strip is 150 micron, the two strips are separated by a 25 or 50 micron thick layer of kapton . Both of the strips are glued on a 100 micron FR4 plate to achieve reasonable flatness as shown in Figure 8. The read out plane is vertically separated by a distance of 0.5 mm from the closest THGEM card and it is connected to 16 connectors, each connector has 20 traces. The 16 connectors are sent to a 130 pin adaptor allowing the use of a digitization card known as the VFAT card which sends a digital signal to a break board and then to the DAQ system.

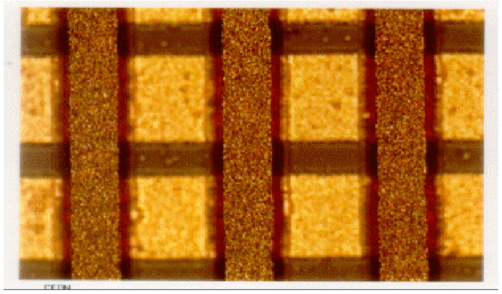


Figure 7: Read out plate design.

With the new design for the THGEM card, it becomes robust with a higher operating voltage and relatively higher gain. The vertical distance between THGEM and the thickness of the cards ,in addition to, the rim around the holes prevent any discharge, either in the card itself or with the other THGEM cards. But the detector may have a higher noise compared to that of the GEM preamplifier.

THGEM preamplifier is robust with a higher operating voltage and relatively higher gain with the least discharge. It has 0.2 mm rim, 1 mm thick insulator and 2.6 mm vertically separating distance from the next THGEM card, so the probability of discharge is minimized either in the card itself or with the other THGEM cards. But the detector may have a higher noise compared to that of the GEM preamplifier.

## Detector Signal

### Ionization

Ionization is the liberation of an electron from the confines of an atom. The minimum amount of energy required to liberate the electron is referred to as the ionization energy. Energy transferred to the electron in excess of this ionization energy will appear in the form of the ejected electron's kinetic energy. Photons or charged particles like fission fragments interacting with a gas volume can induce ionization. The ionization process depends stochastically on the ionization cross section which is mainly affected by the fission fragment energy, type of the fission fragment (heavy or light), the gas pressure in the chamber, and the atomic properties of the gas. Generally, the amount of energy needed to have an ionization event in a gas is the same on average, regardless of the incident particle type or energy as shown in the following table for argon gas.[13]

| Type of particle and its energy | Energy per ion-electron pair (eV) |
|---|---|
| X-rays 9 keV | $27 \pm 1.5$ |
| Electrons 10 keV | 27.3 |
| Electrons 40 keV | 25.4 |
| X-rays with beta (5-7 MeV) | $27.0 \pm 0.5$ |
| Alpha 7.68 MeV | 26.2 |
| Protons 340 MeV | 25.5 |

### The Fission Fragments Ionization

Fission fragments are a source of ionization when they penetrate an Argon gas chamber. The energy used for such an event is highly dependent on the fission fragment mass and velocity. At low fragment velocities, recoiling becomes a competitive process that decreases the probability of ionization. In the case of a high velocity fragment, the probability of ionizing the gas increases to be closer to that of the alpha particles as they are penetrating the same medium. The ionized nuclei that are ejected from a heavy nucleus that has undergone the fission process can ionize atoms in the vicinity of the fission event. These ejected nuclei are referred to as fission fragments. The fission fragments have path lengths in matter which are on the order of few microns. The energy loss process that these fission fragments undergo over the short range may astochastically be described in terms of three steps; as the fission fragment is totally ionized, as the fission fragment is exchanging the charge with the gas atoms, and as the fission fragment is totally neutralized.

First, the total energy of a fission fragment without a bound electron is given by

$$E = \frac{kZ_1Z_2e^2}{r} + \frac{1}{2}Mv^2$$

where $\boldsymbol{Z_1}$,**M** and **v** are the atomic number, the mass and the velocity of the fission fragment directly after the fission reaction, $\boldsymbol{Z_2}$ is the atomic number of the gas atom. The coulomb force represents the repulsion force between the ionized gas atoms and fission fragments, as well as the attraction force between the fission fragment and electrons. The second term dominates until the fission fragment begins to probe the charge within the neutral ionization gas atoms.

When the fission fragment decelerates, a charge exchange starts between the fission fragment and gas atoms, as the electrons are either scattering away from the fission fragment nucleus or attached to it as it is in motion. The total energy loss of the fission fragment suggested by Bohr in 1940 is given as[6]

$$\frac{1}{N}\frac{dE}{dx} = \frac{4\pi e^4}{mv^2}(Z_1^{eff})^2 Z_2 \log\frac{1.123mv^3}{we^2Z_1^{eff}} + \frac{4\pi e^4}{M_2v^2}Z_1^2Z_2^2 \times \log\left(\frac{M_1M_2}{M_1+M_2}\frac{v^2a_{12}^{scr}}{Z_1Z_2e^2}\right)$$

where **N** is the number of particles of the stopping medium per cubic centimeter, $\boldsymbol{M_1, M_2}$ are masses of the fragment and the absorber, $\boldsymbol{Z_1, Z_2}$ are the atomic number of the fragment and the absorber, **e** is the electron charge, **v** is the fragment velocity, $\boldsymbol{Z_1^{eff}}$ is the charge of the fragment, changes from 20 for the beginning of the track to a value of 2 close to the end of the track.[6] $\boldsymbol{a_{12}^{scr}}$ is an impact parameter which tells at what distance the energy loss in the nuclear collisions is effectively zero owing to the screening of the charges of the nuclei by the atomic electrons, $\boldsymbol{w = I/\hbar}$ is the average oscillation frequency of the electrons in the atom.

This formula is an initial estimation of the total energy loss by the fission fragment under each stage of charge carrier exchange between the fission fragment and the gas atoms. It relies on how well Z-effective is estimated at each ionization stage. Consequently, the first term is dominant in the beginning of the interaction between the fission fragment and the ionization gas. The second term dominates close to the end of the fission fragment track.[6]

Bethe's theory is commonly used to estimate the energy loss for fission fragments. it involves using a diverse model for the effective charge obtained based on experimental data analysis for energy loss data.[7]

$$-\frac{dE}{dx}[\frac{MeV}{mg/cm^3}] = 3.072 \times 10^{-4}\left(\frac{Z^{eff}}{\nu/c}\right)^2\left(\frac{Z_m}{A_m}\right)\ln\left(\frac{m_e\nu^2}{I}\right)$$

$$where\ \ Z_{eff} = Z\left[1 - Aexp\left(-B\frac{\nu}{\nu_o Z^{\frac{3}{2}}}\right)\right]$$

$\mathbf{Z}$ is the nuclear charge of the fission fragment, $\boldsymbol{\nu_o}$ is the speed of the electron in first Bohr orbit, $\boldsymbol{\nu}$ is the speed of the ion, $\boldsymbol{Z_m, A_m}$ are the nuclear charge and the atomic mass of the medium, $\boldsymbol{m_e}$ is the mass of the electron, $\boldsymbol{I = KZ_m}$ is the mean excitation energy of the atomic electrons of the medium of atomic number $\boldsymbol{Z_m}$. $\boldsymbol{A, B}$ are the fitting parameters dependent on the medium, for example A=0.92, B= 0.72 for Light fission fragments. A=0.99, B= 0.82 for heavy fission fragments are they are passing Ar/$CH_4$ (95/5 %) medium.[14]

The Final step describes the neutral charged fission fragment. The probability of ionization is very low during this step because of the fission fragment's neutral charge and low kinetic energy.The lowest energy at which a fission fragment can ionize a gas is expected to be equivalent to the energy of its weakest bound state electron which can be between 15.7 eV and 3.2 keV. In more specific studies that are based on classifying the fission fragments into light and heavy fission fragments, the researchers tried to measure the amount of fission fragment energy consumed by processes other than ionization. The energy is referred to as the ionization defect energy $\boldsymbol{\Delta E}$ (ionization defect).[8]

$$\Delta E = E - Iw_\alpha$$

Where **E** is the energy of the primary particle, **I** is the number of ionization events, and $\boldsymbol{w_\alpha}$ is the mount of energy use to produce an ion pair.Light fission fragments have a measured $\boldsymbol{\Delta E}$ of 2.5 MeV when their initial energy was energy 67 MeV.[8] and heavy fission fragments have measured $\boldsymbol{\Delta E}$ of 4.2 MeV when their initial energy on average was 98 MeV.[8] The ionization defect energy experimentally indicates that you need lowest kinetic energy a fission fragment need to ionize the gas is actually higher than the fragments least bound electron binding energy.

## The Neutron fission Cross Section for U-238 and Th-232

The cross section is defined by the following equation

$$\sigma(E) = \int \frac{d\sigma}{d\Omega}.d\Omega$$

where

$$\frac{d\sigma}{d\Omega} = \frac{1}{\Phi}\frac{dN}{d\Omega}$$

$\boldsymbol{\Phi}$ is the number incident particle per unit area per unit time, **dN** is the average number of particles per unit time that interacted per unit solid angle, and $\boldsymbol{\Omega}$ is the solid angle. Since the cross section has an area unit (barn), some authors define this quantity as the area to which the particle is exposed to make an interaction.[18] The cross section values are represented as a function of energy that gives the value of the cross section for each energy value and shows the resonance peaks. Theoretically, there is not any model that gives a detailed prediction of neutron fission cross section curve, but statistically it is possible to evaluate the parameters for an assumption that describes part of the cross section curve within a certain error.[6]

Neutron fission is one of the interactions that commonly takes place spontaneously or under certain experimental conditions. An incident neutron with a certain kinetic energy hits a nucleus, and if the energy is enough to go over Coulomb barrier then the neutron produces new nuclei (fragments) and particles. The new products interact with the surrounding medium depending on their energy and the type of the medium that contains them.

Both U-238 and Th-232 are members in the actinides group. They are characterized by relatively high neutron fission cross sections for fast neutrons with fission thresholds above the thermal neutron energy. The fission reaction in both elements is expected to eject 1-2 neutrons when the incident neutron energy is between 5-10 MeV as shown in Figure 7 and Figure 8.

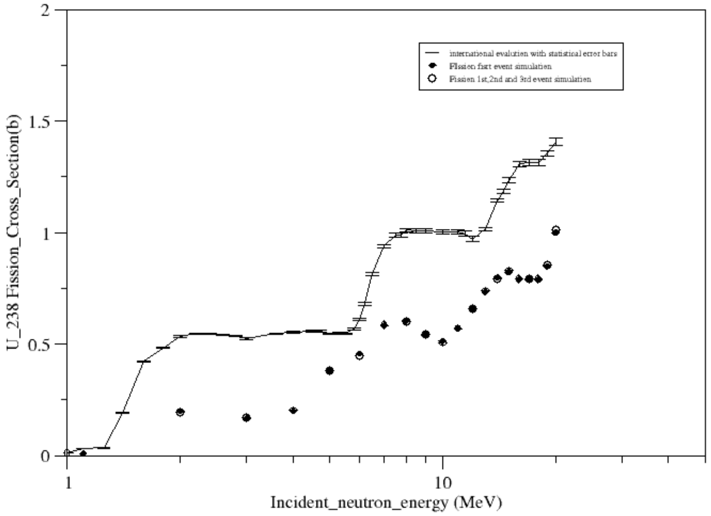


Figure 8: Simulated (dotted) and ENDF data for U-238 neutron fission cross section.[9]

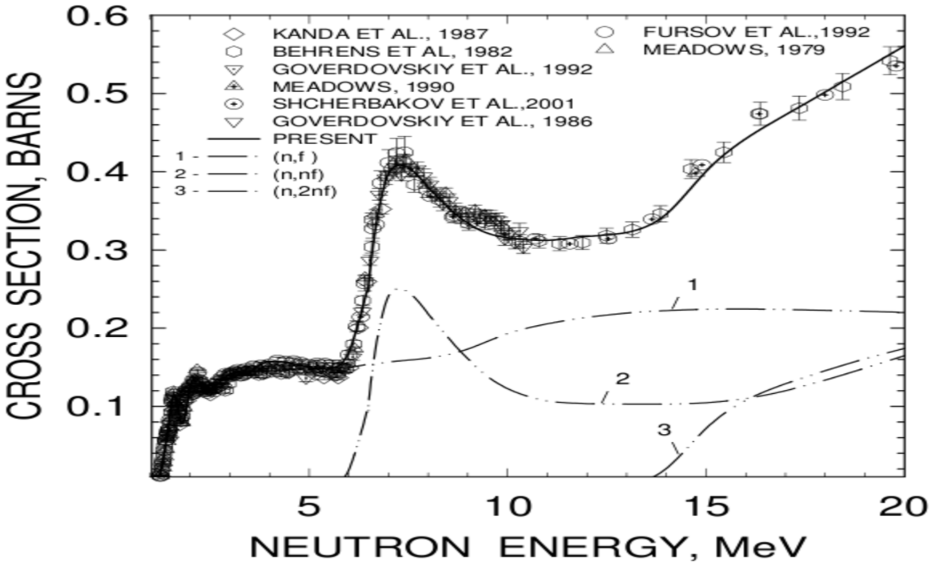


Figure 9: Th-232 neutron fission cross section.[10]

### The Signal Size

An electron, freed by ionization and immersed in an external electric field, can ionize other atoms in a gas volume as a result of its acceleration in the external electric field. The number of additional freed electrons can be determined in terms of the external electric field **E**, the pressure of the surrounding gas **P**, the parameter $\boldsymbol{\alpha}$ is known as the Townsend coefficient and two fit parameters **A** and **B** which are dependent on the gas properties as shown in the equation[13]

$$\alpha = APe^{(\frac{-BP}{E})}$$

In the case of a THGEM preamplifier, an electric field of $4X10^4 \ \frac{V}{cm}$ is established when a potential difference of 2 kV is applied between the top and bottom sides of the plate that are 0.1 cm apart. In this work, the gas chamber contains a 1 Atm mixture that is 90/10 Ar/$CO_2$ by volume. The parameters from reference[15] are not given for this mixture. To estimate the THGEM pre-amplification, the A and B parameters for a 96/4 Ar/$CO_2$ mixture gas which are 5.04 $cm^{-1}Torr^{-1}$ and 90.82 $Vcm^{-1}Torr^{-1}$ respectively.

Using the above equation we would expect $\alpha$ to be about 121 per cm (which is a factor of 30 less than the coefficient for a GEM foil). A free electron traveling through the 0.1 cm THGEM hole should produce 12 additional freed electrons due to the electric field of the THGEM pre-amplifier. We would expect a single freed electron to produce a maximum of $10^3$ electrons if it traverses three THGEM preamplifiers.

The number of electrons emitted from a fission fragment is $5.1X10^4 \ cm^{-3}.s^{-1}$ as result of a 30 MeV proton projected toward a U-238 target,[16] while GEANT4 simulation of

Cd-123 ionization gets the same result when it is traveling in 50 atm $Ar/CO_2$ gas (Cd-123 with 81.6 MeV is one of the fission fragment of a fission event for a 1 MeV neutron projected toward U-238). So the expected signal for the fission fragment detected by 50 ohm oscilloscope is roughly 2-20 mV at 50 ns. For a single ionization event, the THGEM detector signal would be small, while for a fission event the number of freed electrons will be substantially larger resulting in a large signal.

## The Efficiency of THGEM

The efficiency of a detector is the ratio of the detected events to the total number of events entering the detector. In order to detect a neutron entering the gas chamber the neutron must induce fission and the resulting fragments must ionize the gas. The cross-section for U-238(n,f) is given in Figure 7. The probability of a fission event for a $1\,cm^3$ U-238 target varies from 1 to 5% as shown in Figure 9.

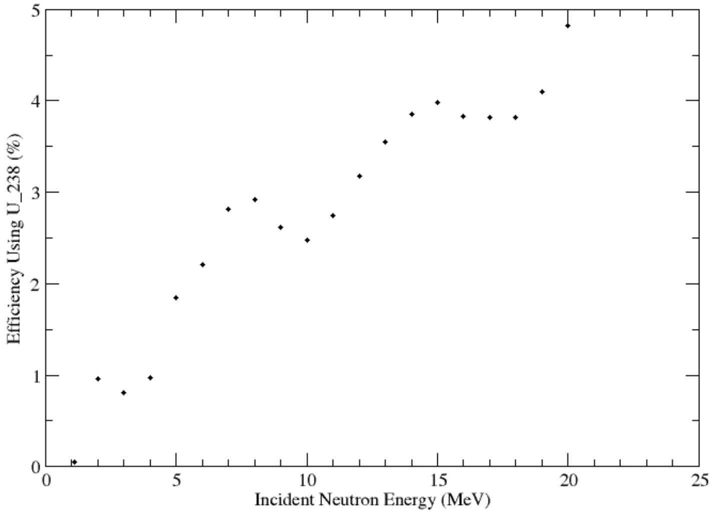


Figure 10: The probability of fission interaction for U-238.

The probability of a fission fragment escaping into the ionization gas is also required to calculate the detector's efficiency. The number of fission fragments that escape from the surface of a $UO_3$ film relative to the number of fission events is given by the following formula[17]

$$\frac{N}{A} = \frac{\ln(\frac{d}{R_T} + 0.5)}{8\pi[1 - \frac{d}{R_T}] + \frac{d}{R_T}}$$

where **N** is the number of fission fragments that escaped from the surface per unit area, **A** represents the number of fission interactions per unit volume, **d** is the thickness of film in micron and $\boldsymbol{R_T}$ is The mean range of the fission fragments (12.07 $\mu m$).

Assuming that the number of fission fragments is given by the following

$$N = \int_{V_1} A\frac{cos\theta}{4\pi r^2}dV + \int_{V_2} A\frac{cos\theta}{4\pi r^2}dV$$

and the average range of the fission fragment through the emulsion $R_E$ is represented by

$$< R_E >=< R_T > - < r >$$

where $\boldsymbol{< r >}$ is the fission fragment's range in the thin film.

The detector's intrinsic efficiency can be roughly estimated based on the figures above. The probability of neutron fission (1-5%), and the probability of a escaping fission fragment, when the thickness of U-238 thin film is 0.5 micron, is 0.1; the detector intrinsic efficiency is 0.1-0.5% (assuming that the probability of a fission fragment to ionize the gas is 1).

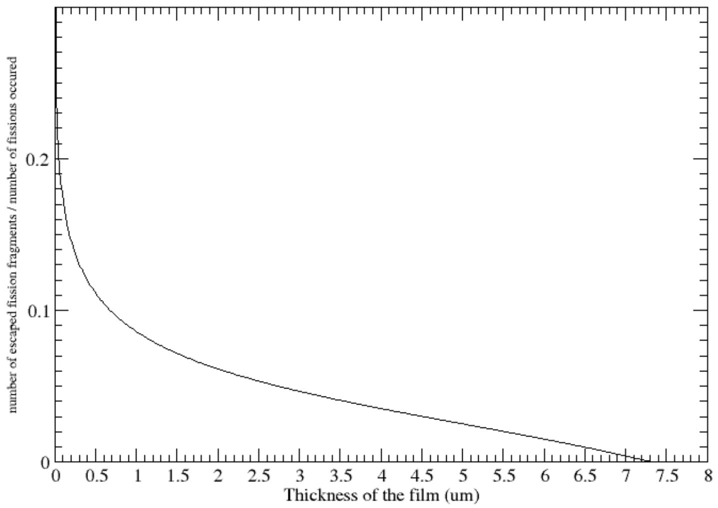


Figure 11: The probability of a escaping fission fragment as a function of film thickness.

## Summary

Thick gas electron multipliers (THGEM) will be used to preamplify a fission chamber used to detect the location of fast neutrons within the detector. The detector will be built using a U-238 or Th-232 fission target, depending on availability, to take advantage of the large neutron fission cross section between 0.1 - 1 barn. A fission event, in the above targets, stochastically ejects a fission fragment having an energy of 65 to 100 MeV that may lose energy in the form of ionization in a Ar/CO2 gaseous medium surrounding the fission interaction and free on average $10^4$ electrons. The electrons are directed by a drift electric field towards a THGEM preamplifier and, using three TGEMS, are amplified $10^6\ to\ 10^7$ times. The electrons are collected by a wire mesh read out producing a signal between $2 - 20mV$.

# References

[1] F. Sauli, et al, NIM A **386**, 531 (1997).

[2] G. Agocs, B. Clark, P. Martinego, R. Oliveira, V. Peskov,gand P. Picchi,JINST **3**, P020112, (2008).

[3] JP Holtzhausen, Dr WL Vosloo *High Voltage Engineering Practice and Theory*, ISBN: 978-0-620-3767-7.

[4] A.Bressan, et al, NIM A **424**, 321 (1999).

[5] Shalem Chen Ken, Master Thesis, Scientific Council of the Weizmann Institute of Science, 2005.

[6] Earl K. Hyde,*The Nuclear Properties of the Heavy Elements* (Academic,Denver Publications,1971), Vol.3, p 195-210.

[7] V.A Rykov, Atomic Energy **83**, 1 (1997).

[8] J.M. valentine, C.Curran, Reports on Progress in Physics **21**, 1 (1958).

[9] IAEA INDC(BLR)-016, Printed by the IAEA in Austria, 2003.

[10] IAEA STI/PUB/1291, Printed by the IAEA in Austria, 2007.

[11] R.Chechik,A.Breskin,C.Shalem, NIM A **535**, 303 (2004).

[12] Bondar,A.Buzulutskov,A.Grebernuk, JINST **3** P07001 (2008).

[13] William R. Leo,*Techniques for Nuclear and Particle Physics Experiments* (Springer-Verlag,1995).

[14] D. C. Biswas, M. N. Raob and R. K. Choudhury,NIM B **53**, 3, 251(1991).

[15] A.Sharma,F. Sauli, CERN PPE/93-50, 1993.

[16] M. Facina, Master Thesis, Leuven, 2004.

[17] J.C.Hudler, Radiation Measurements **43**, S334 (2008).

[18] Syed Ahmed, Physics and Engineering of Radiation Detection (Academic Press 2007).