Spring 2010 Research on Gas Electron Multipliers

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This report is a compilation of a "journal" article that I wrote about my research for my Senior Seminar 2 class and some data analysis of data recorded this semester. The first part is what I submitted to Dr. Dwyer for class and the second part is the data which we have collected. I hope that this is a sufficient and representative report on what I have done with the HEP research group.

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Assembly and Testing of a Gas Electron Multiplier (GEM) Detector to be Used for Cosmic Ray Muon Tomography Imaging

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Abstract: This paper presents some research and work I contributed to as part of a project to build a prototype for a larger Muon Tomography Station which it is hoped will eventually be able to reconstruct images in three dimensions to aid in the effort of detecting nuclear contraband. In this paper I present the procedures which were followed for the construction of the 10 cm x 10 cm GEM detector that I helped assemble at Florida Tech. Also presented are some problems which were encountered as the detector was powered up and readied for operational testing. The results of some of the detector tests are also discussed and presented.

Keywords: Gas Electron Multiplier, GEM, Kapton, muons, x-rays

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1.1

Introduction

A gas electron multiplier (GEM) is a micropattern particle detector invented in 1996 by Fabio Sauli at CERN [1]. It consists of the detector chamber, the GEM foils, a drift cathode, and an x-y readout board. The detector chamber is nothing more than a sealed, air-tight container into which a gas (or gas mixture) is introduced. The gas mixture that is utilized in our detector is argon carbon dioxide—$ArCO_2$—(70 to 30 percent, respectively). The GEM detector that I worked on is 10 cm by 10 cm in active area. The GEM foils are made of a thin (approximately 50 micrometers) layer of Kapton (which is an insulating polymer) clad on both sides by a thin (approximately 5 micrometers) layer of copper, which is then chemically pierced on both sides by a large number of holes. The density of holes is usually between 50-100 holes per mm^2. The diameter of each hole is approximately 70 micrometers on the copper sides and 50 micrometers at the center of the Kapton. The holes are in a triangular pattern and the distance between holes is 140 micrometers from center to center [2]. When a potential difference is applied across the foil, electrons released from ionization processes in the gas mixture on one side drift into the holes and gain enough energy to ionize other gas molecules, which results in a multiplication of the number of electrons—essentially an electron avalanche. This multiplication can be increased if multiple GEM foils are stacked on top of each other. Typical gains for a triple stack of GEM foils (i.e. three GEM foils in one detector) are on the order of 10^5 [3]. The drift cathode is simply a wire grid to guide the ionized electrons toward the GEM foils. The x-y readout board is imperative to be able to find a 2-D position (hence allowing recreation of an image) and is able to spatially resolve within 40 micrometers [4].

1.2

Assembly of the Complete Chamber

The assembly of a GEM detector must be done in an extremely clean environment. This is because the holes in the foils are small enough that dust or other particulate matter can get stuck in the holes and then, when powered with a high voltage (HV), cause sparking and a short, thus damaging the foils and rendering them unusable. The room at Florida Tech where I helped to assemble the GEM detector was a Class 10000, according to our measurements of particulate matter. Researchers and scientists at CERN recommend a Class 1000 clean room for the assembly of GEM detectors [2]. We tried to make our clean room as close to that level as possible, but were unable to, so we—carefully and with great caution—assembled our GEM detector in the Class 10000 clean room. We took several steps to keep our clean room as particulate-free as possible. In order to enter the clean room, shoe covers, gloves, a mask, a hair covering, and a special coat must be worn. During the assembly process both Dr. Hohlmann and I were extremely cautious to avoid placing the GEM foils on anything besides the container they were shipped in, as well as spraying the GEM foils with compressed nitrogen gas after any procedure which might have created particulate matter that may then have settled on them. The precaution of blowing the GEM foils off with compressed nitrogen gas is a standard procedure at CERN [2]. We receive the detector and the GEM foils separately from CERN and then must finish assembly of the complete detector ourselves. This entails first disassembling the detector chamber which consists of squares of a composite material stacked on top of each other and glued together (referred to as the 'composite box') which contains the gas inlet channel and is set on the 'baseplate', and a 'roof' which contains a drift plain and the gas outlet channel. The composite box has an O-ring inlaid so that the roof component will apply pressure on it when the entire thing is held together (indeed, rendered air-tight) by a series of bolts which go through the roof and composite box and are secured on the bottom of the baseplate by circular nuts. Then the GEM foils are placed on plastic posts set at the inside corners of the composite box and are separated by plastic spacers (approximately 0.2 mm in height each). The distances at which each GEM foil is to be placed has been pre-determined to be 1 mm between the readout board and GEM 3 (this is called the induction gap), and then 2 mm between both GEM foils 3 and 2, and between GEM foils 2 and 1 (referred to as the transfer gaps), the distance between GEM 1 and the drift cathode is 3 mm (called the ionization gap) [5]. This entire process must be carried out carefully and without allowing any particulate matter to contaminate the readout board or the GEM foils. After the detector is disassembled, spacers are placed on the posts so that the bottom pre-determined gaps are met. Please note that GEM foils are numbered from the top to the bottom, i.e. the one closest to the readout board is GEM 3. Then the GEM foil is set in place on the posts and the electrical connections must be made. In order to power the GEM foils, there are high voltage (HV) feedthroughs (basically just strips of metal) that run between the composite box and the baseplate. Each framed GEM foil has a short strip of copper on both sides running from the active area (i.e. the section with holes) to the edge where it can be soldered to the HV feedthroughs. This soldering process must be done with the utmost care and precision because of the close proximity to the components of the detector. Also, the act of soldering inherently creates particulate matter that poses a risk to the GEM foil and the readout board, so after any soldering the entire area is blown with compressed nitrogen gas. After this, more spacers are placed on the posts and then

GEM 2 is placed on the posts and the copper HV connections are soldered to HV feedthroughs different than the ones used for GEM 3. Due to the geometry of the GEM foils, HV feedthroughs, and the readout board electronics, one or other of the GEM foils were rotated in order to be able to make the electrical connections. Also, a small strip of copper wire was utilized to provide adequate and/or additional connectivity to some of the soldered points. The entire area was again blown with nitrogen to dislodge any particulate matter that may have settled on any of the components. More spacers were added and then GEM 1 was added using the same process described above. The detector was then blown with nitrogen gas again. Plastic spacers were then added so that a distance of 3 mm separate GEM 1 from the drift cathode (i.e. the negatively-charged metal grid which guides electrons from ionization toward the GEM foils) and the drift cathode was placed on the posts and the single electrode connected to a single HV feedthrough (versus two HV feedthroughs for each GEM foil). After the drift cathode was in place, plastic nuts were tightened onto the posts to hold everything in place. Once again everything was blown with nitrogen to help ensure that no particulate matter would remain in the detector area. The final part of the assembly process was to put the composite box back onto the baseplate, set the roof on, and then reinsert all the bolts to hold the entire thing together and tighten them down until the detector was rendered air-tight. At this point the assembly process was complete and our detector was ready to be taken out of the clean room and tested.

1.3

HV Board

Before the GEM detector can be tested, the HV board that will power the GEM foils and drift cathode must first be tested to ensure that it is working properly. The HV board used for providing the specific voltages to the GEM foils is also received in its basic components from CERN and must be assembled on site at Florida Tech. The HV board consists of a printed circuitry board with holes into which the various resistors are to be inserted and then soldered into place. The exposed metal is then covered with a clear epoxy in order to prevent oxidation. The HV board is then tested to ensure that it is working properly and behaves according to theory. This test is conducted by applying a certain voltage into the HV board and then measuring the current which is drawn by it. We tested several different voltages ranging from 500 to 4000 volts in 500 volt increments and recorded the current. After graphing the current as a function of voltage, we found that the line is indeed linear, which is what it should be according to Ohm's Law. This proved that all of the resistors and circuitry work correctly. The HV board is then wired to the HV feedthroughs on the GEM detector baseplate and soldered.

1.4

Testing of the Completed GEM Detector

The completed GEM detector is now ready to be set up and tested. The first step in the process is to flush the detector volume with CO_2 for two to three days to ensure that there are only very small trace amounts of oxygen inside the detector volume (if any at all). We run the gas at a flow rate of about 5 volume changes per hour. This is enough to ensure that the detector gets thoroughly flushed out. The input gas is then switched from CO_2 to an $ArCO_2$ (70-30) mixture for operation. This gas mixture is run through the detector for several hours at the same rate as before (i.e. 5 volume exchanges per hour) before any power-up is attempted. We monitor the oxygen and humidity of the atmosphere inside the detector via both oxygen and humidity sensors which are attached to the gas output. This allows us to know if there is a leak or other problem with the atmosphere inside the detector volume, which is important because those factors can contribute to either damage to, or bad performance of, the detector.

1.4.1

The NIM crate and Electrical Connections

A NIM crate is used to provide power to the HV supply and the amplifier. The electronics are set up as follows: the HV supply powers the HV board via coaxial cable, then a pre-amp is connected to the x-y readout electronics via a 130 pin Panasonic connector, a Gassiplex card, and a short length of coaxial cable, which then goes into the amplifier. The output signal from the amplifier is fed into an oscilloscope by coaxial cable simply for observational and recording purposes, the oscilloscope does not change the signal created by the GEM detector. For testing purposes, the Gassiplex card has all of its separate pins soldered together so that one output signal is created—this makes it easier to perform tests on the GEM detector.

1.4.2

Power Up Procedure

Once the oxygen and humidity levels are at appropriate and acceptable levels and all the electronics are connected, the HV power supply is turned on and set to 500 volts. After giving the detector time to adjust to this power level (about 1-3 minutes) the voltage is raised to 1000 volts. This process is repeated in 500 volt increments until a voltage of around 4000 volts is reached. Operating voltage is between 3800 and 4200 volts (based upon early measurements and calculations). Once again, the current is monitored throughout this process to be sure that everything continues working properly.

1.4.3

Problems Encountered and Solutions

The first problem that we encountered was noise. The noise levels at operating voltage were so large (approximately 200-250 mV) that no signal could be seen, even when using a Fe^{55} x-ray source. This was a major problem because there would be no way to see a signal if the noise level could not be reduced. So we tried to find the source of the electrical noise and took steps to reduce or eliminate it. We wrapped the pre-amp in aluminum foil, we provided a better ground connection between the HV board input and the HV supply, and we soldered a wire from the HV board coaxial cable power input to the ground on the GEM detector baseplate in order to provide a common ground to the electronics. We also found that having other electronics plugged into the same power strip caused noise, so we removed them from that power strip and saw some reduction in the amount of noise. Another thing that we found caused noise in our signal was having the overhead florescent lights on. It was discovered that when the lights were turned off, the noise in the signal almost completely went away! Hence, through various measures and techniques (including turning off the lights!) we were able to reduce the noise to an acceptable level (approximately 20-50 mV, versus 200-250 mV as before). After the noise was reduced sufficiently, several tests were run over a series of days (see section 1.5) and then the detector was shut down for a short time. During this time, the detector was disconnected from the $ArCO_2$ gas and its atmosphere mixed with that in the lab. In order to return the detector to operating capacity, it was connected to CO_2 gas in order to flush out the oxygen in the detector volume. After allowing sufficient time for the oxygen to be flushed from the volume, the detector was powered on and another current test was performed. As the current test was progressing, several pulses were seen at lower than operating voltages (i.e. around 2000-2500 volts versus 3800-4200 for operating voltages). This is strange for two reasons: 1) pulses should not be seen in pure CO_2 because ionization should not take place in the pure CO_2 gas at the energy levels of the radiation, and 2) pulses should not be seen at such a low voltage input. In order to further explore this unusual situation, the Fe55 source was placed on the detector to see if the pulse rate would increase, but it did not. The source was removed and the pulse rate again monitored to see if there was a difference, but once again, the rate was about the same. At first it was believed to be a malfunction in the equipment, but everything was tested and all the equipment seems to be working properly. As of right now, we are not sure what is causing these pulses, but we hope to determine the cause soon. We plan to soon be running the detector as normal (i.e. with an $ArCO_2$ gas mixture) and try to observe low voltage pulses in that gas mixture to see if they are present with both configurations.

1.5

Tests Run

This allowed pulses and signals to be clearly seen apart from the background noise. After the noise was diminished to an acceptable level, there were several tests that needed to be performed to be able to document the properties of the GEM detector. The first and simplest test was done by placing a Fe^{55} x-ray source above the detector and seeing if pulses could be detected. This was done and pulses were indeed observed. Next it was determined that a uniformity test should be run. The basic idea of a uniformity test is to see if all parts of the detector output the same signal. This was done by placing the Fe^{55} source at 7 different points around the detector and recording the output signal at each of those points and then plotting that data. After this was done, it was shown that this GEM detector provides a relatively (i.e. with only small variations in the output signal) uniform output over the tested area of the detector which is an important property. Next, the Fe^{55} x-ray source was removed and we tried to observe pulses from cosmic ray muons. It is important that we are able to observe pulses from cosmic ray muons because that is the end goal of these GEM detectors—to detect and use cosmic ray muons to reconstruct a 3-D image. That can only be done if the GEM detector can actually detect muons, hence the reason that we looked for pulses which we thought might have been made by cosmic ray muons. At operating voltages (i.e. between 3800 and 4200 volts) and without any radioactive source nearby, pulses were observed and are believed to have been caused by detection of cosmic ray muons. It is possible that there is some other explanation for the pulses, but in all probability the observed signal is most likely from muons.

1.6

Future Work and Conclusion

Now that we have determined that our detector can indeed detect cosmic ray muons, the next step is to record those pulses so that we can obtain a spectrum of their energies, their total flux over our detector area, and other important parameters. I am currently working on creating a program that will read in the amplitude of each observable pulse and store it in an Excel file for further study. This is accomplished through the use of macros in Excel. In addition, we are also trying to determine the best way to trigger on and output data that will be used to gain more information about cosmic ray muons, which will be eventually utilized to perform 3-D image reconstruction. In conclusion, the assembly and testing of this GEM detector is a step in the right direction toward making 3-D muon tomography imaging a reality.

References

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This was not a part of my original "journal" entry, but this is some of the data taken by Amilkar, Mike, and myself.

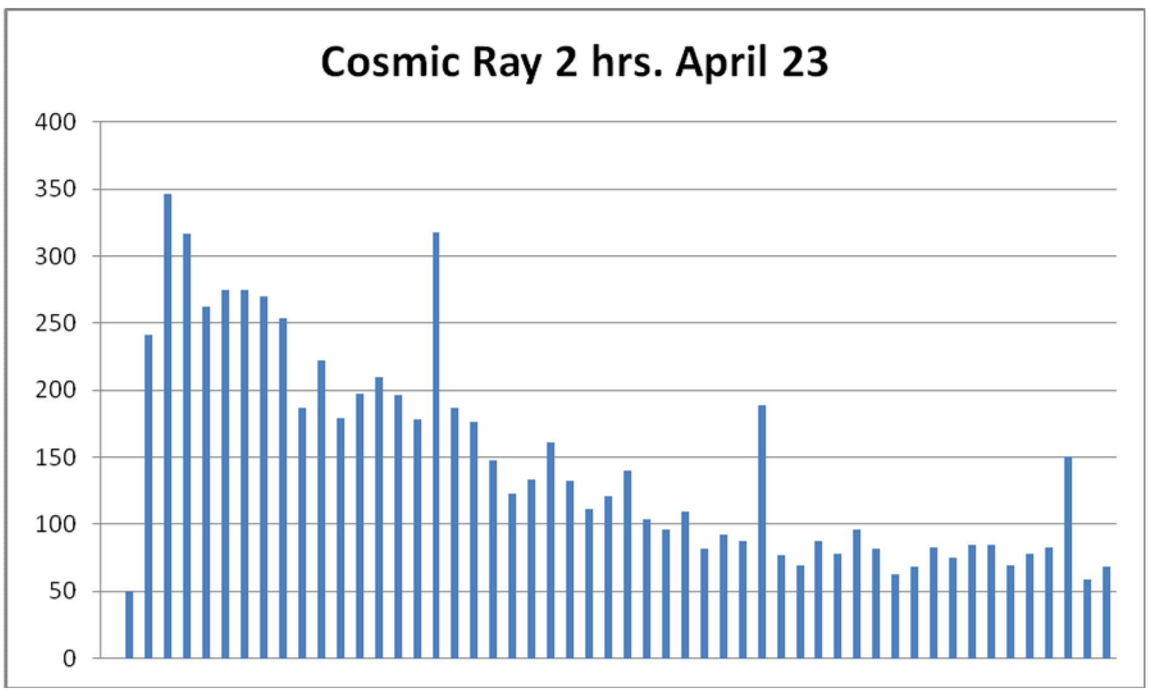
Additional Tests Run and Data Generated

I helped to write a Visual Basic Lite program which allows us to capture information about the pulses and record that data in an Excel file. I helped with the basic logic and platform and Amilkar finished the program and got it running effectively. We recorded data from two main sources; the first being Fe-55 and the second being naturally-occurring cosmic rays. Several runs were done and the number of events varied from 10000-65536 (the latter being the most that can be recorded in one column in Excel) over periods of different times.

The data and graph below are cosmic rays from an approximately 2 hour run on April 23rd from 3:13 p.m. to 5:05 p.m. The rate for this run was 1.51 events/second where 10000 events were recorded.

Bin	*Frequency*	*Bin*	*Frequency*
0.70397296743805	0	2.50166393610511	82
0.73789166496007	50	2.53558263362713	65
0.77181036248209	241	2.56950133114915	58
0.80572906000411	346	2.60342002867117	67
0.83964775752613	317	2.63733872619319	56
0.87356645504815	262	2.67125742371521	48
0.90748515257017	275	2.70517612123723	46
0.94140385009219	275	2.73909481875925	55
0.97532254761421	270	2.77301351628127	51
1.00924124513623	254	2.80693221380329	53
1.04315994265825	187	2.84085091132531	56
1.07707864018027	222	2.87476960884733	41
1.11099733770229	179	2.90868830636935	34
1.14491603522431	197	2.94260700389137	35
1.17883473274633	210	2.97652570141338	81
1.21275343026835	196	3.01044439893540	44
1.24667212779037	178	3.04436309645742	44
1.28059082531239	318	3.07828179397944	43
1.31450952283441	187	3.11220049150146	33
1.34842822035643	176	3.14611918902348	26
1.38234691787845	148	3.18003788654550	40
1.41626561540047	123	3.21395658406752	44
1.45018431292249	133	3.24787528158954	24
1.48410301044451	161	3.28179397911156	28
1.51802170796653	132	3.31571267663358	37
1.55194040548855	111	3.34963137415560	27
1.58585910301057	121	3.38355007167762	36
1.61977780053259	140	3.41746876919964	39

1.65369649805461	104	3.45138746672166	35
1.68761519557663	96	3.48530616424368	35
1.72153389309865	109	3.51922486176570	33
1.75545259062067	82	3.55314355928772	61
1.78937128814269	92	3.58706225680974	38
1.82328998566471	87	3.62098095433176	30
1.85720868318673	189	3.65489965185378	23
1.89112738070875	77	3.68881834937580	26
1.92504607823077	69	3.72273704689782	23
1.95896477575279	87	3.75665574441984	24
1.99288347327481	78	3.79057444194186	24
2.02680217079683	96	3.82449313946388	31
2.06072086831885	82	3.85841183698590	30
2.09463956584087	63	3.89233053450792	26
2.12855826336289	68	3.92624923202994	19
2.16247696088491	83	3.96016792955196	24
2.19639565840693	75	3.99408662707398	25
2.23031435592895	85	4.02800532459600	21
2.26423305345097	85	4.06192402211802	16
2.29815175097299	69	4.09584271964004	540
2.33207044849501	78	4.12976141716206	0
2.36598914601703	83	4.16368011468408	0
2.39990784353905	150	4.19759881220610	0
2.43382654106107	59	4.23151750972812	0
2.46774523858309	68	More	0

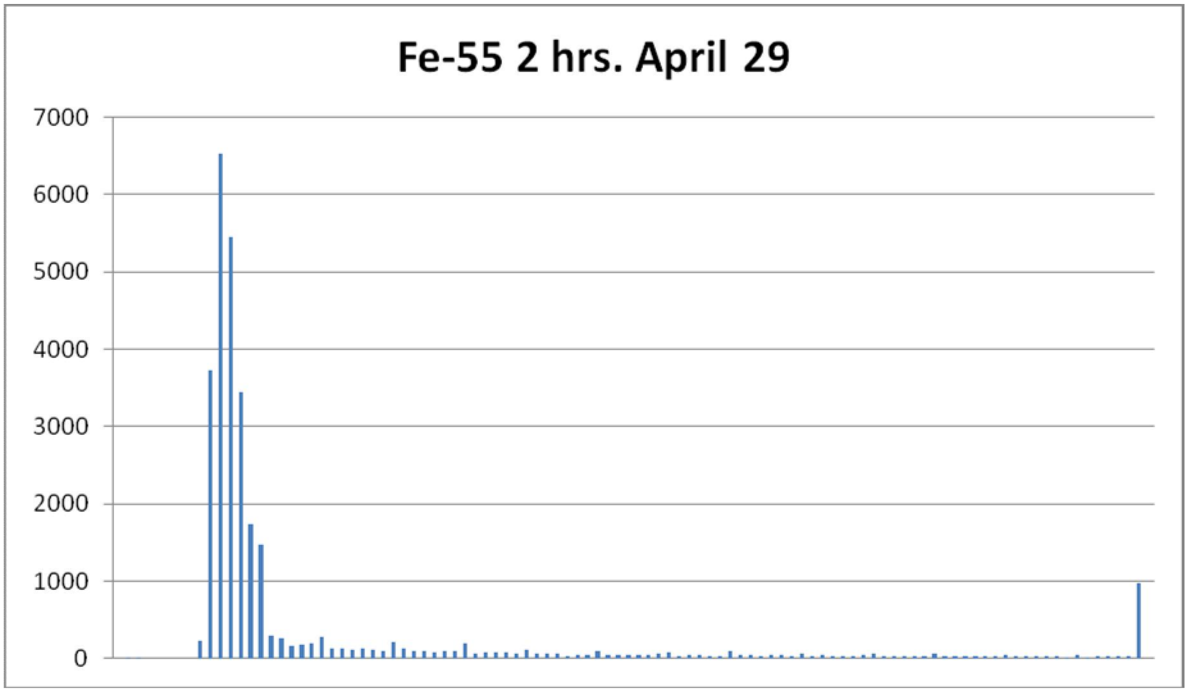


Graph #1 Cosmic Ray Data from 2-hour run on April 23rd with 10000 events.

The next set of data and the graph is from an approximately 2 hour run with Fe-55 on April 29th where 10000 events were recorded.

Bin	*Frequency*	*Bin*	*Frequency*
0.41598402621339	0	2.29271195986101	47
0.45278261314766	1	2.32951054679527	44
0.48958120008193	1	2.36630913372954	55
0.52637978701619	0	2.40310772066381	80
0.56317837395046	0	2.43990630759808	31
0.59997696088473	0	2.47670489453234	39
0.63677554781900	0	2.51350348146661	39
0.67357413475326	0	2.55030206840088	34
0.71037272168753	223	2.58710065533514	35
0.74717130862180	3727	2.62389924226941	88
0.78396989555606	6533	2.66069782920368	48
0.82076848249033	5455	2.69749641613795	45
0.85756706942460	3443	2.73429500307221	29
0.89436565635886	1734	2.77109359000648	50
0.93116424329313	1478	2.80789217694075	46
0.96796283022740	300	2.84469076387501	31
1.00476141716167	257	2.88148935080928	64
1.04156000409593	162	2.91828793774355	36
1.07835859103020	177	2.95508652467781	37
1.11515717796447	187	2.99188511161208	24
1.15195576489873	282	3.02868369854635	32
1.18875435183300	127	3.06548228548062	34
1.22555293876727	124	3.10228087241488	38
1.26235152570153	117	3.13907945934915	65
1.29915011263580	130	3.17587804628342	36
1.33594869957007	110	3.21267663321768	26
1.37274728650434	102	3.24947522015195	30
1.40954587343860	206	3.28627380708622	23
1.44634446037287	122	3.32307239402048	22
1.48314304730713	96	3.35987098095475	59
1.51994163424140	98	3.39666956788902	36
1.55674022117567	84	3.43346815482329	28
1.59353880810993	97	3.47026674175755	29
1.63033739504420	87	3.50706532869182	20
1.66713598197847	188	3.54386391562609	21
1.70393456891274	66	3.58066250256035	33
1.74073315584700	79	3.61746108949462	42
1.77753174278127	78	3.65425967642889	33
1.81433032971554	76	3.69105826336315	30
1.85112891664980	65	3.72785685029742	22
1.88792750358407	112	3.76465543723169	20
1.92472609051834	64	3.80145402416596	27
1.96152467745260	62	3.83825261110022	18
1.99832326438687	53	3.87505119803449	51
2.03512185132114	36	3.91184978496876	18
2.07192043825541	50	3.94864837190302	23

2.10871902518967	51	3.98544695883729	30
2.14551761212394	97	4.02224554577156	21
2.18231619905821	47	4.05904413270583	22
2.21911478599247	44	4.09584271964009	980
2.25591337292674	44	4.13264130657436	0
		More	0

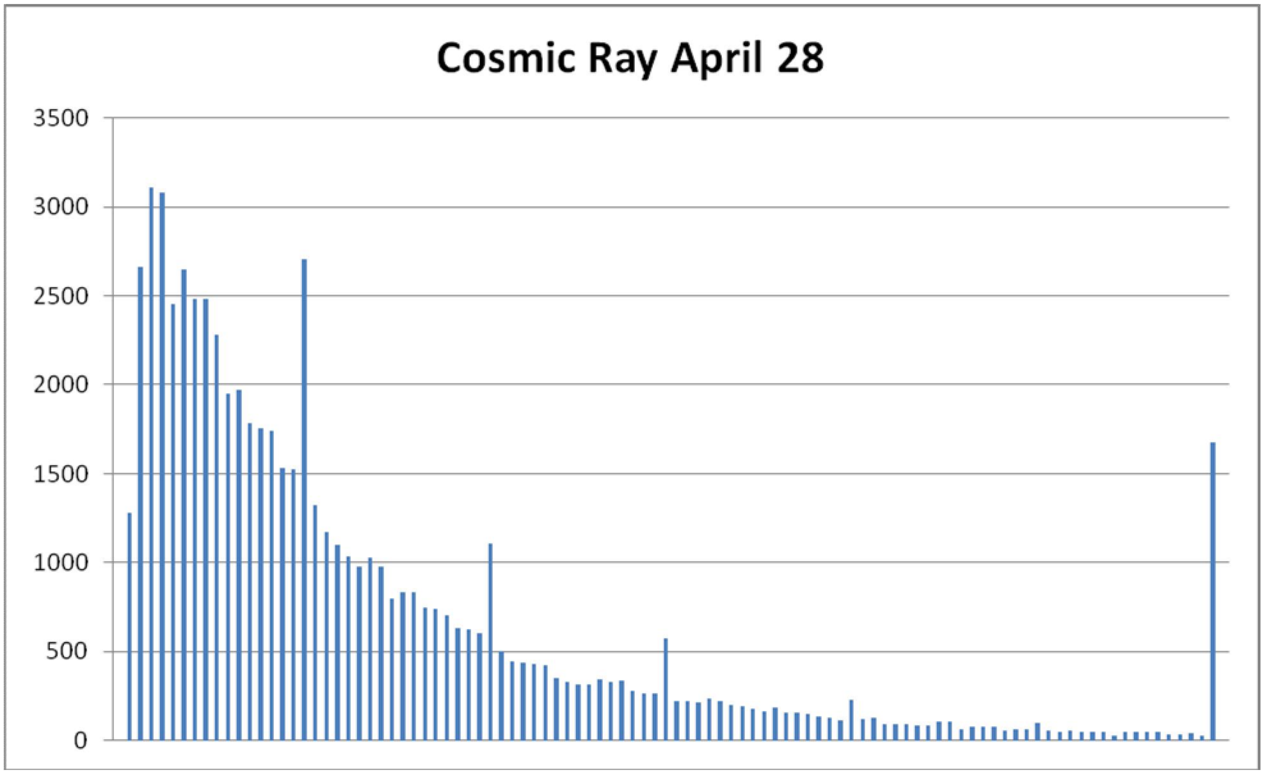


Graph #2 Fe-55 Data from approximately 2-hour run on April 29th with 10000 events.

The data and graph below is from a cosmic ray run taken on April 28th where 65536 events were recorded.

Bin	*Frequency*	*Bin*	*Frequency*
0.70397296743805	0	2.43382654106107	220
0.73789166496007	1282	2.46774523858309	220
0.77181036248209	2660	2.50166393610511	217
0.80572906000411	3111	2.53558263362713	235
0.83964775752613	3079	2.56950133114915	222
0.87356645504815	2456	2.60342002867117	202
0.90748515257017	2646	2.63733872619319	196
0.94140385009219	2485	2.67125742371521	181
0.97532254761421	2484	2.70517612123723	162
1.00924124513623	2278	2.73909481875925	183
1.04315994265825	1952	2.77301351628127	159
1.07707864018027	1972	2.80693221380329	155
1.11099733770229	1784	2.84085091132531	152
1.14491603522431	1754	2.87476960884733	137
1.17883473274633	1743	2.90868830636935	125

1.21275343026835	1533	2.94260700389137	115
1.24667212779037	1526	2.97652570141338	230
1.28059082531239	2704	3.01044439893540	117
1.31450952283441	1326	3.04436309645742	128
1.34842822035643	1171	3.07828179397944	93
1.38234691787845	1097	3.11220049150146	95
1.41626561540047	1033	3.14611918902348	89
1.45018431292249	981	3.18003788654550	85
1.48410301044451	1028	3.21395658406752	83
1.51802170796653	981	3.24787528158954	106
1.55194040548855	798	3.28179397911156	106
1.58585910301057	832	3.31571267663358	62
1.61977780053259	835	3.34963137415560	74
1.65369649805461	744	3.38355007167762	75
1.68761519557663	737	3.41746876919964	78
1.72153389309865	704	3.45138746672166	54
1.75545259062067	632	3.48530616424368	61
1.78937128814269	621	3.51922486176570	61
1.82328998566471	604	3.55314355928772	102
1.85720868318673	1106	3.58706225680974	56
1.89112738070875	499	3.62098095433176	52
1.92504607823077	443	3.65489965185378	59
1.95896477575279	438	3.68881834937580	46
1.99288347327481	430	3.72273704689782	50
2.02680217079683	424	3.75665574441984	47
2.06072086831885	352	3.79057444194186	27
2.09463956584087	330	3.82449313946388	47
2.12855826336289	314	3.85841183698590	45
2.16247696088491	318	3.89233053450792	50
2.19639565840693	346	3.92624923202994	50
2.23031435592895	327	3.96016792955196	36
2.26423305345097	335	3.99408662707398	36
2.29815175097299	279	4.02800532459600	38
2.33207044849501	262	4.06192402211802	30
2.36598914601703	265	4.09584271964004	1675
2.39990784353905	571	4.12976141716206	0
		More	0

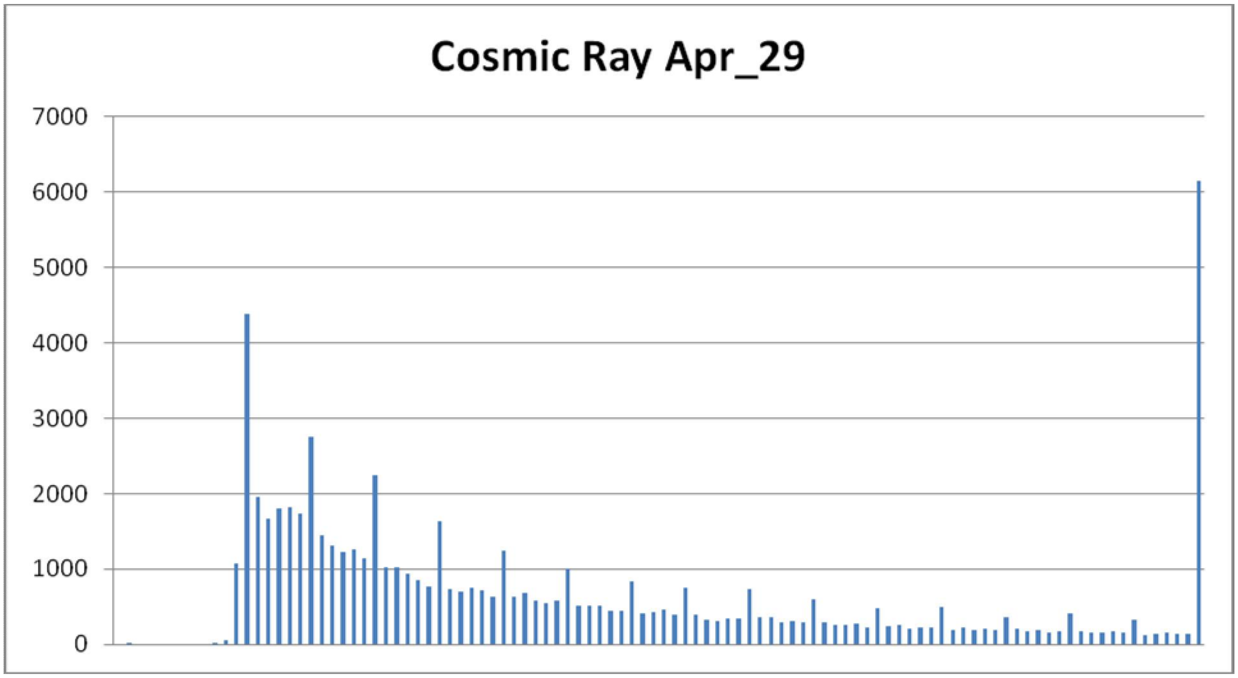


Graph #3 Cosmic Ray Data from 65536 events taken on April 28th.

The data below is from a second cosmic ray run taken on April 29th where 65536 events were again recorded.

Bin	*Frequency*	*Bin*	*Frequency*
0.35198648371903	0	2.26135316403847	468
0.38942504607823	1	2.29879172639769	388
0.42686360843744	0	2.33623028875689	750
0.46430217079664	0	2.37366885111609	388
0.50174073315585	0	2.41110741347529	332
0.53917929551505	0	2.44854597583450	312
0.57661785787426	0	2.48598453819370	339
0.61405642023346	0	2.52342310055292	346
0.65149498259267	0	2.56086166291212	732
0.68893354495187	1	2.59830022527132	359
0.72637210731108	63	2.63573878763053	353
0.76381066967028	1072	2.67317734998973	298
0.80124923202948	4386	2.71061591234893	307
0.83868779438869	1958	2.74805447470815	293
0.87612635674789	1667	2.78549303706734	600
0.91356491910710	1811	2.82293159942656	289
0.95100348146630	1816	2.86037016178576	258
0.98844204382551	1737	2.89780872414496	258
1.02588060618471	2748	2.93524728650416	275
1.06331916854392	1448	2.97268584886337	232
1.10075773090312	1319	3.01012441122257	476

1.13819629326233	1227	3.04756297358179	243
1.17563485562153	1265	3.08500153594099	254
1.21307341798074	1134	3.12244009830019	216
1.25051198033994	2249	3.15987866065940	233
1.28795054269915	1028	3.19731722301860	233
1.32538910505835	1028	3.23475578537780	492
1.36282766741756	934	3.27219434773702	200
1.40026622977676	855	3.30963291009621	231
1.43770479213596	771	3.34707147245543	196
1.47514335449517	1632	3.38451003481463	215
1.51258191685438	732	3.42194859717383	199
1.55002047921358	707	3.45938715953303	369
1.58745904157278	756	3.49682572189224	206
1.62489760393199	710	3.53426428425144	178
1.66233616629120	639	3.57170284661066	184
1.69977472865041	1249	3.60914140896986	160
1.73721329100960	637	3.64657997132906	170
1.77465185336881	676	3.68401853368827	412
1.81209041572801	580	3.72145709604747	174
1.84952897808723	553	3.75889565840667	157
1.88696754044643	580	3.79633422076589	164
1.92440610280563	1009	3.83377278312508	181
1.96184466516483	511	3.87121134548430	162
1.99928322752404	509	3.90864990784350	321
2.03672178988325	510	3.94608847020270	127
2.07416035224246	445	3.98352703256190	133
2.11159891460166	445	4.02096559492112	152
2.14903747696086	843	4.05840415728032	147
2.18647603932007	419	4.09584271963953	139
2.22391460167928	422	4.13328128199873	6153
		More	0

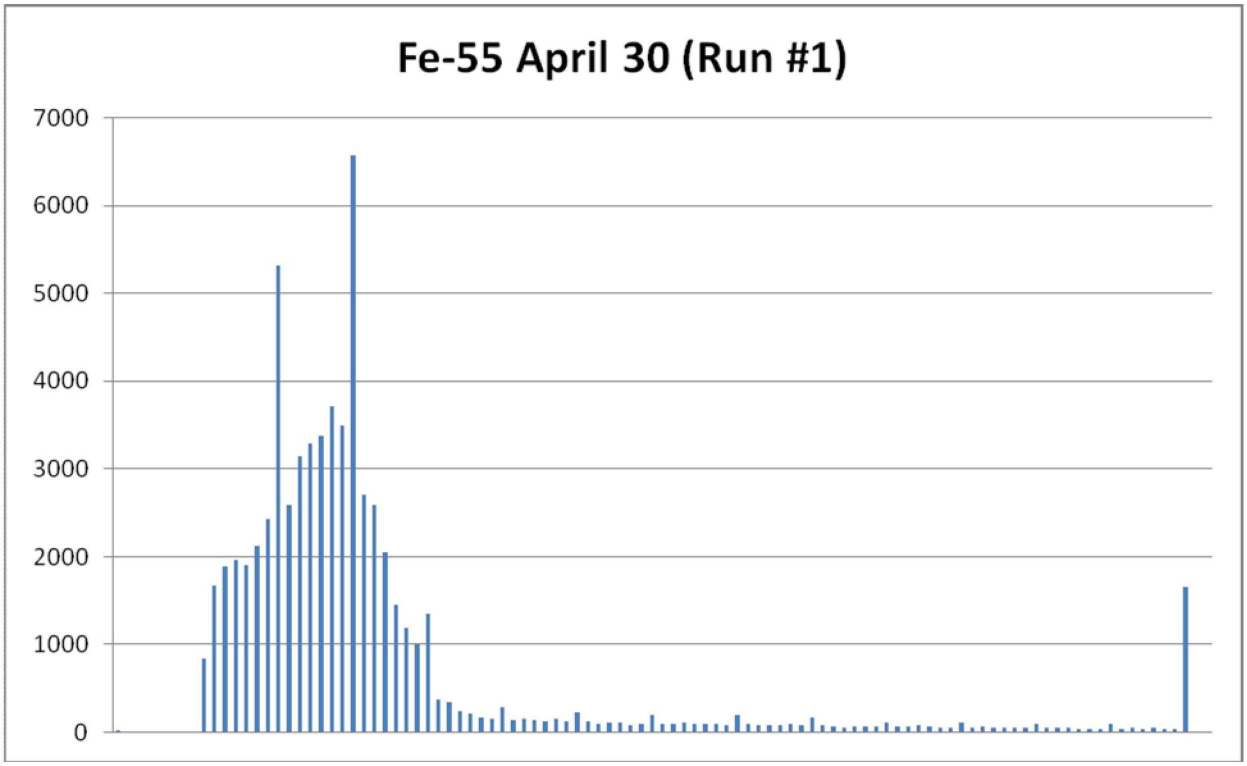


Graph #4 Cosmic Ray Data from 65536 events taken on April 29th.

The following data and graph below are from the first approximately 2 hour run with a Fe-55 source on April 30th from 9:40 a.m. to 11:28 a.m. The rate for this run was 10.17 events/second where 65536 events were recorded.

Bin	*Frequency*	*Bin*	*Frequency*
0.44798279746058	1	2.30839135777197	89
0.48446139668237	0	2.34486995699376	98
0.52093999590416	0	2.38134855621555	104
0.55741859512595	0	2.41782715543735	102
0.59389719434775	0	2.45430575465914	95
0.63037579356954	0	2.49078435388093	90
0.66685439279133	0	2.52726295310272	78
0.70333299201312	0	2.56374155232451	200
0.73981159123491	846	2.60022015154631	95
0.77629019045671	1677	2.63669875076810	84
0.81276878967850	1883	2.67317734998989	73
0.84924738890029	1960	2.70965594921168	74
0.88572598812208	1909	2.74613454843347	90
0.92220458734387	2117	2.78261314765527	84
0.95868318656567	2436	2.81909174687706	162
0.99516178578746	5314	2.85557034609885	83
1.03164038500925	2596	2.89204894532064	69
1.06811898423104	3138	2.92852754454243	58
1.10459758345283	3285	2.96500614376423	71
1.14107618267463	3373	3.00148474298602	69

1.17755478189642	3707	3.03796334220781	65
1.21403338111821	3490	3.07444194142960	114
1.25051198034000	6572	3.11092054065139	70
1.28699057956179	2705	3.14739913987319	60
1.32346917878359	2593	3.18387773909498	78
1.35994777800538	2056	3.22035633831677	68
1.39642637722717	1456	3.25683493753856	56
1.43290497644896	1186	3.29331353676035	54
1.46938357567076	994	3.32979213598215	103
1.50586217489255	1347	3.36627073520394	50
1.54234077411434	374	3.40274933442573	72
1.57881937333613	338	3.43922793364752	53
1.61529797255792	234	3.47570653286931	56
1.65177657177972	213	3.51218513209111	58
1.68825517100151	172	3.54866373131290	57
1.72473377022330	158	3.58514233053469	88
1.76121236944509	286	3.62162092975648	49
1.79769096866688	132	3.65809952897827	44
1.83416956788868	154	3.69457812820007	48
1.87064816711047	140	3.73105672742186	37
1.90712676633226	124	3.76753532664365	43
1.94360536555405	146	3.80401392586544	32
1.98008396477584	125	3.84049252508723	101
2.01656256399763	233	3.87697112430903	41
2.05304116321943	117	3.91344972353082	48
2.08951976244122	102	3.94992832275261	38
2.12599836166301	111	3.98640692197440	53
2.16247696088480	104	4.02288552119619	43
2.19895556010659	86	4.05936412041799	41
2.23543415932839	102	4.09584271963978	1660
2.27191275855018	196	4.13232131886157	0
		More	0

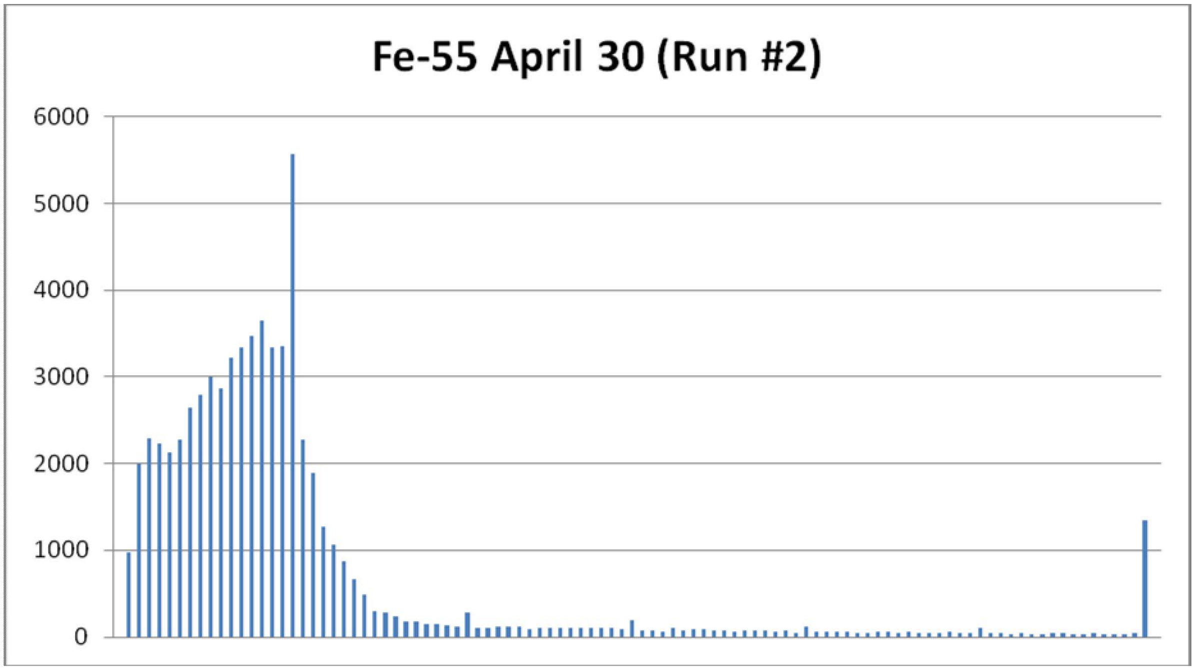


Graph #5 Fe-55 Data from the first approximately 2-hour run on April 30th with 65536 events.

The data and graph below are from a second approximately 2 hour run on April 30th again with a Fe-55 source. 65536 events were recorded from 11:30 a.m. to 1:25 p.m. and the rate for this run was 9.53 events/second.

Bin	*Frequency*	*Bin*	*Frequency*
0.70397296743805	0	2.43382654106107	80
0.73789166496007	972	2.46774523858309	77
0.77181036248209	1998	2.50166393610511	64
0.80572906000411	2287	2.53558263362713	101
0.83964775752613	2228	2.56950133114915	69
0.87356645504815	2124	2.60342002867117	93
0.90748515257017	2272	2.63733872619319	89
0.94140385009219	2642	2.67125742371521	70
0.97532254761421	2795	2.70517612123723	70
1.00924124513623	2993	2.73909481875925	59
1.04315994265825	2864	2.77301351628127	74
1.07707864018027	3220	2.80693221380329	71
1.11099733770229	3331	2.84085091132531	71
1.14491603522431	3466	2.87476960884733	62
1.17883473274633	3643	2.90868830636935	69
1.21275343026835	3344	2.94260700389137	41
1.24667212779037	3349	2.97652570141338	123
1.28059082531239	5561	3.01044439893540	59
1.31450952283441	2281	3.04436309645742	54
1.34842822035643	1897	3.07828179397944	56

1.38234691787845	1274	3.11220049150146	56
1.41626561540047	1070	3.14611918902348	49
1.45018431292249	876	3.18003788654550	49
1.48410301044451	662	3.21395658406752	59
1.51802170796653	484	3.24787528158954	62
1.55194040548855	292	3.28179397911156	41
1.58585910301057	275	3.31571267663358	59
1.61977780053259	232	3.34963137415560	46
1.65369649805461	176	3.38355007167762	49
1.68761519557663	184	3.41746876919964	48
1.72153389309865	145	3.45138746672166	55
1.75545259062067	155	3.48530616424368	40
1.78937128814269	141	3.51922486176570	49
1.82328998566471	118	3.55314355928772	98
1.85720868318673	279	3.58706225680974	49
1.89112738070875	105	3.62098095433176	50
1.92504607823077	97	3.65489965185378	37
1.95896477575279	114	3.68881834937580	38
1.99288347327481	122	3.72273704689782	36
2.02680217079683	123	3.75665574441984	32
2.06072086831885	96	3.79057444194186	45
2.09463956584087	100	3.82449313946388	43
2.12855826336289	111	3.85841183698590	33
2.16247696088491	105	3.89233053450792	30
2.19639565840693	101	3.92624923202994	42
2.23031435592895	109	3.96016792955196	32
2.26423305345097	110	3.99408662707398	33
2.29815175097299	99	4.02800532459600	33
2.33207044849501	105	4.06192402211802	38
2.36598914601703	85	4.09584271964004	1346
2.39990784353905	195	4.12976141716206	0
		More	0



Graph #6 Fe-55 Data from the second approximately 2-hour run on April 30th again with 65536 events.

In conclusion, this semester has been productive because we have finally gotten a GEM detector working and recording data which we can analyze to determine important characteristics of both cosmic rays and other radioactive sources. The data included above is not everything recorded, but it is the most useful and (I think) well-representative of what we have collected so far.