Copper Source Optimization for use in Moderated Positron Apparatus

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Abstract

We attempted to develop an intense positron source by irradiating copper on an aluminum holder at the Nuclear Engineering Teaching Lab at the University of Texas at Austin. While this was not accomplished in the time frame required in order to include it in this thesis, I have included the design of the proposed sources for testing. Also included is my work on the development of the positron system while I was at NETL. Multiple sources are proposed to be developed with different thicknesses of copper to determine the optimum thickness and then develop a source around that known value.

I. Background

Since their discovery in 1932, positrons have steadily seen an increase in use for different fields of science. Specifically in the past couple decades, positron imaging techniques such as positron emission tomography and positron annihilation have grown to be widely used over not just the academic and medical industry but in the commercial industry as well. A key application of positron annihilation imaging is finding defects in silicon chips used in computers. One of the limiting factors of the size of the computer's components is the integrity of the silicon chips on which the transistors and other components of the computer are built upon. Defects in the chips lead to the inability of the electrical signal to transfer across the chip leaving the chip useless. By implementing positron annihilation imaging, the defects of the chips can be seen and evaluated effectively. This has its drawbacks. At the current maximum flux for positrons on a target is around 10^4 to 10^5 positrons/sec, so to image one silicon chip takes on the order of a day or two. In order for the technology to assist the computer industry better, evaluations of the silicon chips should instead be done on the order of minutes. Our research has the goal to do this. The copper source that we are developing has the ability to raise the flux to between 10^7 and 10^8 positrons/sec. This would allow for one chip to be imaged and evaluated in roughly 2 minutes. This huge reduction in time would streamline analysis and give the opportunity for the manufacturing process to optimize in real time, the quality of silicon chip outputs.

II. Introduction

The concepts used in this project are from nuclear physics. The following reactions are used to create positrons:

$^{63}\text{Cu} + \text{n} \rightarrow {}^{64}\text{Cu}$ (1)

$^{64}\text{Cu} \rightarrow {}^{64}\text{Zn} + \text{e}^+$ (2)

Previously, electroplated sources were used to get the copper onto a graphite base but now we will place the copper foil on an aluminum holder and place the holder in the reactor and activate the Cu. The emitted positrons will be moderated. The moderator consists of 12 tungsten meshes which cause the positrons which have a high energy originally to scatter and slow down by contacting the crystalline structure created by annealing the tungsten. The moderated positrons are accelerated back up to 2-5 keV by two electrically charged grids, one at ground and the other at 2-5 keV focusing the slow positrons across the gap and down the beam pipe. We use magnetic coils to guide the positrons down the beam pipe and to a bending magnet. It removes the fast positrons and the slow ones bend around the pipe bend and impact on a graphite target. The development of an optimal source is key since the stronger the source, the more positrons we have and eventually the beam can be used for more applications.

III. Experimental Procedure and Apparatus

Since the new source was not yet available I will discuss the refinements made to the vacuum chamber, actual performance of the vacuum chamber, the tuning I did to make it perform better, and the eventual testing procedure for the sources.

During a couple months on the project, Brad Hurst and I made a few adjustments to the vacuum system overlapped that greatly improved our understanding and performance of the system.

At first, a couple adjustments to the magnetic system were made to optimize the transport through the system.

a. Beam Alignment

Originally, our alignment of the beam was done by replacing the source in its holder with a laser pointer and sending the light beam down the beam pipe (this was done before a bend was included in the beam pipe). A paper crosshairs was attached to the end of the beam pipe and we observed where the laser beam illuminated the crosshairs. The source holder was rotated to adjust the pointer's accuracy on the crosshairs, mark that position, and use that position for the actual Na-22 source (or Cu-64 source). This alignment allowed for solid results but when the bend in the pipe was added, the laser method can not be used. Therefore, a Faraday cup was used. It was placed at the end of the beam pipe. The Faraday cup was used to find out where the beam of positrons would strike the graphite target. This would allow us to align and control the beam inside of the pipe. The prongs of the Faraday cup each received different flux of the charged particles that are traveling down the beam pipe. This maximal intensity showed the location of the beam. Since the beam wasn't directly in the center, a bending magnet was created and used to help to not only separate the fast positrons from the slow (moderated) positrons, but it also allowed for fine tuning of the beam location in the pipe. The first reason for the bend will be discussed later but the latter is an issue of alignment. Depending on the current applied to the magnet, the field would vary and bend the positrons according to the following equation:

$$r = \frac{1}{B}\sqrt{\frac{2mV}{q}} \tag{3}$$

Where r is the radius of the curve in the beam pipe, B is the magnetic field required, m is the mass of the particle (positron), V is the energy the positrons were accelerated to, and q is the charge of the particle.

The actual field used differed slightly from the calculated values, most likely because the beam wasn't going down the exact center of the pipe.

Another problem with the alignment is associated with the fact that the positrons are not traveling in a straight line down the pipe, they actually spiraled because of the guiding magnets that forces the positrons to stay close to the center of the beam pipe. This makes the bending tougher but increases the acceptance of positrons that would not have occurred if they were just traveling in a straight beam down the pipe. Finally, the alignment was performed as best as possible where the fast positrons were removed in the bending and the slow positrons reached the graphite block.

To give the slow positrons a better chance of successfully making it down the full length of the beam pipe, two magnetic coils, placed in the two planes perpendicular to the guiding magnets, were introduced to the system. The currents were controlled by individual power supplies and, by varying the current; the magnetic field influenced the particles inside of the beam pipe. I was able to optimize both directions (graphs included in the data section) so that the particles were going down to as close to the center of the beam pipe as possible before they reached the bending magnet. This allowed for a higher percentage of the slow positrons to make the turn as compared to the situation without the two correcting magnets.

b. Acceleration of moderated positrons

The positrons leaving the surface of the copper enter the tungsten moderator, they will constantly collide with the tungsten meshes and thermalize the positrons allowing them to be accelerated into a monoenergetic beam. Two methes were used to setup the acceleration voltages and allow the positrons leaving the end of the meshes to travel farther down the beam pipe. Ideally, an accelerating voltage of around 8-10 keV would be most desirable but the power supply that was originally used maxed out at 5 keV. In order to increase this voltage, a new power supply was hooked up that ranged to 15 keV but it began sparking at 6 keV so that voltage was limited again. An idea for the future would be to install a new power supply in order to better moderate the positrons.

c. Filtering of fast positrons out of the system

The key to this whole experiment is making a strong monoenergetic beam of positrons. This was attained fairly well after moderation but some of the positrons will make through the system unmoderated with varying energies making them quicker than the 2-5 keV energy of the thermalized positrons. This will be used to image a target. Therefore, an idea was devised to add a chicane (bend) to the beam pipe and bending the moderated positrons around the pipe while the fast positrons (unmoderated) remain on a straight line and never reached the target. The chicane in the pipe is shown by a CAD drawing in Figure 1:

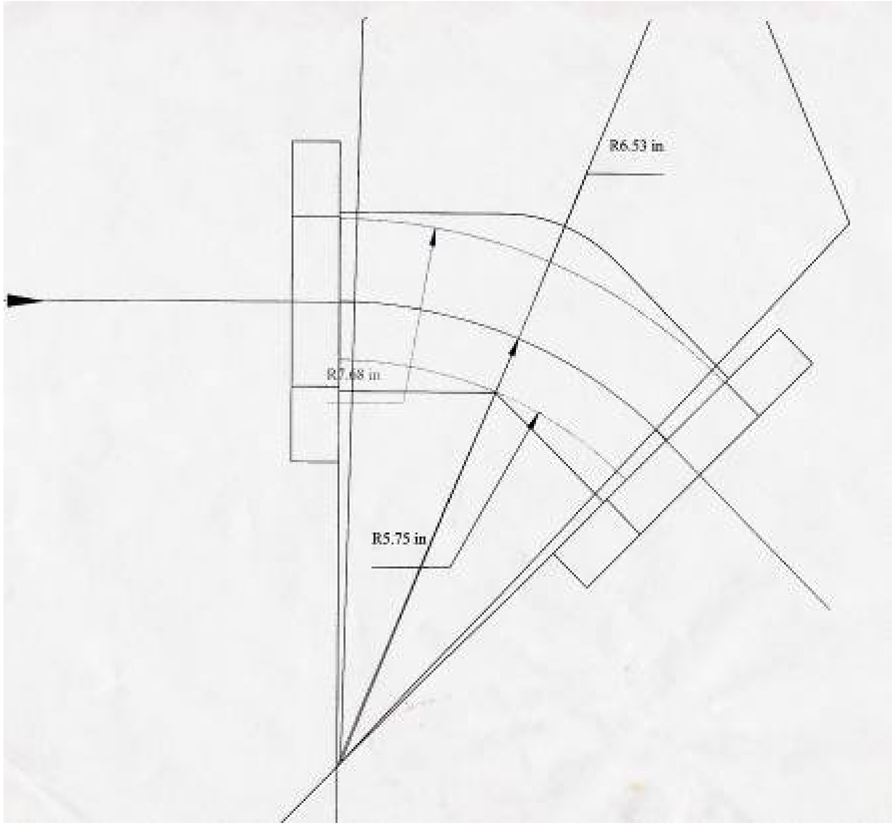

Fig. 1

The bending magnet is used for this purpose and one can be seen in the presentation. This allowed for the monoenergetic beam to separate from the fast unmoderated positrons.

d. Monoenergetic beam and imaging

In order to get good images, the beam must be monoenergetic since depending on the energy of the incident positrons, they will penetrate further into the material and depending on the depth the positrons traveled, a profile can be created of the composition of the target. In addition, the energy of the incident positrons, the cross section, or chance of the interaction between the positrons and the electrons in the material, changes. So the energy of the positrons must be known to correctly analyze an image of the target.

e. Apparatus

The main apparatus for testing the sources is follows:

Fig. 2

The apparatus uses the following pieces:

Stainless steel vacuum chamber, Gate valve for the chamber, Vacuum pump, Diffusion pump, Power supplies, 5keV HV power supply, Sodium Iodide (NaI) detector, Copper source/Na-22 source depending on what is being tested, Bending magnet, Magnetic coils for focusing, Leaded concrete, lead bricks and lead pellets for protection, Ion gauge, Computer with the program GENIE for data analysis

The basics

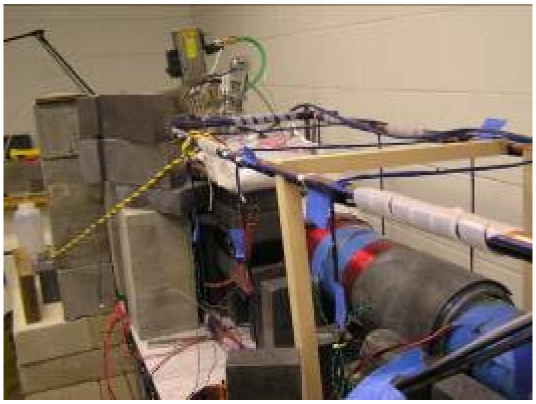

Fig. 3 Vacuum chamber

The vacuum chamber is composed of stainless steel with 12 point bolts securing the pieces together. Copper o-rings are compressed between the pipe flanders to form a vacuum seal, these have to be replaced after each separation of the piping.

Fig. 4 and 5 Pumps (mechanical and turbo)

These pumps and their power supplies make the vacuum down to roughly 10^{-9} torr. To operate the system correctly, the mechanical pump is turned on (orange) for roughly 20 minutes until the green light in front of the pump is on, meaning the pressure is low enough to start the diffusion pump. Start the turbo pump and make sure it reaches 740 on the display meaning it is running at full capacity. After about 30 minutes then the ion gauge can be turned on. The gauge should have no problem reading the pressure. Do not turn on the ion gauge before it the vacuum is established. It will be worthless since the gauge can't get a reading. Below is the ion gauge readout.


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Fig. 6 Ion gauge readout

The bending magnet shown in Fig. 7 hidden behind the lead wall, is supplied a highly regulated current by a power supply creating a constant stable magnetic field.

Fig. 7 NaI detector and bending magnet

A gauss meter is used to confirm that there is the magnetic field oriented in the correct way and that responds to changes in current. The slow (moderated) positrons are transported down the bend of the pipe to the graphite target while the unmoderated, fast positrons don't make it to the target. A NaI detector will record the x-ray production generated by the annihilation of the positrons interacting with the electrons on the surface of the graphite (or a little deeper). The NaI detector will absorb the resultant 511keV gammas. By calculating the solid angle of the detector, we can estimate the number of pairs produced and therefore the amount of positrons hitting the target per unit time.

Inside of the vacuum chamber lies the two electrically charged plates that are connected to the HV power supply shown below:

Fig. 8 HV power supply

The power supply has to maintain at least 3 keV for the acceleration of the moderated positrons without sparking so the experiment can be carried out. The higher the energy the better it will be to image. Once the vacuum chamber is pumped down to around 10^{-8} torr, the NaI detector is ready to go, the power supplies are checked and ready, then the testing can begin. First, the magnets need to be turned on.

Fig. 9 Na-22 source that is used for testing moderators and alignment.

The source, moderator, and source holder are shown in Fig. 10a and 10b:

Fig 10a Source, moderator, and holder (side view)

From the top:

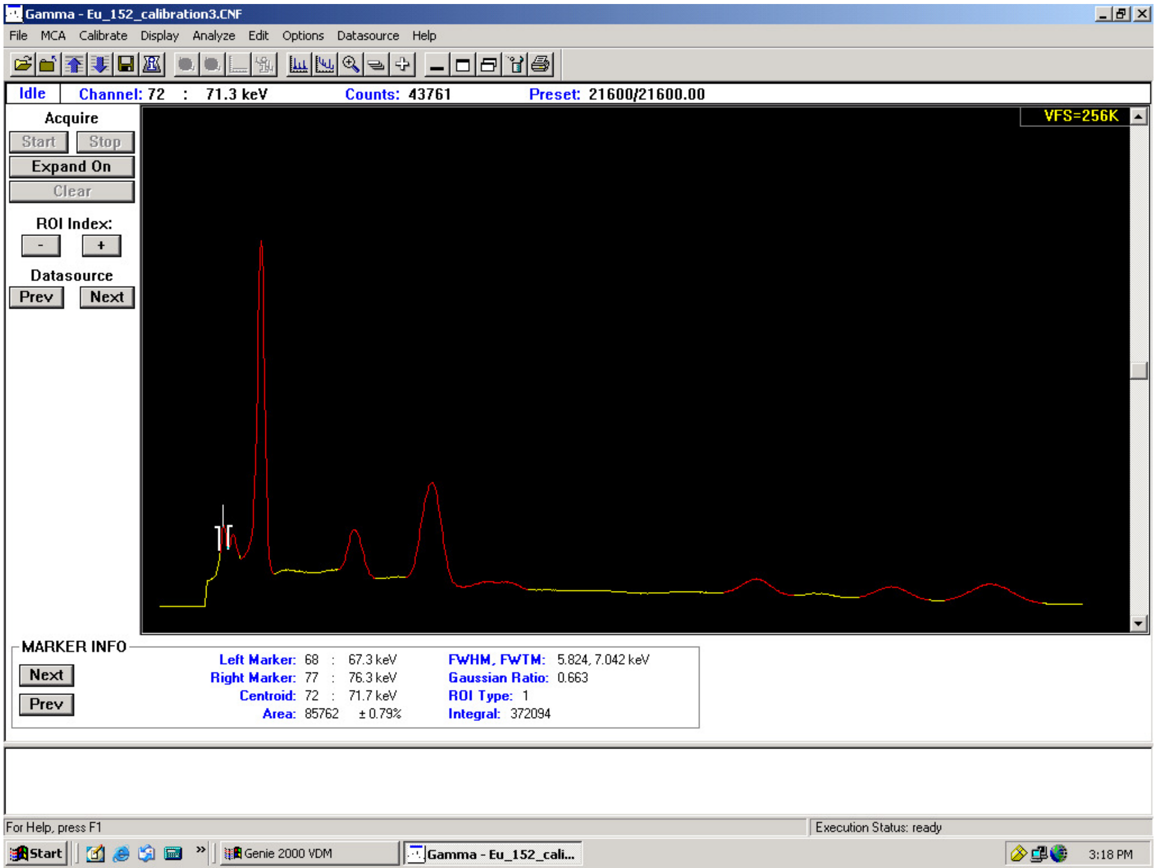
Fig 10b Source, moderator, and holder (top view)

The ^{22}Na source goes into the aluminum holder on the right, and the moderator is placed on top and both slides into the groove cut on the holder. Tape is placed on the moderator connecting it to the holder to make sure it stays in place. The whole assembly is placed into the stationary holder inside of the chamber and the chamber is closed (this all occurs while the vacuum chamber is not yet pumped down). When the source is installed and the vacuum is at 10^{-8} Torr, the high voltage can be applied to the meshes to accelerate the positrons after they pass through the moderator (provided by Dr. Fink). The positrons travel with 3 keV of energy down the pipe where the magnets are adjusted to have the maximum efficiency in keeping the path of the positrons centered in the pipe. The positrons reach the guiding magnet, the current to the magnet is adjusted until the maximum number of counts/sec are recorded with the NaI detector. The magnets placed in perpendicular directions to align the beam in the exact center are adjusted until the counts were at a maximum and to optimize the beam. This is done by counting for 5 minutes with the GENIE program and adjusting the field in this fashion. A graph of the fine tuning is supplied in the data section. Once the beam has been optimized, calibrations can be started.

f. NaI calibration

In order for the results to be accurate, the sodium iodide detector has to be calibrated for its energy resolution. This is not needed to count the number of positrons the detector sees, it will be advantageous later on when imaging is required since the energy of the positron entering the material must be known in order to properly evaluate the depth the positron was annihilated. Also, it is a good check that actually gamma particles are detected as a result from the annihilation and not a peak due to a faulty detector. Initially, a ^{137}Cs source is used for calibration. The ^{137}Cs is known for its strong peak at 1.16 MeV. This was also used to put the detector in the right general area.

To enhance the accuracy of the detector further, a ^{152}Eu source was used. This provides a better calibration since instead of a one point calibration from ^{137}Cs, a 3 point calibration can be used, making the detector very accurate. An example of the calibration screen and graph is in Fig 11.



Idle Channel: 72 : 71.3 keV Counts: 43761 Preset: 21600/21600.00

Left Marker: 68 : 67.3 keV
Right Marker: 77 : 76.3 keV
Centroid: 72 : 71.7 keV
Area: 85762 ± 0.79%
FWHM, FWTM: 5.824, 7.042 keV
Gaussian Ratio: 0.663
ROI Type: 1
Integral: 372094

Fig. 11 ^{152}Eu calibration

Fig. 11 shows the gamma spectrum for ^{152}Eu. Other sources can be used but since ^{152}Eu has multiple strong peaks of emission, it is an ideal source for calibration.

g. Procedure

The following procedure was developed for creating a new radioactive source. Previously, it was created by electroplating copper onto graphite and then setting the source into the nuclear reactor and the copper was activated. Depending on the time of electroplating, the thickness of the copper is different, allowing us to test different thicknesses. There are severe problems with this process however. The electroplating is not uniform over the target area, the electroplating would sometimes occur in not just the target area, and the source would sometimes be too radioactive to handle and become worthless. The new idea is to stack copper foils which are 1 micron thick. We will use the fact that they adhere to metal very easily to attach them to our holder. The holder will be made out of aluminum and the copper placed at the center on a small island of aluminum to insure it is in the middle of the source (picture in data section). The foil can be stacked so that we can obtain higher thicknesses up to roughly 20 microns. We will test different thicknesses 1,2,3,5,10, etc. micron thick copper stacks and determine the optimum thickness for our source. More copper does not mean more positrons since positrons emitted deep in the material can not escape the copper above it and are worthless radiation that can only harm us (the gammas from the same reaction). We will to find the optimum thickness so the project can proceed in testing more moderators and hopefully, eventually positron imaging. To test a source the following protocol will be performed:

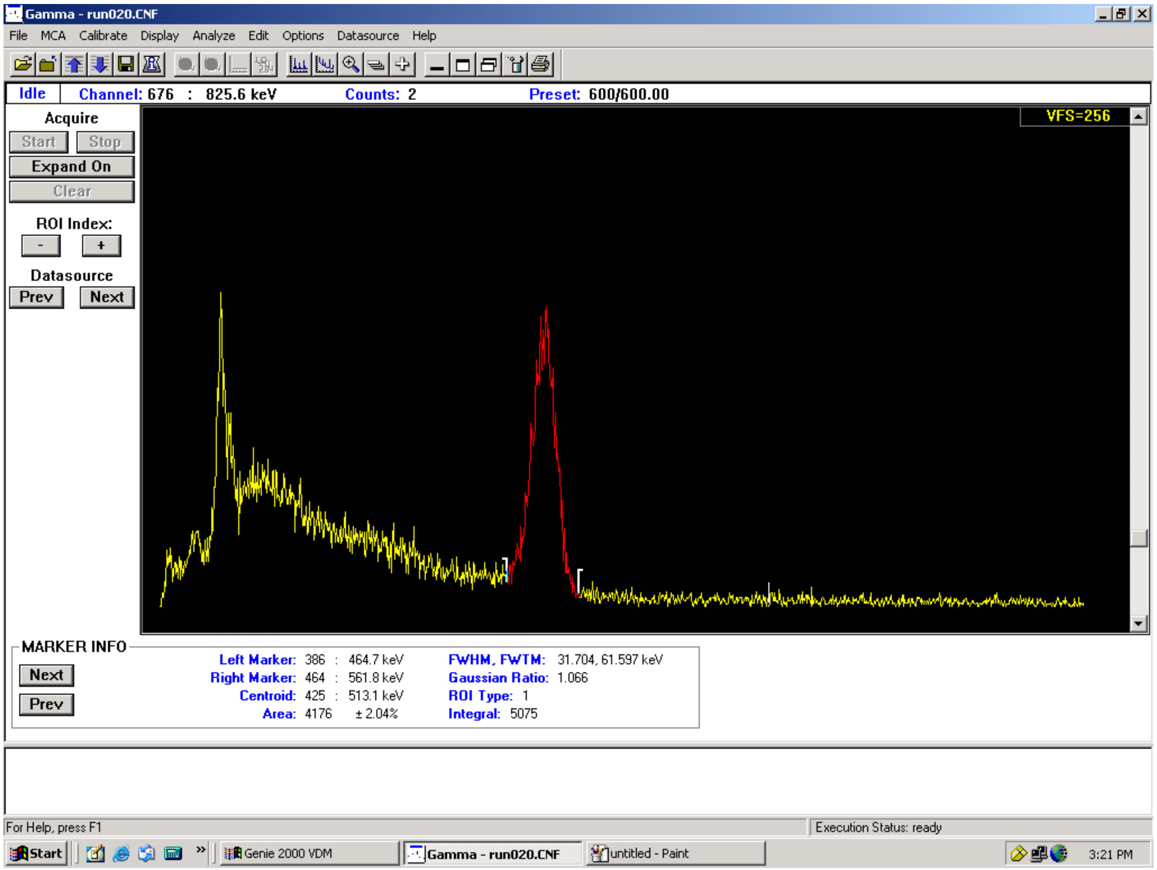
1. Carefully place the source in its holder with tongs.
2. Seal the source with the moderator at the top.
3. Place holder into chamber and seal the chamber with the gate valve.
4. Pump the chamber down to 10^{-8} or better Torr.
5. Turn on the HV power supply and accelerate the positrons to 3 keV.
6. Turn on the bending magnet and focusing magnets so that the slow positrons can only be measured.
7. Measure the gammas leaving the graphite target with the NaI detector and calculate the number of positrons per second.
8. Open up the chamber and remove the source carefully with tongs.

9. Place the source into the lead pig and remove it after it has had sufficient time to decay away (half life is 12 hours so wait about a week or so).

Overall, the procedure is not difficult but all the aligning, tweaking, and other tasks make the project a tedious one. Picture of the proposed source and data from the alignments of the beam are attached in the next section.

IV. Experimental Data

Results from testing of different supplied voltages and different moderators yielded different output values in terms of positrons/sec. The graph (Fig. 12) below gives an example of the result from one of the tests:



Idle
Channel: 676 : 825.6 keV
Counts: 2
Preset: 600/600.00

Left Marker: 386 : 464.7 keV
Right Marker: 464 : 561.8 keV
Centroid: 425 : 513.1 keV
Area: 4176 ± 2.04%
FWHM, FWTM: 31.704, 61.597 keV
Gaussian Ratio: 1.066
ROI Type: 1
Integral: 5075

For Help, press F1
Execution Status: ready

Fig. 12: Example of NaI display from a positron test

As one can see, the centroid for the peak lies at 513.1 keV. This is very close to the 511 keV energy that is expected from the gamma rays resulting from the positron-electron annihilation. Discussion of the peaks will be presented in the analysis section.

Data that resulted from these tests can be seen below:

8/17/2007	Time of day	Run number	Read B	Read HV	Cnts	cnts/sec	Vacuum
Cu 59mg	24um						
	12:19	10	27.13	5	938	1480	7.20E-07
	12:33	11	24.11	4.422	532	839	5.20E-07
	12:44	12	21.6	3.6	426	672	4.90E-07
	12:53	13	28.24	5	806	1272	4.10E-07
	13:09	14	28.24	0	240	379	3.90E-07
	13:06	15	0	0	222	350	3.70E-07

Table 1: Data taken from multiple runs of positron tests

The column Read B was the determined field inside of the magnet, Read HV was the voltage supplied from the power source, Cnts was the number of counts under the area of the peak collected during the duration of the test, cnts/sec was the calculated total gammas being emitted from the source per second (calculation shown in the analysis section, and the vacuum was the pressure inside of the vacuum chamber in Torr.

Here is one other table:

8/17/2007	Time of day	Run number	Read B	Read HV	Cnts	cnts/sec	Vacuum
Cu 233mg	104um						
	14:47	16	27.16	5	2209	3485	7.20E-07
	15:01	17	25.62	4.62	1017	1604	6.30E-07
	15:10	18	19.95	3.88	1553	2450	5.70E-07
600 sec	15:23	19	26.82	5	3840	3029	5.10E-07
600 sec	16:05	20	27.42	5	4162	3283	3.40E-07
600 sec	16:16	21	27.42	0	268	211	3.30E-07
600 sec	16:28	21	0	0	139	110	3.10E-07

Table 2: Data taken from multiple runs of positrons tests.

Many more of these tables were taken but for space purposes only two examples are shown. The trends discussed in the analysis however pertain to all the data taken, not just the tables above.

No data of the designed sources could be taken yet, the report is limited to the design plans and the data used to make the beam line more effective.

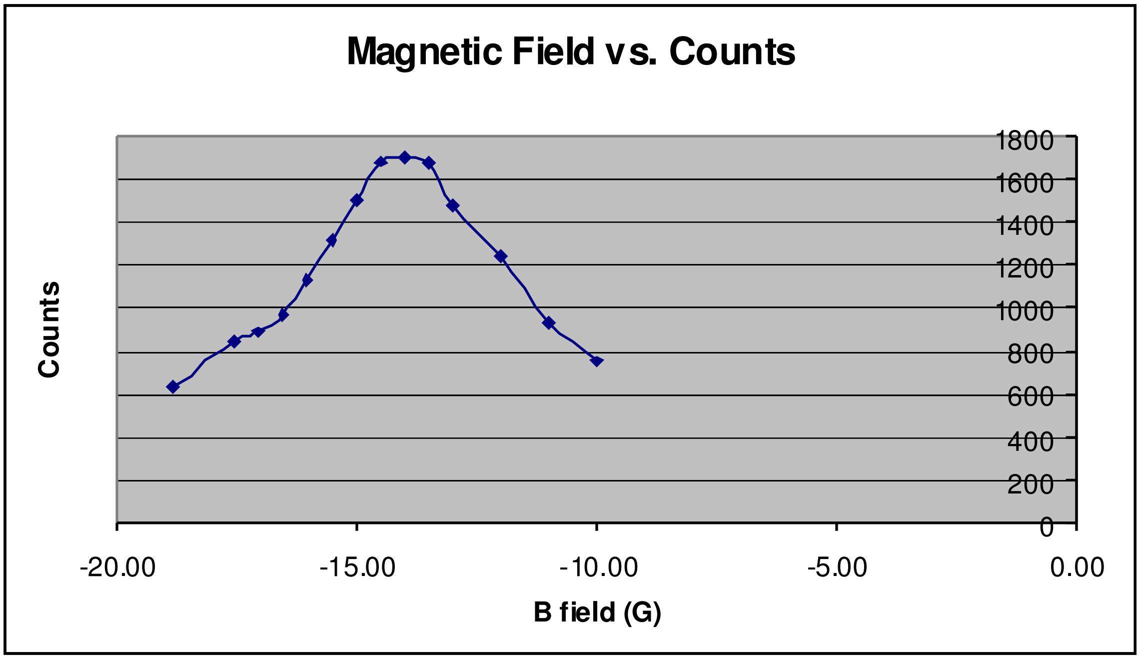


Fig. 13

Example of one of the graphs displaying the number of counts of positrons versus the field inside of the bending magnet.

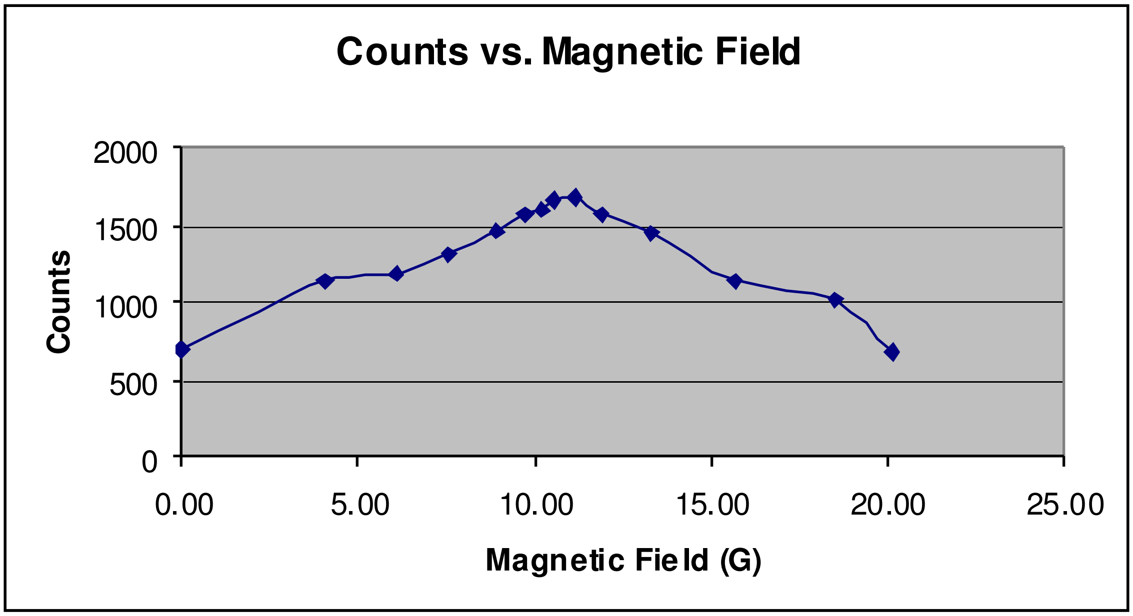


Fig. 14

Example of a graph from the adjustment of the perpendicular magnets to help align the beam better in the middle of the pipe.

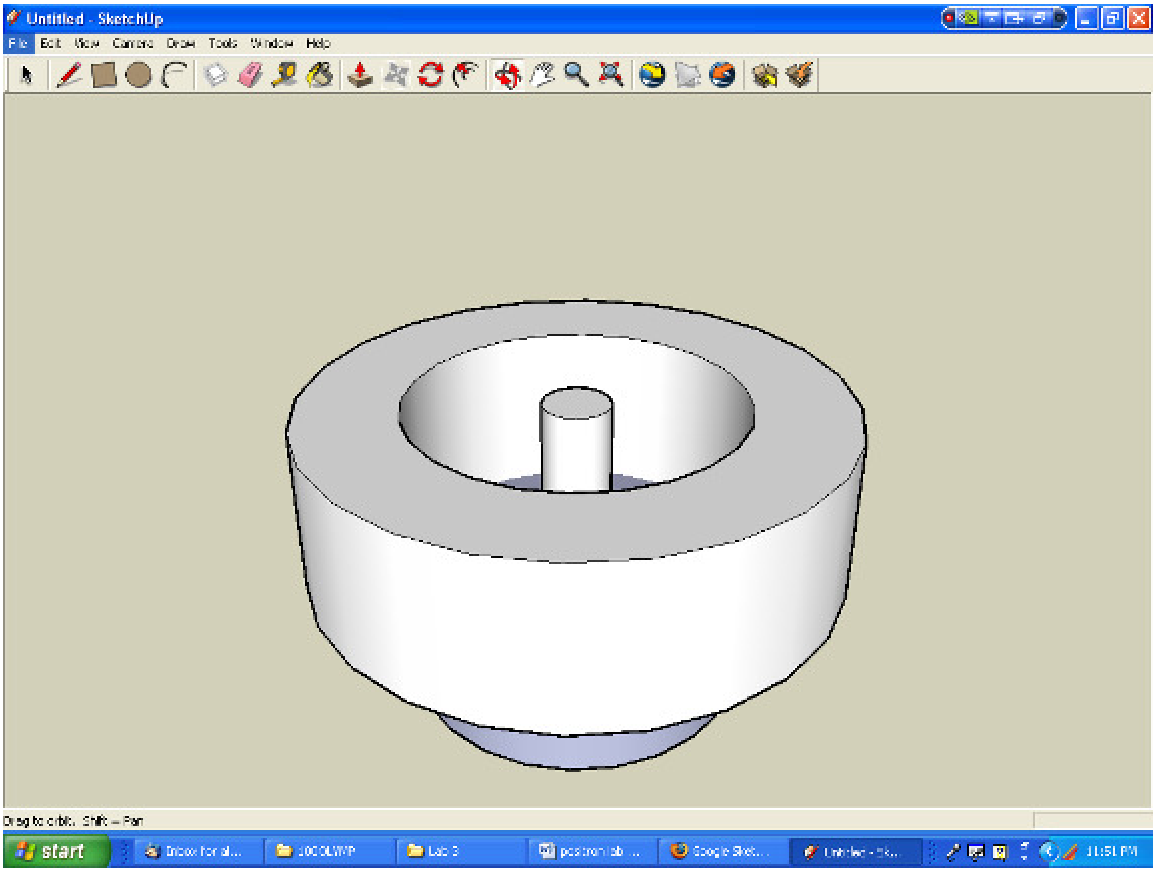


Fig. 15

Proposed aluminum source base. Stacks of copper sheets 1 micron thick are to be placed on the small center pedestal.

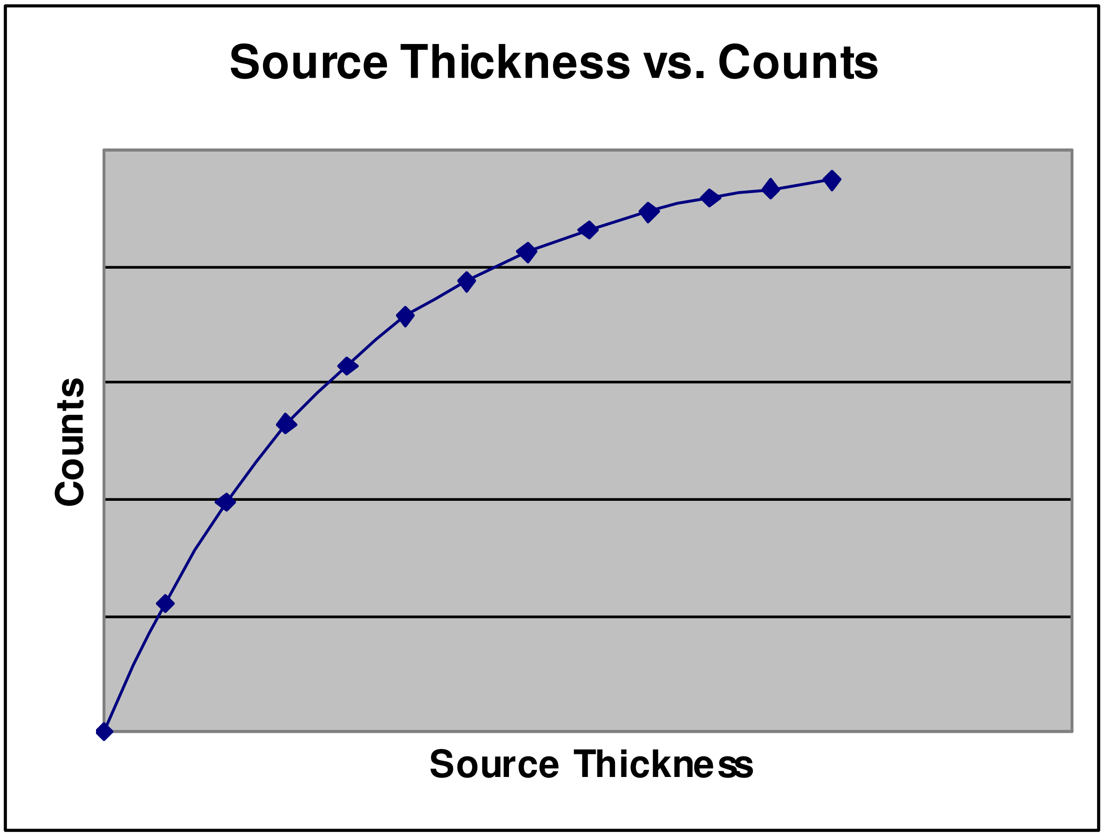


Fig. 16

Example of the graph we hope to see after out testing.

V. Analysis

The first graph in the experimental data section (Figure 12), a number of important factors can be observed. The peak occurs at 511 keV which is equal to the energy of a gamma particle released from the annihilation between a thermal positron and an electron. Thus, the peak observed is the one resulting from the annihilation and not a peak from external sources. The peak has a width. This results from two different effects occurring during the annihilation. The peak's base ranges from 464 keV to 512.5 keV.

The area under the peak above the background results from the addition of kinetic energy that results from the collision of the positron and electrons within the solid. The width shows the finite energy resolution of the NaI detector as seen in Fig. 12.

Using the data obtained from the tests, the number of positrons/sec incident on the target can be calculated. To find the actual number of positrons annihilating per second using our detector we had to use a few different concepts.

The counts/sec are divided by the total time (in seconds) by 2 since 2 gammas per annihilation are produced. In this case, the tests were run for 600 seconds. All of the gammas that are emitted from the target don't hit the detector, only some of them do. To find this ratio we need to account for the solid angle. Imagine a surface area of a sphere surrounding the target with a radius equal to the distance from the detector to the target. All of the possible directions and locations the positrons are at this distance from the target. No direction is favored so the sphere is an ideal shape to use for each reaction of the 2 gammas to be emitted about 180 degrees from each other in the lab frame. The detector only seeing some of the gammas but we can use the solid angle to correct for this. The acceptance cone is given by:

$$\Omega = \frac{A}{4\pi r^2} \tag{4}$$

Where r is the distance from the target to the detector and A is the surface area of the detector that detects the gammas. One step remains, to put it all together. By using the equation below, the # of counts that are received from the NaI detector can be converted into the number of positrons/sec entering the target if the detector has a detection probability of 1:

$$\frac{positrons}{\sec} = \frac{\#\, of counts}{t\Omega} \tag{5}$$

Where t is the number of seconds the test was run for and Ω is the solid angle defined above.

The positron test results show a few trends: Generally, as the voltage accelerating the positrons increases, so does the counts/sec. Also, as can be seen from Table 2, a slight change in the applied current to the magnets affects the field inside and changes significant numbers of positrons reaching the target. Higher voltages applied are therefore desired since the number of positrons reaching the target increases so the high voltage power supplies were switched out for this reason but the new power supply shorted above 6 keV.

The differences in the new and old copper sources are improving on the errors in the original design are analyzed here. I will also talk about the aligning process of the beam and the expected outcome from the tests.

The new source has a couple of refinements that will really help the project. First, it is recommended that we move the source to moderator distance from 2 mm to 0.5 mm to allow for less of a surface area spread on the moderator leading to a more focused beam. Next, the copper source size should be smaller. Previously the source was roughly 10 mm in diameter. This is much larger than the effective area of the moderator and causes a large spread which makes it very hard to focus. We propose to make it the same size as the Na-22 source, 4 mm^2 to make the beam more localized and easier to focus when switching between the Na-22 source and the copper source. The island feature of the source is to make sure that the source is truly in the middle of the holder and allow for easier focusing. By varying the thickness of the foils, we expect to find the optimum thickness of the foils for maximum output. The alignment of the magnetic fields is less critical. With some small adjustments, almost no change is seen since the target is just on a different area of the graphite block and still produces full output. The fall off to the right and left comes when the bending does not guide the positrons directly down the pipe or the adjustments of the beam before it reaches the bending magnet are shift too far off center. Through these methods we will make an optimum source and then focus on the next problem, the moderator.

VI. Conclusion

Overall, the vacuum chamber improvements and aluminum source holder design worked quite well. Time turned out to be an issue since the tests on the new design for the holder and copper foils could not be carried out. We had a few set backs, the vacuum chamber and its components breaking down and not working as well as we had hoped; also waiting for the copper foils to come in that put us behind schedule. The mechanical and magnetic refinement will definitely help to make this apparatus a more promising project and hopefully yield a very strong positron beam that can be used for a variety of applications, especially short time positron imaging.

VII. References

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