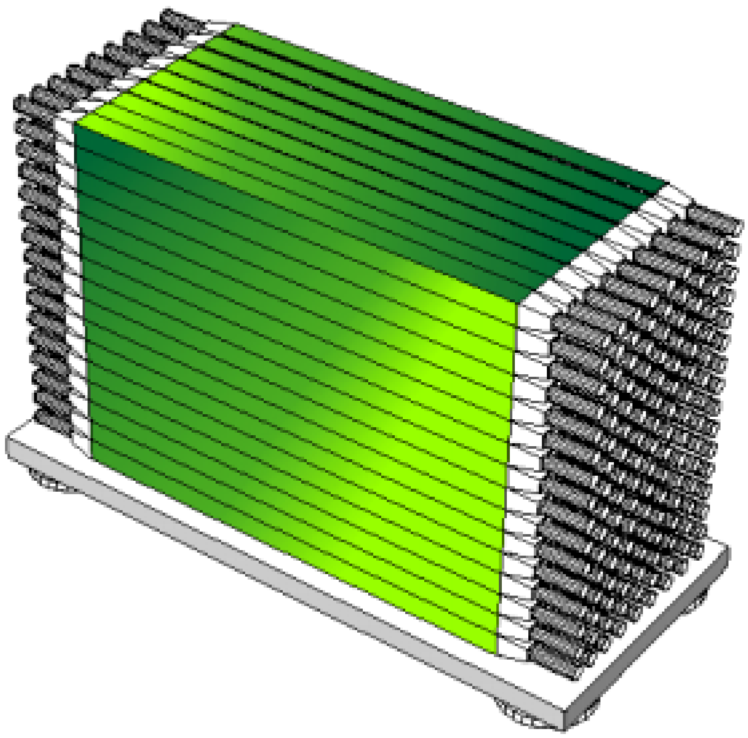
The MoNA Project

Module Assembly and Testing Manual



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Outline

Chapter 1: The MoNA Project

1.1 Nuclear Physics at the Neutron Drip-Line

There are slightly less than 300 stable isotopes that comprise the 82 stable elements that are found in nature. On Earth a few additional (unstable) isotopes can be found. These unstable isotopes are radioactive — they decay to other isotopes. The average time for a specific isotope to decay (its lifetime) can range from less than a thousandth of a second to billions of years. Short-lived isotopes cannot be found naturally on earth — they have long decayed since the earth was formed some billions of years ago. Yet, thousands of short-lived isotopes are continually created in the cosmos. They may have only a fleeting existence, but they play a crucial role in the still ongoing creation of the elements in the cosmos, as they did in the creation of the elements in our solar system billions of years ago.

The *chart of the nuclides*, shown in figure 1.1, plots nuclei in terms of the number of protons and neutrons in each isotope. The black squares indicate stable nuclei while the yellow region indicates those unstable nuclei that have been measured or created in the laboratory. The green region describes the isotopes that are predicted to exist by theoretical calculations but have yet to be experimentally produced. The edge of the green region is determined by the heaviest and lightest isotope for each element that is predicted to exist. These boundaries describe the nuclear drip-lines. The actual positions of the drip-lines are poorly known. The neutron drip-line is particularly uncertain.

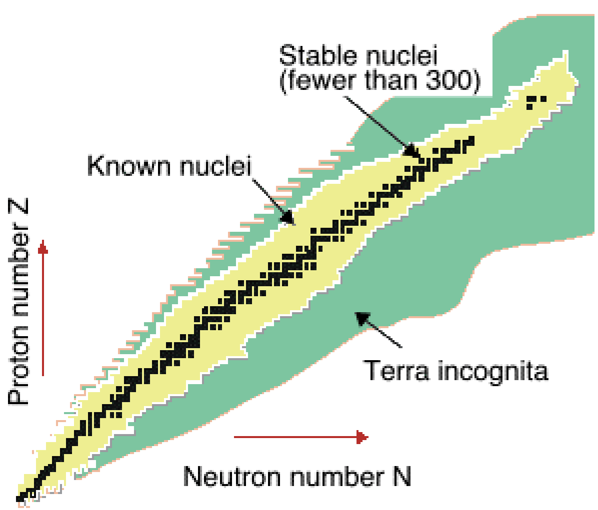

Figure 1.1: The chart of the nuclides

The study of nuclei close to the neutron drip-line and the investigation of nuclear systems even beyond the drip-line has greatly expanded in recent years. This increased interest is based on new phenomena that already have been observed or that are predicted to occur in these nuclei. At the neutron drip-line, the binding energy of a single neutron vanishes, leaving a system that is unbound with respect to prompt neutron emission. So far, the study of neutron-rich nuclei has been limited to the lightest elements, and the neutron drip-line has been experimentally verified only up to oxygen ($Z = 8$). With the coupled cyclotron facility, it should be possible to determine the actual position of the neutron drip-line up to sulfur ($Z = 16$). This will offer a large number of neutron-rich systems to be studied for the first time. Near the neutron drip-line, sequences of isotopes with odd neutron numbers are encountered that are unbound, while the next heavier isotope with even neutron number is bound. The investigation of these neutron-unbound systems can provide important insight into the interaction between nucleon and nucleus far from stability.

New phenomena that have been observed so far in nuclei close to the neutron drip-line include nuclear systems with very diffuse surfaces caused by loosely bound states of low angular momentum, which are referred to as halo states due to their large spatial extension. For light nuclei like ^{6}He, ^{11}Li, and ^{11}Be, theoretical few-body calculations lead to quite accurate descriptions of their experimental properties. Only recently could these studies be extended to heavier systems, revealing more complex structures. Furthermore, nuclear closed shells, which manifest themselves in especially stable systems with magic numbers of nucleons, are found to wash out towards the neutron drip-line. Collective excitations are also affected significantly by the large N/Z ratio of neutron-rich nuclei. The shift of giant dipole resonance strength to lower energies has been predicted, and soft modes of giant resonances are studied in light halo nuclei.

An already well-established technique to study neutron-rich systems is to measure the products of a breakup reaction. In order to be able to make a full reconstruction of the nucleus before the breakup, the detection of the neutron (or neutrons) in coincidence with the charged breakup fragment is necessary. Although breakup cross sections for loosely bound systems are relatively high, the beam intensities for these extreme nuclei are typically low, and a highly efficient detector is especially needed if one wants to study the correlation of multiple neutrons. Breakup reactions also have been applied to form neutron-unbound states, where the effects of final-state interaction are revealed by measuring the constituents of the unbound state in coincidence.

1.2 The National Superconducting Cyclotron Laboratory (NSCL)

Funded primarily by the National Science Foundation and Michigan State University, the NSCL operates two superconducting cyclotrons. The K500 was the first cyclotron to use superconducting magnets, and the K1200 is the highest-energy continuous beam accelerator in the world. The two cyclotrons are coupled together with the K500 accelerating the nuclei up to 20 MeV/nucleon before sending them into the K1200 for acceleration up to the 100 MeV/nucleon range.

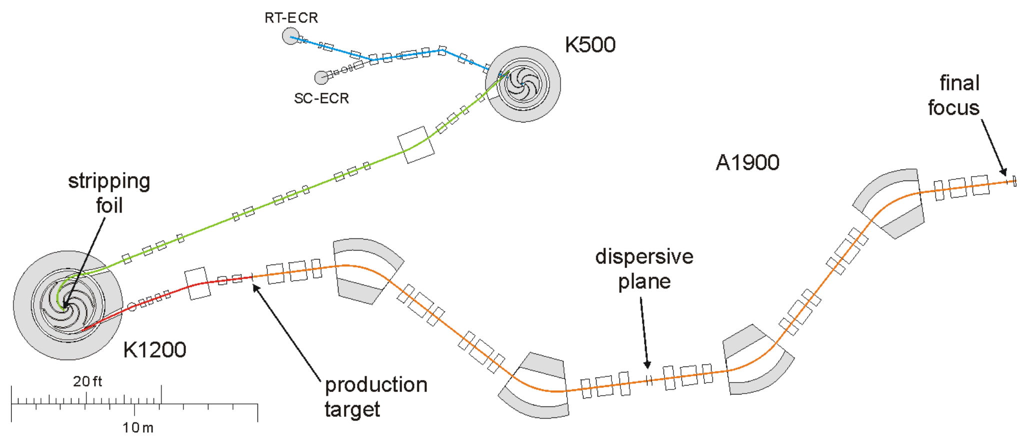

Figure 1.2: The coupled cyclotrons and the A1900 fragment separator.

Radioactive nuclear beams are created using a fast fragmentation method. A primary beam is accelerated by the coupled cyclotrons and strikes the production target. A wide range of nuclei are created at the production target. The nuclei of interest are selected using the A1900 fragment separator and sent to the appropriate experimental areas. The coupled cyclotron facility at the NSCL can provide a wide variety of neutron-rich nuclear beams for study.

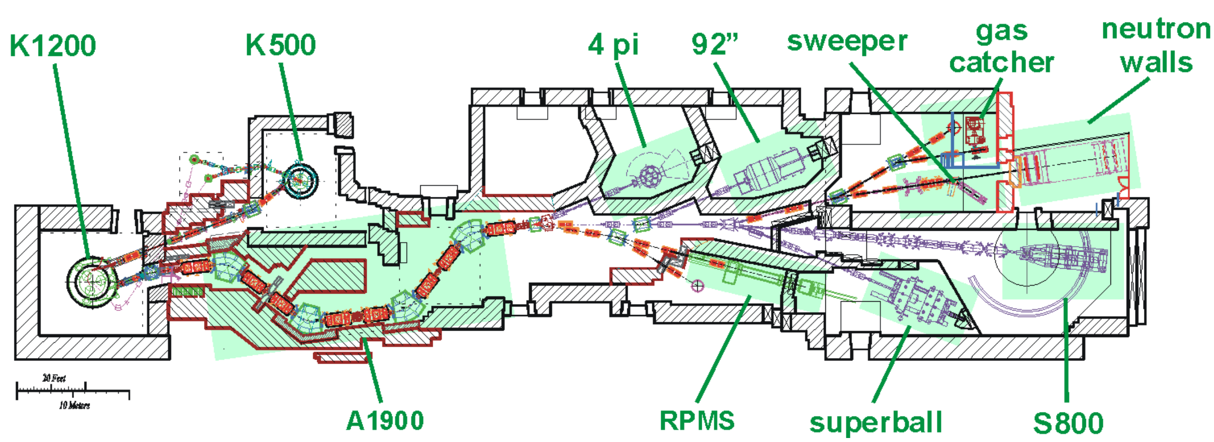

Figure 1.3: A diagram of the cyclotrons and the experimental areas at the NSCL

1.3 The Modular Neutron Array (MoNA)

In order to take advantage of the capabilities of the coupled cyclotron facility at the NSCL a highly efficient neutron detector optimized for neutron energies between 50 and 250 MeV has been designed.

The Modular Neutron Array (MoNA) consists of 144 individual detector modules. Each module is based on a 200 x 10 x 10 cm^3 block of BC-408 plastic scintillator. The modules are stacked in nine vertical layers of sixteen scintillator blocks giving a detector volume of 2.0 x 1.6 x 0.9 m^3. In addition to the plastic, the detector also incorporates thin layers of steel, which has a much higher density and therefore yields more reactions with the neutrons. The charged particles that exit the steel are detected in a following scintillator layer.

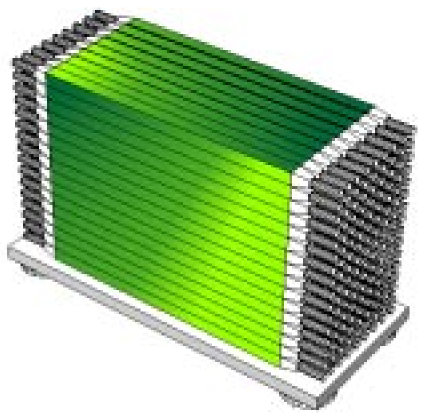

Figure 1.4:
A perspective front view of the simulated MoNA detector, showing plastic scintillator blocks (green) fitted with light guides and phototubes, and the iron plates (black).

In the detection process neutrons collide with protons in the scintillator bars. The recoiling protons excite molecules in the scintillation material that give off flashes of light as they deexcite. The ends of each detector bar are fitted with photo-multiplier tubes to convert the light into usable electrical signals. The position along the block where the light is emitted is reconstructed by measuring the time difference between the signals from the two phototubes. The energy of the neutron can be determined by measuring the time of flight between the target and the interaction position in the detector.

The neutron detector is designed to have a detection efficiency of approximately 70% for neutron energies between 50 and 250 MeV. In order to yield a high sensitivity for neutrons above 100 MeV, thin layers of iron will be used as a passive converter material. The reason for adding iron to the detector volume is that the nuclear interaction length (at high particle energies) for this material is only around 17 cm, while it is 80 cm for plastic. If the amount and distribution of iron layers between the scintillator layers are chosen correctly, the overall thickness of the detector can be reduced while maintaining a high detection efficiency.

1.4 The MoNA Collaboration

The institutions participating in the MoNA collaboration are Michigan State University, Florida State University, Ball State University, Central Michigan University, Concordia College at Moorhead, Hope College, Indiana University South Bend, Millikin University, Western Michigan University, and Westmont College.

Each of the layers will be constructed and tested by one of the nine institutions in the collaboration. The layers will then be brought to the NSCL on the campus of Michigan State University where they will be assembled into the final MoNA detector configuration. The MoNA project will involve a large number of undergraduate students from the collaborating colleges and universities and give them the opportunity to take part in cutting-edge research at the forefront of nuclear physics.

Chapter 2 Detector Module Operation

2.1 The Scintillator Bars

Scintillating materials are used to detect particles via fluorescence. This is the process by which visible light is emitted when a substance is excited in some manner. In particular the passage of charged particles through a fluorescent material can excite it hence a variety of particle detectors are based around scintillating substances.

The core of each MoNA detector module is a 10 x 10 x 200 cm^3 block of *organic plastic scintillator*. The fluorescence process in organic scintillators is based on the excitation of single large organic molecules. These molecules deexcite through a series of radiationless transitions to lower states which in turn drop to the ground state through the emission of photons of visible light. The time scale for the deexcitation process in most organic scintillators is a few nanoseconds. The number of photons emitted by the material is proportional to the amount of energy deposited in the scintillator. (The relationship between number emitted photons and energy deposition is actually somewhat complicated and depends, among other things, on the particle type. For more details, see the discussion of Birks' formula in Knoll pg. 227-229.)

Plastic scintillators are made by dissolving the organic molecules in a solvent and then polymerizing the solution into a solid. These scintillators can be easily manufactured in a wide variety of shapes. They are also relatively inexpensive allowing large detectors like MoNA to be constructed at reasonable costs.

One important consideration in using large pieces of plastic scintillator is the attenuation of the light signal. While the plastic is transparent to the wavelengths of the scintillation light a small amount of the light is absorbed or lost by imperfections and impurities in the material. The loss of light intensity (photons) can be modeled approximately by

$$I = I_0 e^{-x/L}$$

where L is the attenuation length (typically on the order of 2 — 4 meters).

When choosing a material for neutron detection it is important to remember that the neutron does not cause the excitation of the material directly. As a neutral particle it does not interact significantly on the scale of atoms and molecules. Neutrons are detected in the scintillator by first colliding with a proton; the recoiling proton excites the organic molecules which in turn emit the scintillation light. In order to have good neutron detection efficiency, we need a substance that has a high proportion of hydrogen (protons) in it. BC-408, the material used in the MoNA blocks, has a hydrogen to carbon ratio of 1.104.

Once the scintillation light is produced it needs to be directed into the phototubes at each end of the detector module. Much of the light will strike the interior surface of the detector bar at a large angle to the normal and be totally reflected. (The index of refraction of BC-408 is 1.58.) To trap light that would normally exit the sides of the detector a wrapping of aluminized mylar is placed around the bar. At the each end of the bar an acrylic light guide is attached to match the bar end to the phototube shape and dimensions.

Figure 2.1:
The scintillator bars as delivered by Bicron. Each bar is enclosed in black plastic and tape to prevent light from entering the detector. The mounting flange and light guide extension can be seen at the end of the bars.

The scintillation bars were manufactured by the Bicron division of Saint-Gobain, Inc. In addition to producing the scintillation bars they attached the light guides and mounting flanges, wrapped the bars in the aluminized mylar, then sealed the them in black plastic and tape to prevent light entering the sides of the bars.

2.2 The Phototube Assembly

When the light reaches the end of the light guide it is converted to an electrical signal by the *photomultiplier tube* (PMT). These devices are designed to convert the weak scintillation light pulse, perhaps no more than a few hundred photons, to a useable electric charge pulse with a very good signal to noise ratio.

The photomultiplier used in MoNA is a cylindrical glass vacuum tube. One end serves as a transparent glass window while the other end has the pins that make the electrical connections to the voltage divider. The interior components of the PMT can be grouped into four main parts: the photocathode, the electron focusing system, the dynode string, and the anode. During operation high voltage is applied to the dynode string to create a ladder of electric potential from the first dynode to the anode.

Light enters into the phototube through the transparent window and strikes the photocathode. The photocathode is made from a material (usually Sb along with K and/or Cs) that produces a photoelectron via the photoelectric effect with high efficiency. The photoelectron is guided by the field created by the focusing electrodes to the first dynode. When the electron strikes the dynode it releases energy to electrons in the dynode causing secondary electrons to be released. These electrons are accelerated in turn to the next dynode where they release more electrons. This process proceeds down the dynode string amplifying the original electron by a factor of 10^3 to 10^8. At the anode the cascade of electrons is collected to give a current pulse. The cable connections for output signals and high voltage are provided by a voltage divider that connects to the pins on the stem of the PMT.

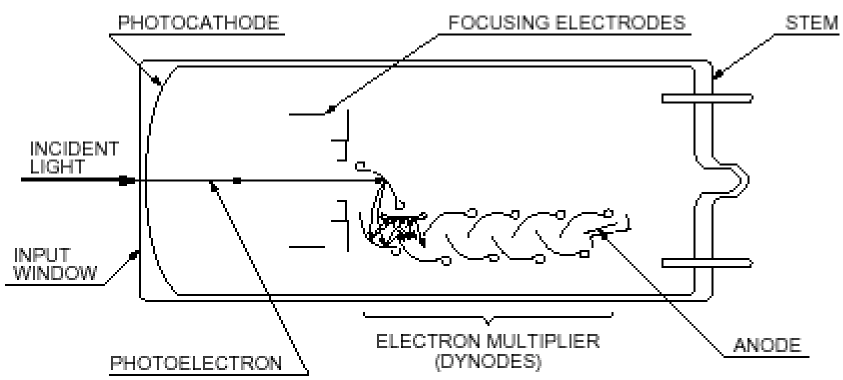

Figure 2.2: A schematic drawing of a typical phototube.

The photomultiplier tube chosen for MoNA is the Photonis XP2262B 2 inch tube. It has a 12 stage dynode string and a nominal gain of 3 x 10^7. It is considered a “fast” tube with a signal rise time of approximately 2.0 ns.

The photomultiplier tube should be handled with care. Like any glass vacuum tube it is fragile. It is also extremely susceptible to light. The tube should **never** be exposed to normal room light while powered with high voltage. This will permanently damage the photocathode. Even when the tube is not attached to voltage you should minimize the light exposure the photocathode receives. Never leave the phototube window exposed to room light for a prolonged period. The PMT will usually recover from room light exposure after a day or two if it was not under high voltage but repeated or prolonged exposure can degrade performance. The plastic cap should be used to cover the window if the PMT is being stored. This will also prevent scratches and dirt.

The operation of the photomultiplier tube can also be disturbed by magnetic fields. The electron focusing and cascade can be distorted by magnetic field lines penetrating the PMT. In order to minimize this a metal alloy with a high magnetic susceptibility can be used to shield the tube. In the MoNA design a sleeve of mu-metal acts as a magnetic shield as well as providing mechanical support for the phototube. The mu-metal should not be subjected to mechanical shocks or heating as this will destroy the magnetic properties of the alloy.

2.3 Electronics Overview

In the MoNA design three important pieces of information will be extracted from a module when a possible neutron event occurs. These signals are the arrival time of the signals a the individual phototubes, the size of the individual photo-multiplier signals and the average arrival time of the two phototube signals. The time signals can be measured versus either the cyclotron RF signal or a start pulse from a detector placed in front of the target.

The electric pulse from each phototube is sent to a charge to digital converter (QDC) that measures the amount of charge in the pulse. The signal is also sent to a constant fraction discriminator (CFD). This module is designed to filter out signals with values outside a preset range and produce a logic pulse that is used for timing. The output of the CFD is sent to a time to digital converter (TDC) which measures the arrival time of the signal and to a mean timer input. The mean timer finds the average of the signals from the two phototubes. The digital output of the QDCs, TDCs and mean timer is read out and stored for analysis.

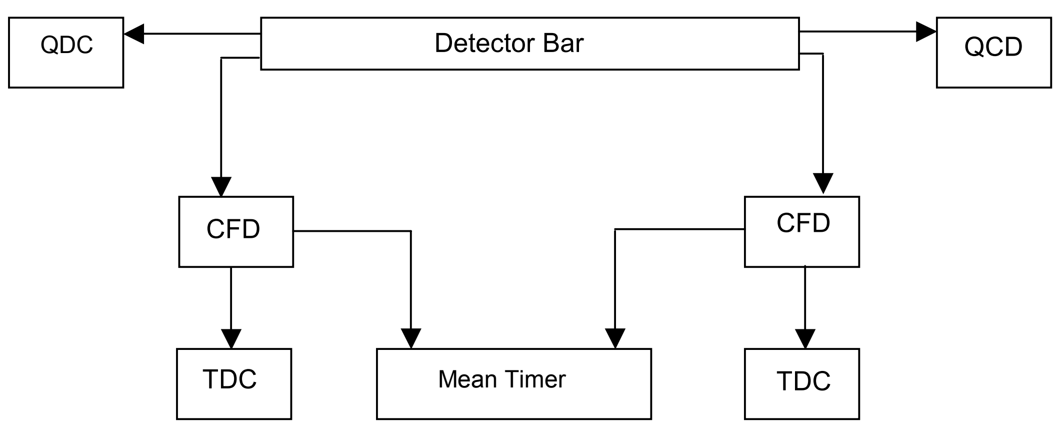

Figure 2.3: A simplified schematic of the MoNA detector module electronics.

Chapter 3 Mounting the Phototubes

3.1 Required Materials

The mounting of the phototube assembly onto the light guides is not complicated but it does require some care and precision. Before beginning make sure you have gathered all the required materials discussed below.

Figure 3.1:
The magnetic shield, phototube, voltage divider base and o-ring. (The shield in the figure is for the prototype bar and has 3 screw holes rather than the 4 on the actual module bars.)

In addition to the phototube, voltage divider base and magnetic shield you will need an o-ring with inside diameter 1-7/8", width 1/8" and outside diameter 2-1/8". You will need four ½" socket cap hex screws with a 10-32 thread size to attach the shield to the flange on the bars.

Black silicone caulk is used to bond the PMT and voltage divider inside the shield and black felt is used to provide a light tight seal between the flange and the shield. The phototube is wrapped in black electrical tape to provide insulation between the tube and the magnetic shield, sparking may occur across the air gap if the tube is not wrapped. In addition, black electrical tape is used to make sure that the seal between the shield and voltage divider is light tight.

Optical grease will be needed to make the light coupling between the phototube window and the light guide. Dow Corning 2Q-3067 Optical Couplant was used in the prototype test but Bicron BC-630 Silicone Optical Grease can be used as well. Wooden "popsicle sticks" work well as applicators of optical grease.

Finally you will need some ethanol and lint-free paper (e.g. Kimwipes) to clean the surfaces of the PMT and light guide. It is important to keep a clean work area when mounting the phototubes.

Figure 3.2:
The photograph shows some of the required materials and the light guide and flange test assembly (indicated by the arrow). The test assembly was used to try out various mounting techniques. The black felt has been cut to match the flange.

In summary, to mount a phototube assembly to the detector bar you will need:

- Photomultiplier tube
- Magnetic shield
- Voltage-divider base
- Black electrical tape (3/4 inch and 2 inch width)
- 4 hex socket cap screws with 10-32 thread and ½” length
- O-ring with 1-7/8” I.D. , 2-1/8” O.D.
- Black silicone caulk
- Black felt cut to match flange
- Optical Grease (Dow Corning Q2-3067 or Bicron B-630)
- “popsicle sticks”
- Black electrical tape
- Kimwipes or other lint free paper
- Ethanol
- Hex wrench

3.2 The PMT and Magnetic Shield

The first step in the assembly is to combine the PMT, voltage divider and magnetic shield. Black electrical tape is wrapped around the phototube to insulate the phototube from the shield. The PMT rests inside the shield and is held in the center by an o-ring. The PMT is connected to the voltage divider, and the voltage divider fits onto the edge of the shield. Silicone caulk is used to provide a mechanical bond between the shield and PMT assembly.

Before beginning be sure to carefully clean the phototube window and the interior of the magnetic shield with ethanol. You may want to record the phototube serial number for identification. Then wrap the phototube with ¾ inch width black electrical tape as shown in figure 3.3.

Figure 3.3: Black electric tape is wrapped around the phototube. Begin at the top of the tube (left) and wrap in a spiral pattern (right).

Figure 3.4:
A phototube completely wrapped in electrical tape. The tube type and serial number is written on the base for identification. You may want to mark the serial number on the outside of the magnetic shield the tube is placed into as well. The plastic cap covers the tube window to protect it from ambient light.

Place the o-ring around the PMT so that it is approximately centered on the tube, as shown in figure 3.5. Carefully insert the PMT into the magnetic shield from the side of the shield that has the flange as shown in figure 3.6. The PMT window has to face the flange when is has been inserted. Use a Kimwipe to avoid putting fingerprints on the phototube window. Push the tube so that the front face is approximately 3 to 4 cm inside the shield. The o-ring should ride forward so that it is near the front face of the PMT. Figure 3.7 shows the position of the PMT and o-ring. If the o-ring rides off the PMT, remove the tube and repeat the process.

Figure 3.5: The o-ring should be placed so that it is approximately in the center of the phototube.

Figure 3.6: Insert the PMT into the magnetic shield as shown. The front face of the PMT should be approximately 3 to 4 cm inside the shield.

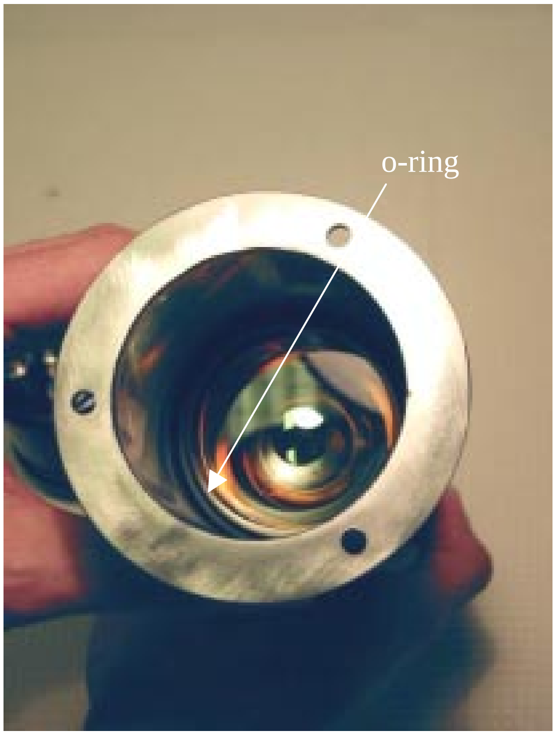

Figure 3.7:
The position of the o-ring after the PMT is inserted is shown.

Place the voltage divider base on the phototube. Note the position of the notch. Make sure that the gap between the tube and divider is closed. This may take some force. Be sure that you have aligned it correctly.

Figure 3.8:
Align the voltage divider base and push it down flush with the phototube. The face of the tube is held inside the shield. A paper wipe is used to avoid fingerprints on the front of the tube.

The voltage divider base will be bonded to the shield by silicone caulk. Using a caulk gun place a line of black silicone around the voltage divider as shown in figure 3.9. When you have finished push the voltage divider down flush on the magnetic shield and wipe away any excess silicone. The voltage divider might drift outwards because of the o-ring, in which case it should be held in place till the silicone caulk begins to harden.

Figure 3.9:
Place a line of black silicone caulk around the phototube/base as shown.

Figure 3.10:
Push the base down flush with the magnetic shield and wipe away any excess silicone caulk.

Place the phototube assembly in an upright position with the flange side down. This is to protect the photocathode of the tube from the room light. Allow the silicone caulk to cure. This should take no more than 24 hours. (Check the instructions on the silicone caulk tube.)

3.3 Optical Coupling and Light Tightness

The phototube has to be optically coupled to the light guide in order to minimize light loss at the interface between the light guide and the photomultiplier tube window. A clear, colorless silicone grease with an index of refraction similar to the light guide and phototube window is placed between the two surfaces for this purpose.

Optical coupling is crucial to good performance of the detector module. The key is to use the correct amount of optical grease and apply a roughly uniform pressure when making the seal. For our assembly a “blob” of grease with approximately the area of a dime and about ½ cm high works well. Figure 3.11 shows the proper amount placed on the light guide and flange test assembly. If the tube is mounted correctly the optical grease will completely fill the area between the phototube window and the light guide with no bubbles or air pockets. Figure 3.12 shows a phototube mounted on the test assembly. You can see that the grease has made a good coupling between the light guide and the PMT window.

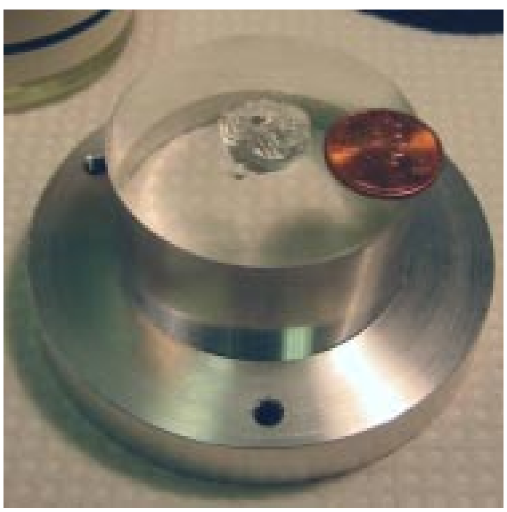

Figure 3.11:
The “blob” of optical grease placed on the test assembly. A penny is shown to give a sense of scale.

Before you begin with the coupling process you will need to cut out a ring of black felt that matches the flange. A cardboard stencil is very helpful with this task. The screw holes can be made with a handheld hole punch. The black felt will go between the flange mounted on the light guide and the flange on the magnetic shield to make a light tight seal.

Be sure that the light guide is free of dust and other particles. The Styrofoam packing material can leave small pieces on the guide. You may want to clean the bar of Styrofoam pieces before proceeding. Tack cloth can be used on the covered part of the bar (but not on the light guide). Clean the light guide end and the phototube window with ethanol and a lint-free wipe. Place the black felt on the magnetic shield flange and hold it in place with the hex screws as shown in Figure 3.13.

Place a “dime-sized” blob of optical grease on the center of the light guide as shown in figures 3.14 and 3.15. It is not advisable to spread the optical grease since this will create more air bubbles. A nice uniform (convex) blob in the center works best because it will push out the air once the gap closes.

Figure 3.12: A photograph looking into the light guide of the test assembly. The optical coupling is smooth showing no air pockets or dust particles.

Figure 3.13: The felt ring is placed on the magnetic shield flange and held in place by the hex screws.

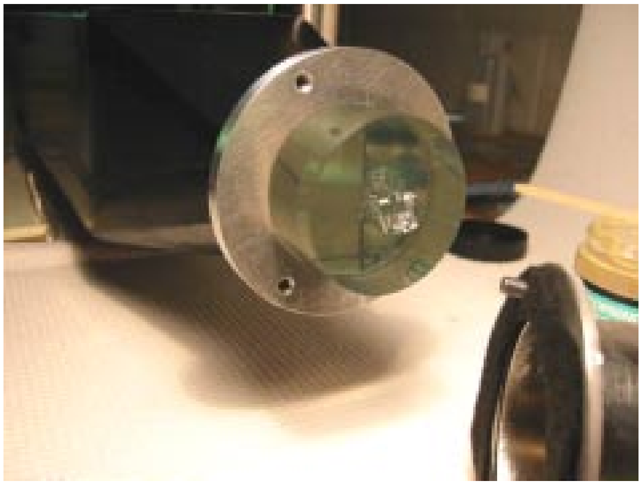

Figure 3.14: The “blob” of optical grease placed at the center of the light guide face.

Figure 3.15: Another view of the amount of optical grease placed on the light guide.

Line up the screws and place the phototube assembly against the light guide. Provide a steady even pressure and loosely tighten the screws. Then slowly tighten the screws down the rest of the way a few turns at a time, moving from one screw to the next to maintain a uniform tightness. As you tighten the screws, you might notice a small gap forming between the voltage divider and the shield. This is an indication that the screws are tightened sufficiently. The gap should remain very small, otherwise the silicone bond is broken and you will have to start from the beginning. It is important not to over tighten the screws as this may strip the thread in the flange but make sure the gap between the flanges is light tight.

Figure 3.16: Tighten down the hex screws evenly so a uniform pressure is maintained across the surface of the light guide.

Once the screws have been tightened wait for about 10 minutes to make sure that the silicone seal is holding. Wrap black electrical tape around the junction between the magnetic shield and the PMT to insure that it is light tight.

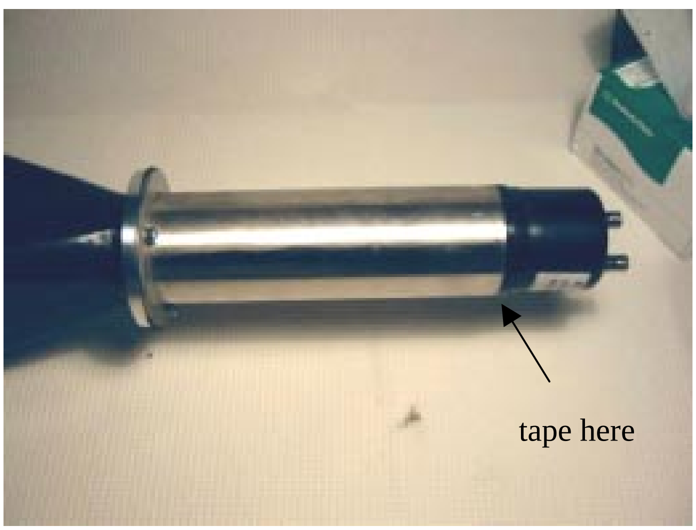

Figure 3.17: Wrap black electrical tape around the join between the magnetic shield and the PMT.

The black epoxy used by Saint-Gobain to seal the flange to the light guide does not provide a perfect light tight seal. Wrap 2 inch width black electrical tape around the back section of the flange as shown in figure 3.18. This should provide a light tight seal.

Figure 3.18:
The 2 inch wide black electrical tape is used to make a light seal at the back of the flange.

Congratulations, you have a completed phototube assembly!

Chapter 4 Signal Testing

4.1 Sources and Cosmic Rays

In order to test the detector modules we need sources of radiation. There are two easily available sources: cosmic rays and low-level gamma sources.

The Earth is constantly bombarded by high energy cosmic rays from our Sun and other sources throughout the galaxy. These cosmic rays are primarily protons with a smaller component of heavier ions. They have extremely high kinetic energies ranging from 1 GeV to 10^{10} GeV and higher. Few of these primary cosmic rays reach the surface of the Earth but instead interact in the Earth's atmosphere producing showers of secondary particles. A tremendous variety of secondary particles are created but roughly 80% of the secondary charged particle flux that reaches the ground is made of high energy muons. The mean energy of these muons is about 4 GeV with a relatively flat energy dependence below about 1 GeV. The flux at sea level is about one muon per cm^2 per minute with an angle dependence of $\cos^2\theta$ where θ is the angle from the zenith.

The cosmic ray muon flux provides a spatially uniform background for our detectors. As the muons have an extremely high kinetic energy they have a relatively low specific energy loss (dE/dx). The energy distribution of the muon flux gives a peak in the energy deposition at 2.0 $MeV \cdot g^{-1} \cdot cm^2$. With a density of 1.032 g/cm^3 and a thickness of 10 cm this yields a peak of 20.7 MeV in the detector bars. Figure 4.1 shows the cosmic ray muon peak in the amplitude spectrum taken from one bar end. The cosmic ray spectrum is useful as a basic test of the operation of a detector bar and as an energy calibration point for the detector.

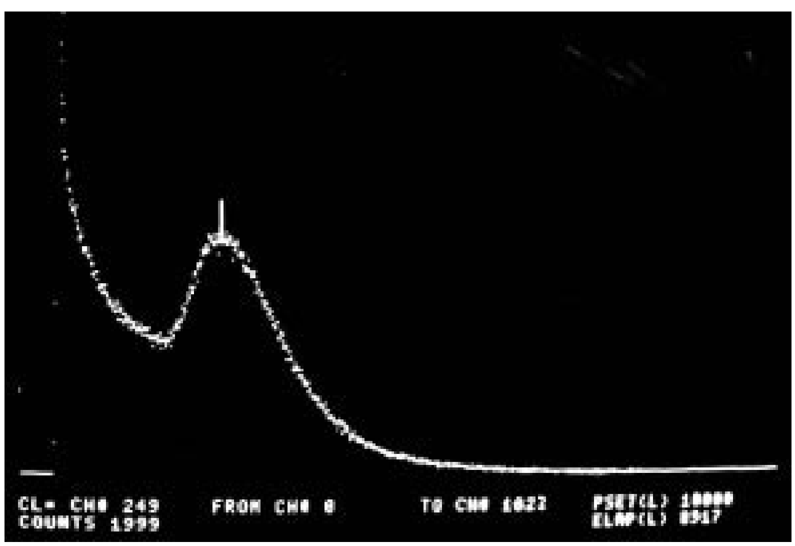

Figure 4.1: The cosmic ray spectrum taken from a detector bar. Notice the prominent peak corresponds to an energy deposition of 20.7 MeV in the bar.

Low-level gamma ray sources provide another method of investigating the properties of the detector bars. Sources such as ^{137}Cs and ^{207}Bi can provide lower energy gamma rays. The ^{137}Cs source emits a 661.7 keV gamma ray and ^{207}Bi has gamma emissions at 569.7 keV and 1063.7 keV. The radioactive sources do not need to be very active. All the measurements done for the manual used a 7.0 μCu ^{137}Cs source and a 10.0 μCu ^{207}Bi source. As with the cosmic ray muons these sources can provide calibration points for the detector. The main advantage of radioactive sources over the cosmic ray flux is that the gamma-ray source is localized. It can be placed along the bar providing events at different positions along the detector module.

4.2 High Voltage

The photomultiplier tubes require high voltage to operate. The operating range of the tubes is between –1500 and –2400 Volts. A nominal value of –2000 Volts is assumed for the tests.

Remember to take care when dealing with high voltage sources. Turn the voltage up and down slowly. If you are not running a test turn off the voltage when you leave the work area. Be sure that the high voltage sources are clearly marked and warnings are placed so as to be easily visible to anyone in the work area. Never connect or disconnect high voltage cables without first checking to see that the voltage has been turned off.

The high voltage connection on the voltage divider base is an SHV connection. It is the larger of the three connectors on the divider as shown in figure 4.2. Make sure you have the appropriate SHV cable. Standard BNC cables can **not** be used for high voltage.

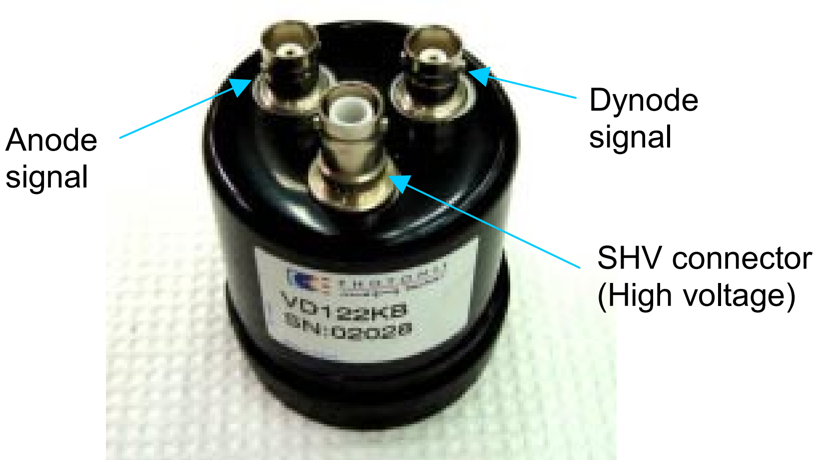

Figure 4.2: The connectors on the voltage divider.

4.3 Signals

Before you power up the phototubes to their operating voltage you should check for light leaks. Connect the anode output (see figure 4.2) to the oscilloscope. Set the oscilloscope at 50 mV and 10 ns. Trigger on a negative slope at about –50 mV. Cover the bar with an opaque material (black plastic trash bags work well) or turn the lights off in the room. Power the phototube up to ~ –1000V. Use a flashlight to shine along the bar ends and other areas that might have light leaks. If the oscilloscope trace suddenly increases in intensity when you shine the light at a particular area it is an indication of a light leak. If you do not see any indication of a light leak increase the voltage on the tube to its operating voltage (~ –2000V). Check again for light leaks.

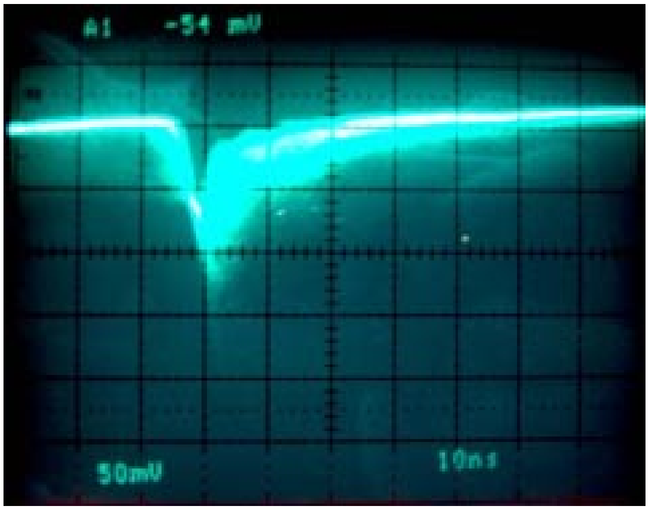

Figure 4.3:
A photograph of the oscilloscopes trace of the anode output of one of the bar end phototubes. The actual trace will not be so broad. This is an artifact of the camera.

Once you have a light tight detector bar look at the signal from the bar more closely. You should see a signal similar to the one in figure 4.3. For a 1 MeV gamma-ray the signal should be around 100 to 200 mV with the tube voltage set at approximately –2000V.

4.4 Pulse Height Spectra and the Multichannel Analyzer (MCA)

Once you have a good signal on the oscilloscope you can use a multichannel analyzer to look at the pulse height spectrum of the phototube signal. A multichannel analyzer is a device that sorts incoming pulses according to pulse height and keeps count of the number of pulses at each height in a multichannel memory. Each memory channel or “bin” contains the number of pulses between two adjacent pulse height values The values in the channels can then be displayed in a histogram format giving the pulse height spectrum associated with the signals from the phototube. Multichannel analyzers come in a wide variety of styles from standalone units to cards and software for personal computers.

The pulse height spectrum is closely related to the spectrum of energy deposited in the bar. When a particle deposits energy in the bar it causes the bar to scintillate. The number of photons given off in the scintillation process is proportional to the amount of energy deposited. These photons travel down the bar to the phototube. (Some photons are absorbed along the way due to attenuation in the bar. See Section 2.1) The photons strike the photocathode of the tube and create electrons. These electrons are amplified by the dynode cascade and an amount of charge proportional to the number of photons arrives on the anode. This pulse of charge is the signal that is fed into the multichannel analyzer. The height of the pulse is proportional to the charge which is proportional to the number of photons reaching the phototube which is in turn proportional to the energy deposited in the bar. Therefore the pulse height spectrum is proportional to the energy deposited in the bar by the particle.

The signal coming directly from the anode of the phototube is usually too small to be used by the MCA directly. It needs to be amplified. Some MCAs have built-in amplifiers while others will require an external amplifier. Check the manual for your MCA to determine if an external amplifier is necessary.

One problem that can arise is incorrect impedance matching between the cable and the MCA input. In this case the signal shows multiple peaks as shown in fig 4.4. This is know as “ringing”. To eliminate this you can use a 50Ω impedance barrel or terminator between the cable end and the MCA input.

Figure 4.4:
The “ringing” caused by incorrect cable termination.

The cosmic ray spectrum shown in figure 4.1 is a pulse height spectrum taken from one of the phototubes on a detector bar. The amplifier gain was set at 30. The peak position in the pulse height spectrum corresponds to an energy deposition of 20.7 MeV in the detector. Figures 4.4 and 4.5 show the pulse height spectra for ^{137}Cs and ^{207}Bi respectively. Both of these spectra were taken with an amplifier gain of 900 and the sources were placed at the center of the detector bar. The peaks in the pulse height spectra correspond to the gamma-ray energies of the sources. They lie on top of an exponential background that is characteristic of large plastic scintillators.

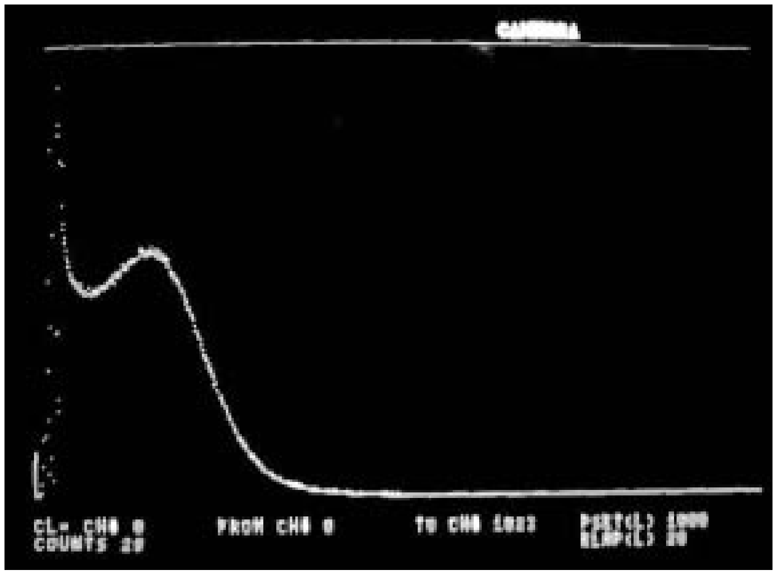

Figure 4.4: The pulse height spectrum from one phototube for a ^{137}Cs source placed at the center of the bar. Amplifier gain was 900.

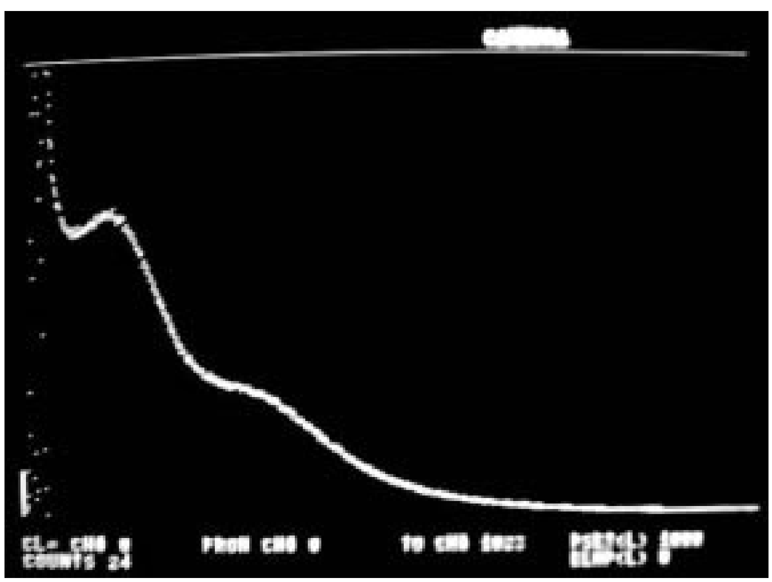

Figure 4.5: The pulse height spectrum from one phototube for a ^{207}Bi source placed at the center of the detector bar. Amplifier gain was 900.

Chapter 5: Detector Bar Tests and Attenuation Lengths

5.1 Gain Matching

The first step in testing the detector modules is to match the gain on the phototubes. The amplification of the photoelectrons created when photons strike the cathode of the phototube is controlled by the voltage applied to the tube. For good performance you want the two ends of the bar to give the same signal for the same number of photons reaching the bar ends. This can be achieved by adjusting the applied phototube voltage.

First you need to be sure that each end of the bar is receiving the same number of photons. There are two possible ways to do this. One method is to use the cosmic rays. As all parts of the bar (with minor exceptions) are illuminated equally by the cosmic ray flux the symmetry of the modules implies that each bar end will on average receive the same total number and distribution of photons. The other method is to place a radioactive source at the center of the bar. To a first approximation the bar symmetry once again requires that the number and distribution of photons on both phototubes is the same on average.

The method using a radioactive source is usually faster as the source activity is greater than the cosmic flux. The cosmic ray method is the one that will be used to gain match the tubes when MoNA is completed but it takes some what longer. Both methods should give the same results within error. You should try each method and determine which works better for your setup.

Regardless of whether you use cosmic rays or a source the method is basically the same. Apply a voltage of approximately –2000 Volts to each tube. Connect the anode output of one of the tubes to the MCA and take a pulse height spectrum. Record the channel number of the peak in your spectrum. Repeat the process for the other tube. If the channel numbers of the peak are not the same try adjusting the voltage on one of the tubes and repeat the process until the spectra match. Remember not to exceed –2400 Volts.

5.2 Calculating Attenuation Lengths

As the light signal travels down the detector bar toward the phototube some of the photons are absorbed. As discussed in section 2.1, this attenuation of the light pulse is modeled by

$$I = I_0 e^{-x/L}$$

where L is the attenuation length and x is the distance from the event to the phototube. The light intensity (i.e. the number of photons) is proportional to the pulse height. This means that as the distance of the scintillation event to the phototube in increases the position of the peak in the pulse height spectrum will be reduced.

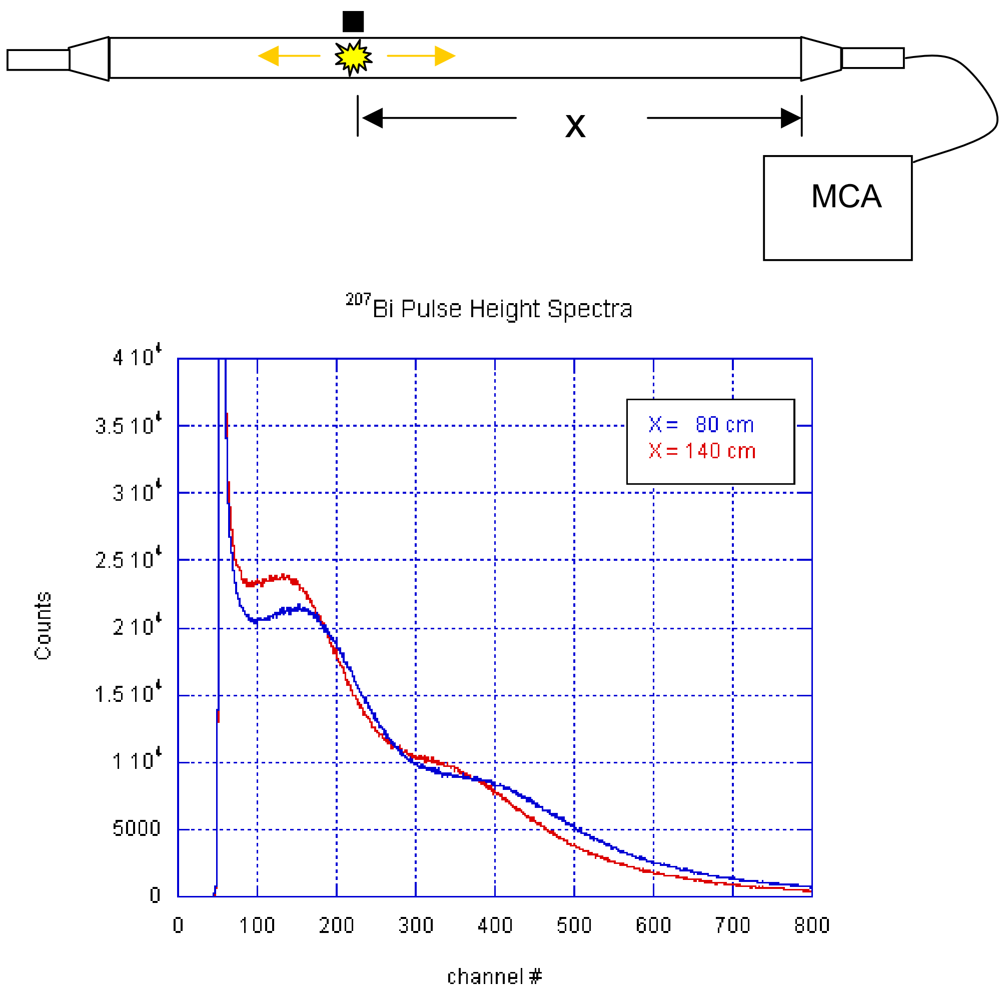

Figure 5.1 : A ^{207}Bi source is placed on top of the detector bar at a position x from the active phototube as shown in the schematic at the top. The plot below shows the raw pulse height spectra for x = 80 cm (blue) and x-=140 cm (red). Notice the peaks shift to a lower channel number as x increases.

As the pulse height is proportional to the intensity of the light reaching the tube, we can model the peak position of the pulse height spectra as

$$\text{Peak channel number} \propto e^{-x/L}$$

This relationship can be used to find the attenuation length.

Place the source at 20 cm intervals along the bar and record the peak channel # at each position. The plot of the peak channel # vs. position along the bar should be an exponential curve. Fit the curve with an exponential function and extract the attenuation length.

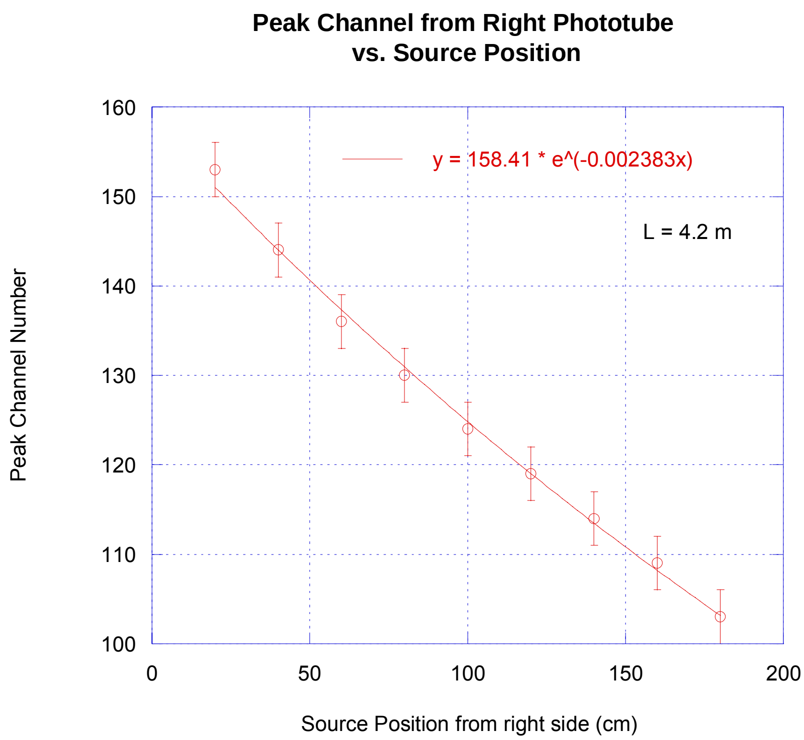

Figure 5.2: A plot of peak channel number vs. the source position using ^{207}Bi source. An exponential fit yields a value of 4.2 meters for the attenuation length.

The attenuation length should be on the order of 2 to 4 meters. Measure the attenuation length for each phototube. In general they will be different due to factors that are not taken into account by our model such as differences in the quality of the optical coupling between the light guide and the phototube. Nevertheless the attenuation lengths provide a good check on performance as well as useful information for calibration.

5.3 Position From Pulse Height

To first order the position of the event in the bar is related to the difference in pulse height at each phototube. This can be seen from our attenuation data. The difference in channel number of the peak positions measured at the two phototubes should be a linear function of the position of the radioactive source along the tube:

$$(\text{Peak Position})_L - (\text{Peak Position})_R = AX + B$$

where X is the distance from the right end of the bar and A and B are constants.

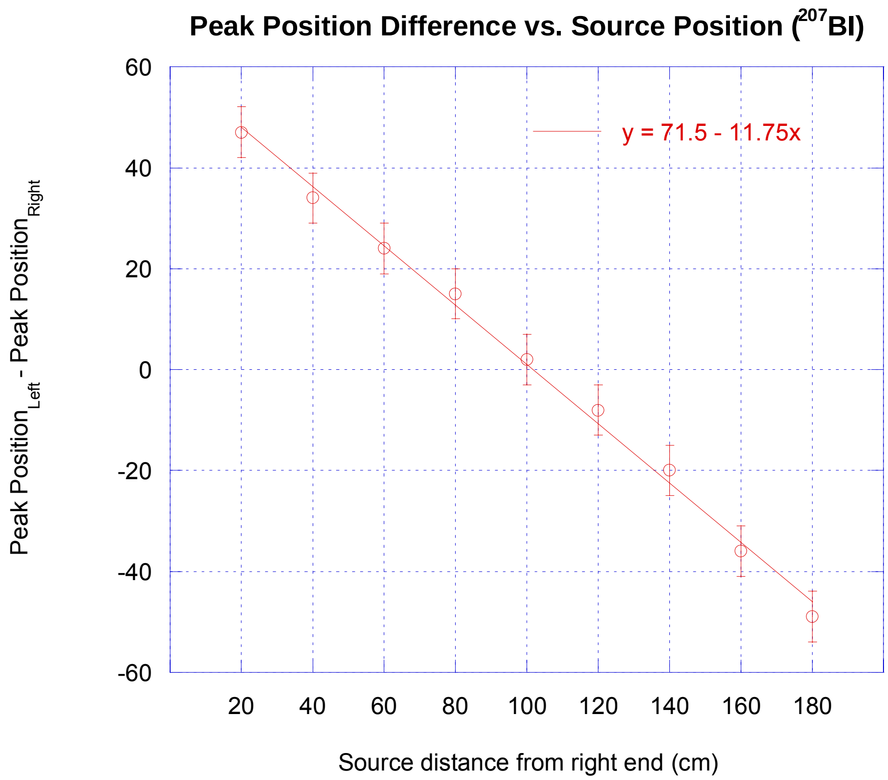

Figure 5.3: A plot of peak channel difference vs. source position using ^{207}Bi. A linear fit yields y = -11.75 X + 71.5.

This method can be used in addition to the timing method to determine the position of the event in the detector.

Chapter 6: Time Measurements

6.1 Electronics Setup

In operation the MoNA detector will determine the horizontal position of a neutron event by comparing the arrival time of light signals at the phototubes mounted on each end of a module. Timing tests are therefore extremely important in determining how well the modules will function in the detector.

A time to analog converter (TAC) can be used to measure the difference in arrival times. The anode or dynode signals from the phototube are first fed into constant fraction discriminators (CFD) which produce a logic pulse whenever the magnitude of the input signal exceeds the threshold value set on the CFD. These logic pulses are sent into the TAC as a start and stop signal. The TAC output is a positive square pulse whose amplitude is proportional to time difference between the arrival of the start and stop pulse. The TAC output can be fed into the MCA to produce a pulse height spectra where the pulse height is proportional to time difference.

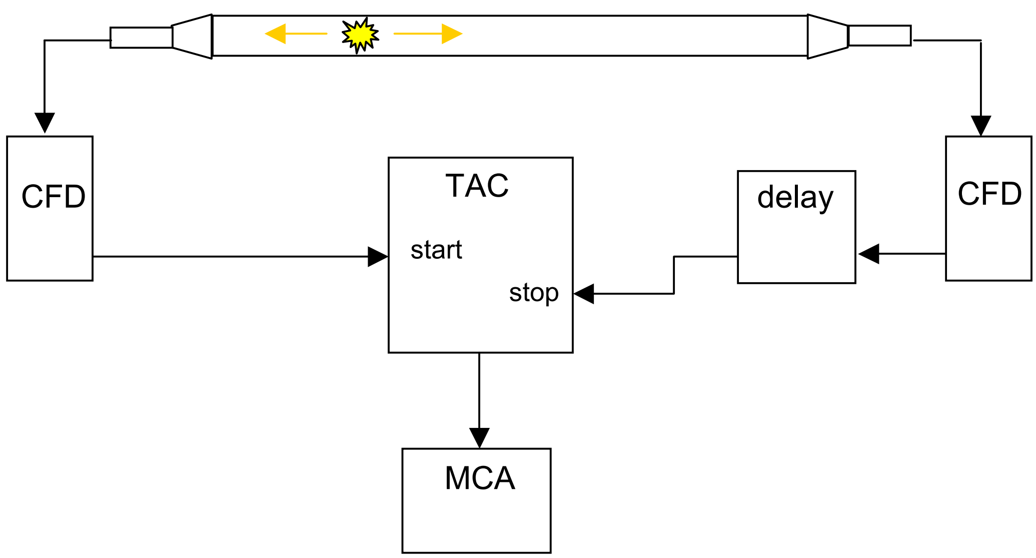

Figure 6.1: A schematic for a basic electronic setup to measure the difference in signal arrival time at the bar ends.

In order to guarantee that the stop signal arrives later than the start signal a delay is placed between one of the CFDs and the stop input on the TAC. A delay of 20–40 ns should be sufficient.

6.2 Cosmic Ray Measurements

The cosmic-ray muon flux provides a source of events in the detector module that is roughly uniform along the length of the detector bar. The pulse height spectrum should look like a rectangular waveform (see figure 6.2) with the width in channels corresponding to the length of the bar. Because the cosmic muons deposit a relatively large amount of energy in the bar (20.7 MeV) the discriminator level can be set quite high to eliminate random background counts. (Remember that in this case the cosmic rays are the signal not the background.)

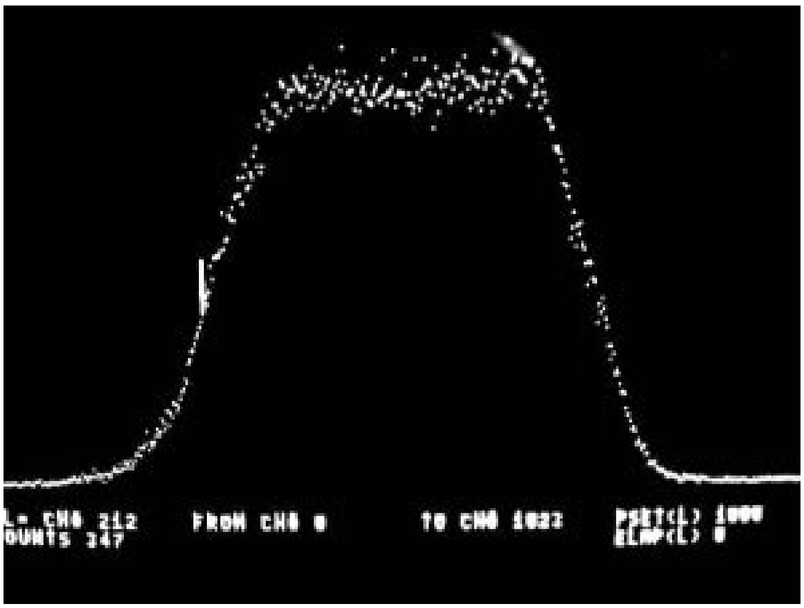

Figure 6.2: A pulse height spectrum of the time difference generated by the cosmic-ray muons. In this run the discriminator levels were set almost at zero. For higher discriminator threshold settings the edges of the “rectangle” should be sharper.

6.3 Source Measurements

A more specific measurement of the timing characteristics of the modules can be done using gamma sources. Place the gamma source along the bar at various positions and record the pulse height spectra using the timing setup detailed above (figure 6.1). Taking a spectrum every 25 cm along the bar is sufficient. Determine the peak position in the pulse height spectrum for each source position. You may need to lower the discriminator thresholds if they were set high for the cosmic ray measurement. A characteristic pulse height spectrum is shown in figure 6.3.

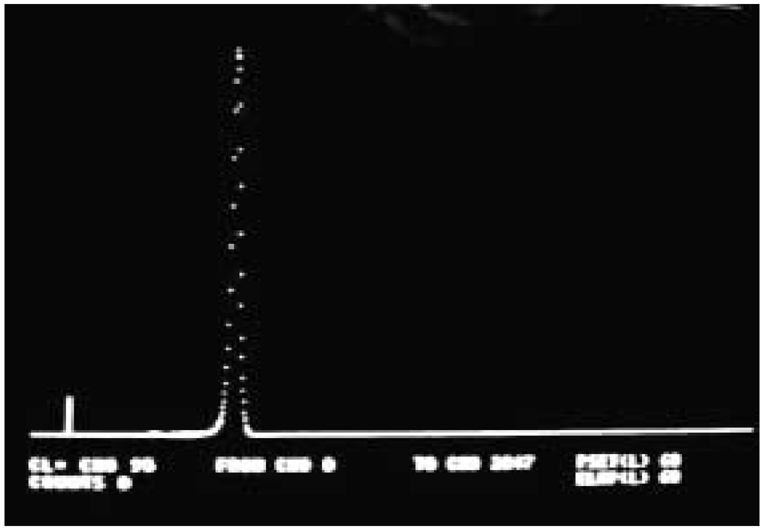

Figure 6.3: A pulse height spectrum of the timing difference with a ^{207}Bi source placed at 25 cm from the left bar end.

From the peak positions a relationship between the source position and time difference can be determined. Figure 6.4 shows the data for and a linear fit to the peak channel vs. source position. If the bar is operating correctly the relationship between peak channel and source position should be linear.

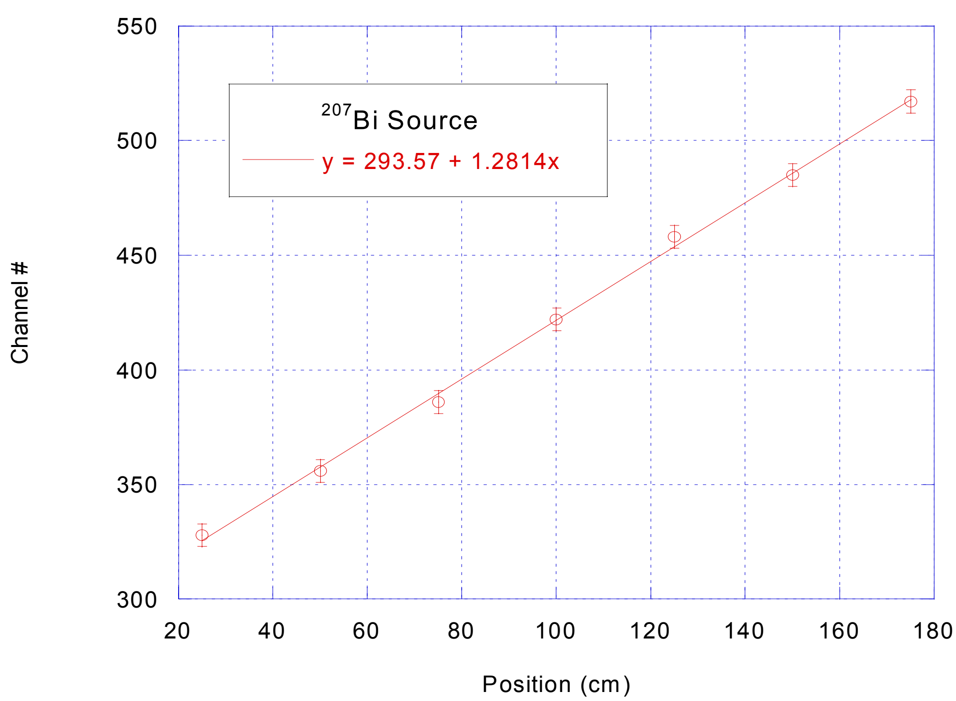

Figure 6.4: A plot of channel number vs. position of a ^{207}Bi source along the bar.

Another useful (but not essential) quantity associated with the timing is the resolution. The timing resolution will determine the spatial resolution of individual events in the bar. In principle this can be determined by finding the full-width of the pulse height peak at half of it's maximum value (FWHM). In practice this width is not only due to the timing resolution but includes geometry considerations due to the source and other factors as shown in figure 6.5.

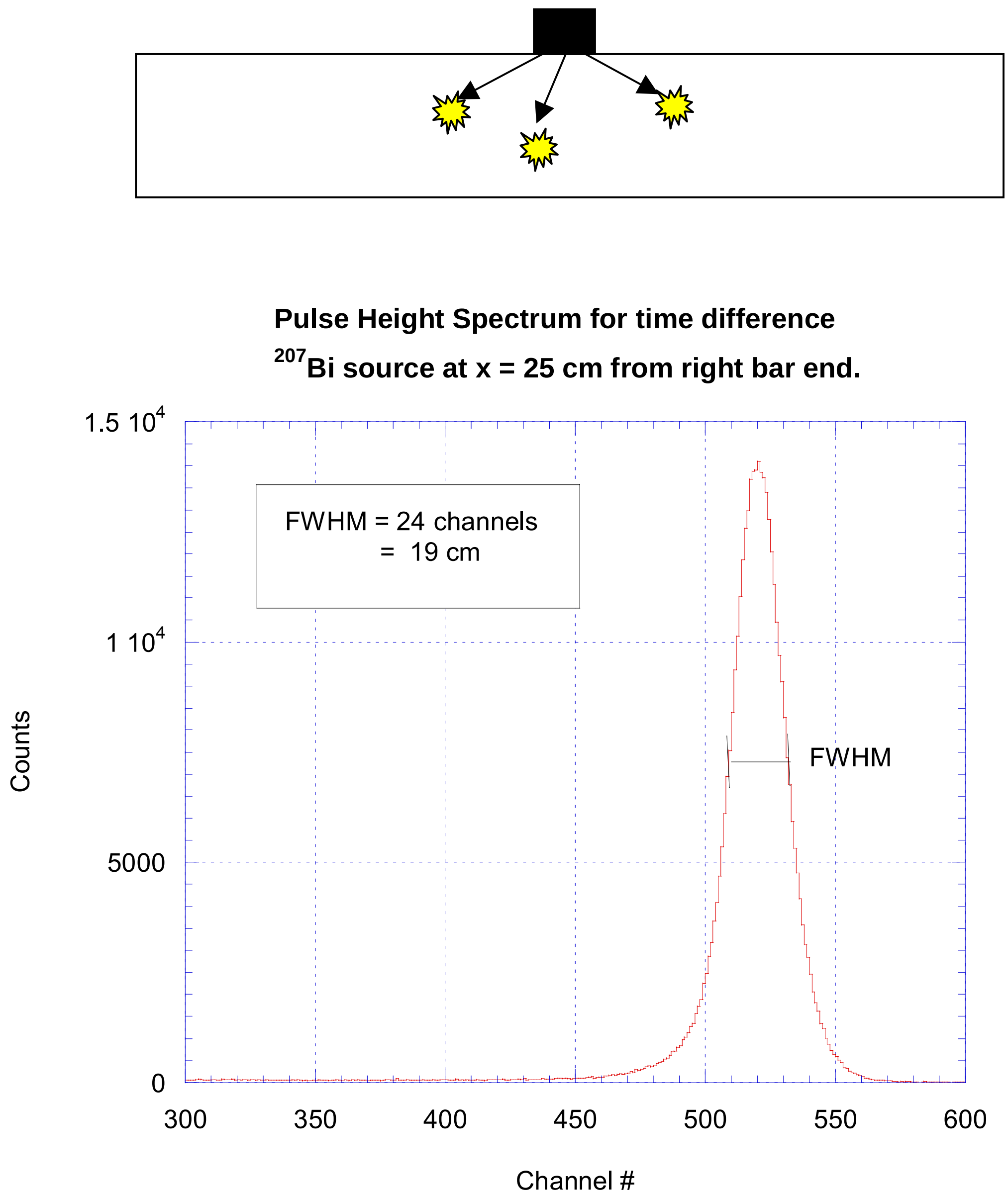

Figure 6.5: In the top diagram the source emits gamma-rays in many directions. The individual events are spread out in position along the bar giving rise to a large spread in the FWHM of the peak as shown in the plot.

There are a number of possible remedies for this problem. A highly collimated (and active) source can be used to limit the spread of events along the bar. Requiring a coincidence with events in small scintillators placed above and below the bar could be used with cosmic muons to localize events as well. If you have time and equipment you may want to pursue these or other methods to measure the spatial resolution of the bars.

Chapter 7: Summary

This manual is designed to provide guidance to the faculty and students assembling and testing the detector modules. It is not meant to be prescriptive. There are a wide number of ways to achieve the needed results especially in testing the bars. In addition there are a number of other tests that could be done on the bars that have not been discussed.

The final assembly of the bars should be the same for everyone though exact details of the assembly may of course vary. Once assembled the bars must be checked for light tightness. The phototubes signals should be checked to make sure they are consistent with expectations and with other bars.

In testing the bars the attenuation lengths measured after gain matching should be recorded and the pulse height peak position difference vs. source position should give a linear relationship. The timing difference should be checked with cosmic rays and sources. The timing difference should be a linear function of the source position.

Any other measurements made with the bars, such as spatial resolution, are welcome and we want to encourage everyone to pursue them. If you do make additional measurements please share your results and insights with other members of the collaboration.

8 Bibliography

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