THE DESIGN AND CONSTRUCTION OF A NEUTRON DETECTOR

by

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INTRODUCTION

Neutrons were first observed by Bothe and Becker in 1930 when they bombarded light elements such as beryllium and lithium with alpha particles from a polonium source. They were first interpreted as high energy gamma rays because of their penetrating power but when a substance of light atomic weight was put between the source of what was thought to be gamma rays, and the detector, an increase of flux was observed; whereas very little difference in flux was noticed with a similar obstruction of large atomic weight placed in the path. Chadwick suggested that the radiation was neutrons which were first postulated by Rutherford in 1920. Rutherford had proposed the hypothesis that there should exist a neutral particle with a mass equal approximately to that of the hydrogen atom. Chadwick showed how the difficulties of explanation of the penetrating radiation disappeared if the neutron hypothesis was adopted.

Neutrons do not have a charge so are slowed (or moderated) only by collision with nuclei.
Because of the lack of charge they travel about 300 meters between collisions with air molecules at atmospheric pressure.

The energies of neutrons are arbitrarily broken up into three groups. The lowest energy group is called "thermal" and includes all neutrons up to about one thirtieth of an electron volt. This group derives its name from the kinetic energy of thermal agitation of atoms, which is found in the kinetic theory of gases. The second group is called "slow neutrons". This energy group extends from the thermal energy to about ten thousand electron volts of energy. The "fast" group contains all of the higher energies.

The Problem

Because of their lack of charge, neutrons are very difficult to detect by methods used for most radiation. A survey of the methods used for the detection of neutrons was made to obtain a better understanding of the problems involved and to make an intelligent choice of the particular method best suited to the prevailing conditions. A reliable instantaneous indication of neutron flux was desired.

Sub-atomic particles can not be seen so they must be detected by the observable changes that they
produce in their surroundings. The changes which can be detected at present are: the formation of ions directly by the passage of an ionized particle, radioactivity induced by the absorption of the particle, and immediate spontaneous disintegration of an atom when a particle is absorbed. These changes are made known by the use of ionization chambers, proportional counters, and most commonly the Geiger-Müller counters, scintillation counters, nuclear plates, cloud chambers and foils.
METHODS OF NEUTRON DETECTION

Scintillation Counters

An examination of the less popular detection methods will be presented first and then the gas filled counters will be discussed. Scintillation counters date back to Crookes and Rutherford who used them to detect alpha particles. The energy of the alpha particles was partially converted into light in the zinc sulfide screen and the scintillations were counted with the aid of a microscope. However, the counting of the flashes by the eye was slow and tedious so spinthariscopes were abandoned in favor of Geiger and proportional counters until photomultiplier tubes were developed to the point where they could be used to detect the light flashes in the phosphor.

There are two ways in which neutrons can be detected with the aid of scintillation counters: one method is to detect the recoil protons and the other is to cause ionization by the absorption of a neutron by an atom that will immediately disintegrate into particles which can be detected. B\textsuperscript{10} which is about 18\% of commercial boron and Li\textsuperscript{6} which is about 8\% of commercial lithium are atoms which have this property and can be used as a "loading" in scintillation counter phosphors.
to detect neutrons. The following reactions are also useful in other detectors. (8, p. 35)

For thermal neutrons,
\[ ^{10}\text{B} + 0n \rightarrow ^{4}\text{He} + ^{7}\text{Li} \]  
\[ ^{6}\text{Li} + 0n \rightarrow ^{4}\text{He} + ^{1}\text{H} \]  

For fast neutrons,
\[ ^{10}\text{B} + 0n \rightarrow ^{4}\text{He} + ^{4}\text{He} + ^{1}\text{H} \]  

**Nuclear Plates**

Nuclear plates are used much the same as scintillation counters in that the emulsion is "loaded" with boron or lithium compounds and the resultant tracks produced by the disintegration particles indicate the neutron presence. Proton recoils are also detected in the emulsions. It is interesting to note that the chemical compound does not affect the cross section of the target atom. (The cross section is defined as the effective target area which each atom presents to the oncoming projectile.) The initial direction of the neutron seems to have no effect on the direction of the disintegration particles. The nuclear plates give a cumulative reading and require microscopic examination. For research they are very useful but for detection of neutrons around a cyclotron an immediate reading is
desirable. The detector would not obviate the use of film badges. (17, pp.203-206)

Cloud Chambers

The neutron cloud chamber is primarily filled with BF₃ or a hydrogenic gas. In the first gas the track of the alpha particle is visible and in the second the track of the recoil proton is visible. Efforts to obtain gaseous forms of fissionable elements that are suitable for this detector have not proven successful. In the BF₃ chamber the efficiency may be improved with the addition of solid boron on the walls and likewise paraffin coatings will improve the recoil chamber efficiency. Fissionable elements have been used on the walls of ordinary chambers and the fragments of neutron induced fission detected.

Cloud chambers require the presence of an observer in the vicinity to watch the chamber and it would only give a qualitative result without the use of film. An immediate indication was desired.

Metal Foils

When neutrons are absorbed by most metal foils the atom which absorbs the neutron is changed to an isotope of one mass unit greater than it was before. In
this process a gamma ray is often given off and the atom becomes beta active, which makes the foil technique possible. The foil is put in the neutron path and after a suitable time it is removed and the beta activity observed. This technique depends on knowledge of either the absorption cross section of the foil or the energy of the neutron. If either is known, the other may be determined. The usual method is to determine the cross section of the foil by other means. If a resonance absorption of neutrons of a particular energy is observed this foil can be used to determine the intensity of an energy band of neutrons from an unknown spectrum. In this way the energy spectrum can be investigated quite accurately. (6, p.151)

Ionization Chambers

The operation of gas filled counters of the more common type will now be described because they lend themselves very well to the solution of most detection problems. The operation of a single tube first as an ionization chamber, then as a proportional counter and last as a Geiger counter will be discussed to give a better understanding of the method used.
Fig. 1 shows the basic counter circuit used in most gas filled counters.

When the potential difference $V$ in Fig. 1 is increased above zero it causes a drift of the ions in the tube toward the electrodes. After these are collected there is no current in the conductors connecting the two electrodes until some other ions are formed by an ionizing event. If some particle traverses the ionization chamber and forms ions, these will drift to the electrodes and the charge on the wire and cylinder will be equal to the charge of the ions formed by the particle. For most gases the potential difference is sufficient to keep many ions from recombining so the number of ions collected is about equal to the number
formed.

The condenser C is understood to include all the distributed capacity in the circuit. The recovery of the wire after a pulse has occurred is controlled by the familiar RC time constant and cannot be made shorter than this value but can, of course, exceed this figure if the discharge conditions are suitably varied.

Because there is a difference in the mass of the ionized particles, the time for them to reach the collecting electrodes is not the same, so the peak voltage pulse is not the absolute peak of the ion collection. In fact the curve representing the discharge is a modified exponential curve. Electrons collect in a micro-second while positive ions take a milli-second.

Two disadvantages of this instrument are: the recovery time is in the order of a milli-second and the position of the original ionizing particle influences the pulse height. The advantage of this type of instrument is that the pulse height is dependent upon the number of ions initially formed. This makes possible the discrimination of alpha pulses from those due to beta and gamma rays.

The chambers used for neutron detection are set up to detect the ionization produced by neutron reactions. The most common reaction used in all counters is the
liberation of an alpha particle by absorption of a neutron by boron, as shown in equation (1). The chamber is usually filled with BF$_3$ or some other gas which has a large cross section for capture and emits an alpha particle. In all of the counters using boron, the enrichment of the isotope $B^{10}$ can increase the efficiency of the counter up to five times that when using commercial boron. Because of the small cross-section at energies greater than one electron volt, boron counters are only good for thermal and some of the slow neutrons. Boron counters can be used to detect fast neutrons but only after they have been slowed down to thermal energies by a moderator.

**Proportional Counters**

As the potential difference in Fig. 1 is further increased, a voltage is soon reached where an electron attracted to the wire gains enough energy from the field in the last mean free path to ionize one atom near the surface of the wire. The wire is always positive with respect to the cylinder which is usually at ground for ease of handling. It should be kept in mind that the field in a coaxial cylindrical counter is given by

$$E = \frac{V}{r \ln \frac{b}{a}}$$  \hspace{1cm} (4)
where $a$ is the radius of the anode or wire, $b$ is the radius of the cylinder or cathode, $V$ is the potential difference in Fig. 1 and $r$ is the distance from the axis to the point in question. The voltage at which one new ion is formed in the last mean free path is defined as the threshold for proportional counter action. As the voltage is further raised the critical distance within which ionization by collision takes place moves out from the wire and additional ions produce other ions by collision, thus forming what is known as an electron avalanche. The critical distance is never more than a few wire diameters. It can be seen that at this voltage the size of the avalanche is dependent on the initial ion's energy and the specific ionization of the gas. The specific ionization is defined as the number of ion pairs formed per cm of path length. The difference of specific ionization between the three types of radiation normally detected makes the use of proportional counters possible. In air at standard temperature and pressure for gamma rays it is about four, for beta particles it is about 400 and for alpha particles it is about 30,000 to 60,000 ion pairs per cm of path. The higher figure is for the region near the end of the path. In order to distinguish between particles, a discriminator circuit is employed which will not pass pulses smaller than a given size. This
will be discussed later in detail. (16, p.49) (11, p.164)

The size of the pulse on the wire is given by

\[ dV = \frac{A \cdot dq}{C} = 1.6 \times 10^{-7} \frac{An}{c}. \]  

(5)

A is the amplification factor, that is, the number of additional ions produced by each electron produced in the primary ionizing event as it travels to the wire, n is the number of initial ions formed by the ionizing particles, and dq their charge. C is the capacity of the counter in micromicrofarads. The number A may vary between the limits of unity, in the case of an ionization chamber, to about \(10^7\) at the end of the proportional region. In general, a counter cannot be operated in the proportional region when values of A exceed about \(10^3\). (10, pp.34-60)

As the amplification is increased above \(10^4\) the counter is operating in the region of limited proportionality. In this region the gas amplification is a function of the number of ions initially formed. The larger pulses soon reach a saturation value, that is, the product A dq becomes essentially constant so it is difficult to distinguish between beta and alpha pulses.

It is evident that any pulse may be amplifier to a desired size either in the counter itself (by varying the potential or size of the wire) or by the associated vacuum tube circuit.
The Origin of the Pulse

As the electrons move to the wire the positive ions form an almost stationary sheath so the charge due to the electrons remains as a bound charge until the positive ions move out of the intense field. Consider the axial wire of the counter as one electrode of a cylindrical capacitor and the positive ion sheath as the other. This was done by the Montgomerys in their analysis of the discharge of the Geiger-Müller tube. The charge on this capacitor remains constant since the number of ions in the sheath remains constant. As the positive ion sheath moves outward toward the cathode, a negative voltage pulse is induced across the counter and this pulse constitutes the "count" registered by a suitable circuit connected across the electrodes. This is a fact often overlooked in the literature. The impression very often given in some texts is that the pulse is due to the collection of electrons on the wire which causes the potential drop. The major portion of the pulse is induced in the first small distance traveled by the space charge where the electric field is the greatest. (13, p. 1031)

The positive ion sheath moves outward and eventually hits the cathode. These positive ions have a high probability of interacting with the cathode surface and releasing secondary electrons if the gas amplification
is over $10^4$, but at lower amplifications there are very few secondary electrons because of the low photoelectric efficiency. The photoelectric threshold of cleaned copper lies at about 3000 Angstroms (corresponding to a work function of roughly 4 volts) and the photoelectric efficiency of many of the surfaces used in counters is in the order of magnitude of $10^{-4}$, although these figures can be altered by a suitable choice of surface elements and preparations. Flushing the copper tube with NO$_2$ has given a surface with a lower photoelectric efficiency. The role of the positive ions will be included here even though it is more important in the Geiger counters because of the few photons formed in proportional counters. A simplified view of the mechanism is given by Mott as follows: When a positive ion approaches a metal surface closely enough, its force field may interact with those of the electrons in the metal. The electron may be drawn out of the metal to combine with the positive ion, thus neutralizing the charge of the latter. In general, the ionization energy of the ion is much greater than the energy required to overcome the work function of the metal. The ion has become neutral but it is usually in an excited state and will radiate a photon when it returns to the ground state. The energy of excitation results in a photon emission and is equal to the
ionization potential less the work function of the surface metal. For the types of gases used in counters the emitted photons lie in the ultraviolet region of the spectrum where they are efficient sources of energy for photoelectrons. These photoelectrons can be drawn from the neighborhood of the cathode by the positive anode of the counter and will rekindle a small discharge if a mechanism is not present to stop it. (14, p.219)

An "external quenching circuit" is used to prevent the rekindling of the discharge in the monatomic gas counter. Unfortunately this nomenclature is somewhat misleading since the discharge is completely over before the effect desired to be eliminated becomes important. It is not a question of quenching the discharge but of preventing the production of secondary discharges. The essential function of the quenching circuit is to prevent the total voltage across the counter from rising to threshold before all the secondary electrons produced by the positive ions at the cathode have been collected by the wire.

The pulse received by the wire is negative and very short in duration so the wire is returned to its original potential very soon after the initial source of ionization has entered the counter. For the counter to function properly, the voltage must drop to a value
sufficiently below the threshold so that it will not recover until ionizing particles left over from the discharge are all collected. The time which elapses while the counter is thus completely insensitive is called the "dead time". The voltage recovery time depends upon the time constant of the circuit, and, since this is an exponential recovery, a relatively long time, compared to the dead time, elapses before the potential across the electrodes returns to its initial value. If an ionizing particle comes into the sensitive volume before the voltage has returned to its operating value, the counter will break down with a smaller pulse than normal. Whether or not this breakdown will be registered as a count will depend on the associated electronic equipment. (16, p. 40)

The recovery time of this type of counter depends on the total capacitance of the counter and leads and the resistance in series with the high voltage. The capacity of the counter is usually kept small so the pulse will be large. The resistance must be of the order of $10^8$ to $10^9$ ohms to achieve a time constant long enough to prevent spurious counts arising from secondary electrons. Time constants in this simplest type of quenching circuit are long enough to interfere seriously with the usefulness of this system even at only moderately high
counting rates, and various circuits have been devised to allow the external quenching to be assured without the use of long time constants.

Polyatomic Gas Counters

The introduction of polyatomic gas into a monatomic, or simple, gas counter changes the discharge characteristics of the tube appreciably even though the monatomic gas contributes 30% to 90% of the total pressure. During the formation of the initial avalanche the simple gas component of the filling mixture acts as it does when uncontaminated by the polyatomic molecules. Brown states: "In the case of the polyatomic component of the gas, it is probable that the inelastic collisions which occur between the electrons of the forming avalanche and the polyatomic molecules result not in ionization but in increasing the rotational and vibrational energy of the molecules. This effect tends to decrease the total photoemission of the avalanche". (1, p.14)

It will be remembered that the ion sheath in the simple gas counter is built up by the secondary photoelectrons from the gas and the cathode. In the polyatomic gas the complex molecules in general prevent photons, which might be produced in the vehicular gas, from reaching the cathode. For the common gas mixtures
used in polyatomic gas counters, the radiation falls within the absorption bands of the polyatomic gases. Thus photon quenching is not perfect, but due to the relative inefficiency of the cathode as a photoelectron emitter these photoelectrons can usually be neglected.

**Geiger-Müller Counters**

The discharge mechanism is essentially the same as has been described for proportional counters except that all of the pulses are about the same size, due to the spreading out of the discharge along the wire, and the effect of photoelectrons is quite important and the use of a quenching mechanism is a necessity.

Since the energy of the photons is readily absorbed by the polyatomic molecules, any subsequent discharge following the initial avalanche will occur in the high field region near the central electrode. The field drops off very rapidly away from the wire so the ionization is localized very close to the anode. On the other hand, at any given distance from the wire along the length of the counter, the field is uniform. Thus the discharge, while being limited radially by the decreasing field, spreads laterally in the high field region of the wire until it meets some discontinuity which lowers the field, such as the physical end of the electrode or, as
was done by Brode and later by Stever, a glass bead. (16, pp.49-52)

**Self-Quenching Mechanism**

The reason that the voltage may be re-applied to the counter before the space charge has been collected at the cathode lies in its so-called "self-quenching" properties.

Most, if not all, of the ions formed by the passage of the initial particle are due to the simple gas, and the polyatomic molecules have no particular effect except to furnish electrons to the simple gas ions and thus neutralize them and also to absorb the photons that are given off in the process. These photons would cause photo ionization of the gas if not absorbed. Because the polyatomic gas molecules reduce the number of ions present in an avalanche the gas amplification is less than when they are not present.

The electrons given off by the noble gas are drawn to the wire where they produce the familiar Townsend avalanche. The discharge spread is confined to the surface of the wire where ionization by collision takes place, because the wide absorption bands of the polyatomic molecules absorb the photons directed toward the cylinder. The complex ion is always chosen with its ionization potential less than that of the main gas so
that there are very few noble gas ions which survive $10^5$ collisions without neutralization by the quenching gas. Thus practically all of the ions that reach the cathode are from the complex gas. As they get about $10^{-8}$ cm from the wall they pull an electron out and become neutralized but remain for a short time in an excited state. They dissociate into two neutral atoms rather than radiate so very few photoelectrons are emitted and they are due to the simple gas molecules which reach the surface and emit a photon directly toward the cylinder.

In time the polyatomic gas is used up and there will be more spurious counts registered by the counter. The counter is said to be then of the intermediate type. The slope of the counting rate versus voltage is thought to be due to the noble ions or metastable atoms at the wall, and, as might be expected the slope becomes greater as the quenching gas is used up. Also the pressure in the tube can be expected to increase with use.

Korff in 1943 mentioned that the slope of Geiger Müller counter tubes remained approximately constant under continued use and then showed an abrupt rise. If the counter was set aside for several days and not used it recovered so that it had a plateau comparable with the previous one. The counter could again be used for a time after which it lost its plateau again. After five or six
recoveries the counter was completely useless. There was no note of how many counts were involved but later he gives a length of counter life for argon-methane as $10^8$ counts and argon-alcohol as $10^9$ to $10^{10}$ counts. The reason for the difference is that methane is far down the list of alcohol decomposition products. Alcohol may dissociate into products which may in turn dissociate. (8, pp.2-4)
SELECTION OF COUNTER DESIGN

In the literature it was noticed that neutron detectors were very inefficient. The efficiency is defined as the ratio of the number of counts recorded to the number of neutrons which pass through a counter. There was no description of a single instrument found in the literature which could be used for the entire energy spectrum or even a large part of it. To do this it was thought that proportional counters could be used in banks with a moderator in between so that a given bank would detect only a certain band of energies. To get the full benefit of the volume in the counting bank, square tubes were designed.

Boron trifluoride (BF\textsubscript{3}) is very commonly used in neutron detector tubes so it was decided to build a BF\textsubscript{3} tube of square cross section lined with solid boron to make it more efficient. The things to consider were:

1. Would the square tube alter the field in the region where cumulative ionization takes place?
2. What metal should be used for the counter wall and how thick should it be?
3. How is a tube filled with BF\textsubscript{3}?
4. What pressure should be used?
5. What size wire should be used?
6. How could the wire be kept taught?
7. How could the wire be mounted?
8. What voltage would be necessary?
9. How to prevent Corona discharge?
10. Recognition of end effects.
11. How can metallic boron or other boron compounds be put on the tube surface?
12. Would the boron interfere with the neutralization of the positive ions?
13. What amplifier should be used?
14. Selection of other necessary electronic equipment.

The factors considered will be related in sequence with the number corresponding to the foregoing list.

1. **Effects of Square Tube**

   From the nature of the field in a counter using a small wire it was believed that the field would not be distorted appreciably in the region of the wire. Experiments verifying this assumption have been made by S. C. Curran and J. M. Reid on rectangular cross section tubes. (2, pp.67-76)
2. Tube Wall Material

Square copper or brass tubing was not available so the possibility of using aluminum was investigated. Korff states that aluminum is undesirable for two reasons. "It is often porous and hard to outgas. Further, with certain filling gases, electrons may be liberated from its surface by chemical action, and thus it may produce spurious counts." (10, p.123) It was also found that boron reacts with aluminum. (4, p.1) A square copper tube can be made out of round tubing and this was done. A square tube of about one inch inside dimension was desired so 1.18 inch tubing, obtained for Geiger counter tubes, was selected. The wall was 0.04 inches thick. An oak mandril was made first so that the rough shape could be obtained without having to make too many steel mandrils. This was done by planing a square wedge 9-1/2 inches long and varying in thickness from 0.8 inch to 0.9 inch. A square hole was made in a block so that the large end of the mandril would just slip through. After the tubing had been annealed and an end flared so it would not cut the mandril, the mandril was pressed through the tube three times with a hydraulic press. The edges of the mandril were rounded slightly. (Radius 1/16 inch)
The tube sides were not flat so it seemed that a larger mandril was needed. It was decided to saw the existing mandril along the axis for 2/3 of its length so wedges could be driven in and the size of the large end of the mandril could be varied at will, as shown in Fig. 2.

![FIG.2](image)

The tube was placed for subsequent pressings on two fiber blocks. After the tube was pressed it was not square. This did not seem to hinder coating but did offer some mechanical difficulty for machining the end shoulders. After consultation with the machinist it was decided not to make a steel mandril. The oak mandril was slightly wider in one dimension so it was put through a different way each time. Great care was taken to keep the inside surface of the tube smooth so coating would be uniform.

The tube was designed so it could be taken
apart and modifications made. The original plan was to have the shoulders about 1/4 inch from the end of the tube so that the tube made a knife edge fit against the ends. It is believed that this would work better than the method used. Fig. 3 shows the construction of the tube.

3. **Method of Filling with BF₃**

A survey was made to find the best method for filling a tube with BF₃ and the result indicated that filling was a technique far from standard. In all of the methods liquid air was used. Time was a factor as well as cost so the boron trifluoride filling gas was changed to argon or argon and alcohol. The literature indicated that the counter could be filled with argon and still operated as a proportional counter as long as the amplification was kept low; however, to make sure a mixture of 1/2 argon and 1/2 ethyl alcohol was used. The filling method will be discussed later with the first tests.

4. **Pressure of Filling Gas**

A total pressure of slightly less than 10 cm had to be used because the vapor pressure of ethyl alcohol at room temperature is about 4.8 cm. For further discussion refer to the first two tests under "Testing
FIG. 3

SECTION A-A

FIG. 4
of the Counter Tubes”.

5. **Size of Counter Wire**

From equation 4 it can be seen that low operating voltages can be obtained by making the wire small. The physical limitation of the wire diameter is about 3 mils for normal laboratory use so 3.5 mils was chosen.

6. **Wire Tension**

The spring used on the end of the wire to take care of any sag from glowing the wire was wound on a lathe, under a slight amount of tension, around a piece of 1/16 inch welding rod. The tungsten wire size was 10 mils and the lathe was turned by hand. The turns were made so that they would touch each other and the length of the spring was about 1/4 inch.

7. **Wire Mounting**

Nickel wire 10 mils diameter was spot welded on the ends of the spring as shown in Fig. 4. On one end of the spring the piece was about three inches long and on the other it was about 1/8 inch long. The spot welder was set for 2/60ths of a second and the variac at 60 volts in the primary. A hydrogen atmosphere was used to
give a better weld. On the small piece of nickel a tungsten wire 3.5 mils in diameter was welded. This piece was about three inches longer than the length of the counter and a piece of nickel 10 mils in diameter was spotted so that the joint would not be in the counting volume but would be below the end guide washers.

End A is the end with the pumping tube. The end of the wire opposite the spring is threaded through 4. Guide 1 is not on A at this time and the end is threaded by bending a loop of wire so that when squeezed together it can be inserted in past 4 to the other end of A. The wire is put in this loop and pulled through the hole 4. Guide 1 (a disk with a hole in it) is put in A and the nickel is soldered to the guide (which is nickel) and this soldered to the previously tinned shoulder. End 2 of the spring is brought up to 1 before soldering. The loose wire is put in a glass tube which is large enough to go over the shoulder at 4 so the wire would not mar the boron coating, as shown in Fig. 5.

A wire R is bent with a loop in the end and is longer than G. The latter is first put through the counter tube and then R put through it. The wire (W) is pulled through the glass tube until the end of G is resting around A. The tungsten wire is then threaded through 5 and B is screwed in place on the counter tube.
WOODEN STAND FOR HOLDING TUBE

SECTION "B-B"

FIG. 5
The wire is then pulled tight and soldered at 7.

8. **Expected Counter Voltage**

Many experimenters have published results from counters of almost every description that can be imagined so a general range of voltages could be expected for proportional counter action. (3, p.11) Nine hundred volts was believed to be a good approximation for the onset of counting, with a gain of $10^4$ on the amplifier.

9. **Corona Discharge**

Corona discharge can cause spurious counts if precautions are not taken to prevent it. We know that there are high fields in regions of large curvature. For this reason the spring was enclosed in a cylinder (which was at the same potential as the wire) outside the counting volume. The spot welded ends would have been sharp enough to cause no small amount of difficulty. Provision was made so that the wire was accessible from both ends so that a current could be passed through to cause a glow and burn off any dust.

One end plate was rounded off at the point of nearest approach to the cylinder surrounding the spring. The other end was not rounded because of an oversight of the machinist. After the tube was assembled and tested
it was found that there was corona discharge. This will be explained in the discussion of the first and second tests.

10. **End Effects**

In the design of good counters the end effects must be considered. However, if the counter is long compared to the cross section, the end effects will be small, so, to simplify calculations they were neglected.

11. **Preparation of Boron Coating**

The next problem was to determine the thickness of the film needed for the coating. Three references were found regarding the thickness of the films and these will be quoted directly.

"The boron was deposited on tantalum foil by the thermal decomposition of $\text{B}_2\text{C}_6$. This is a parallel plate type of detector. The thickness of the deposit is about 25 $\mu$g/sq cm, which is considerably less than the range of either the alpha particle or the lithium recoil." (15, p.197)

"For the boron-lined counter the maximum efficiency is about 5\%. The boron lining need be only 0.1 mm thick, and added thickness will merely reduce the efficiency." (10, p.55)
"Only 6% of the counts will be lost even if the thickness of the boron is 1/2 the range in boron of the alpha-particle. The actual range of the boron disintegration alpha particle in boron is 9.1 x 10^{-4} cm. Thus the coating may be about 5 x 10^{-4} cm. This corresponds to about 1 mg of boron/cm² of surface." (6, p.261)

From the differences in the above it seemed that there was quite a variation in the preferred thickness of the coating. The curves showing neutrons absorbed as a function of the thickness and energy are shown in Fig. 6 A and B. The cross section of the neutrons decreases with the energy. For these curves the total cross section is set equal to the capture cross section. For very low energies there is a definite optimum range but it could hardly be accurately attained in this type of coating.

The average range of the alpha particles in boron is taken to be 6 x 10^{-4} cm so after the thickness is greater than this the number of alpha particles decreases with "x". Then the number of alpha's at a point can not be much greater than the number formed in the previous 6 x 10^{-4} cm. From this it can be seen that the number of alpha's at x is proportional to the derivative of the number of neutrons absorbed. The neutrons are assumed to be coming from one side of a plate, the other side of which has the boron on it.
It appears that the thickness of the coating would not have to be controlled very carefully.

There are six metals, Zn, Hg, Tl, Sn, Pb and Bi which do not react with boron and three others, Cu, Ag, and Au which have been reported as probably non-reacting. [4, p.2] Copper was chosen because it is easy to work and makes a good electrical connection.

Preparation of boron films was investigated and four methods were found. The evaporation of elementary
boron is possible but quite difficult for a number of reasons. The fact that it must be heated to 2500°C would cause trouble but the small tube size would present the greatest difficulty in obtaining an even coating without melting the tube. The decomposition of boron halides has been used by some experimenters for coating wires, but this requires the perfection of a dangerous technique because borides may be formed which have a flash point just above room temperature. This same danger in the preparation of boron is encountered in the decomposition of diborane \( \text{B}_2\text{H}_6 \). There are warnings in the literature stating that serious explosions have resulted from this method. \((4, \text{p.1})\) For these reasons another method for preparation of a boron film was sought. The use of boron compounds was investigated but it was decided to use elementary boron if it could be obtained in fine particles.

Of the four methods of coating the cathode, the deposition of elementary boron was chosen. This method, not discovered in the literature, was suggested by Mr. P. H. Nilsey of the Mackay Company. Because there are no solvents listed for the element boron it was found necessary to suspend the very fine particles in a liquid; isopropyl alcohol was suggested and used.

Following is a description of the boron-coating-
on-copper experiments.

Cleaning the Surface. This turned out to be somewhat of an art. The first trial was rather crude but for some work it seems to be the best method. Five strips of copper were cut by shears so they would be as wide as possible and still go into test tubes; about 7/8" x 5". It should be noted that shears were used because they do not bend the metal like snips, and flatness of the metal is very important in the pattern of boron disposition. Precautions of this sort are necessary for an even coating.

The first method tried was to pour diluted \( \text{HNO}_3 \) directly on the copper. The action was quite vigorous but the dilution of the acid was not known. If the acid did not react long enough the metal was not cleaned, however, if the acid was left on too long some of it would run off and a discoloration would be left. The method of diluting the acid so that the reaction will cease will also determine the condition of the resulting surface. If the water is poured onto the copper out of the tap there are apt to be discolorations, but if the strip is put into a beaker of water for dilution this chance is materially reduced.

The second method tried was to put the acid into a beaker and then dip the metal into it, but when
the strip was taken out for washing there was sometimes discoloration. It was found that if the water was added to the acid the discoloration was nearly always eliminated.

The last method used was to put the water used in the dilution of concentrated acid into a tank and put the metal to be cleaned into it, then add concentrated acid until a slight reaction was indicated by bubbles. When the metal looked clean enough water was added to the acid until the metal was well washed. Hot water was then used so that the metal would dry soon and eliminate most of the water spots. This last method seems to be quite satisfactory. It might be well to add that the flux used to solder the tank did not seem to clean off very readily.

Horizontal Position Coating. The first method of coating tried was to put some of the boron powder into a tube with alcohol and shake. The strip of copper was put in and taken out so that the alcohol could evaporate. The procedure for taking out the strip was as follows: the tube was inclined and the strip taken out until it was just clear of the surface of the liquid. It was then turned on edge so the excess liquid would form a drop. The drop was disposed of by just touching the surface. After the liquid had evaporated, this process was repeated and it was found that the thickness could be increased.
Even with the naked eye some large pieces were seen on the surface so the suspension was allowed to set for four hours and the action was repeated. This resulted in a much smoother surface and it was decided to mix up quite a large amount and let it settle overnight. The disadvantage of allowing it to settle is that unless the liquid is evaporated the number of dippings necessary to built up a significant coat is very great.

It seemed logical to try to put a suspension of the boron in a tray and put the strip of metal in the bottom. The surface of the liquid seemed to have quite a turbulence that prevented the boron from remaining stationary. After being allowed to set overnight, the coating, then completely evaporated, was much more subject to irregularities on the metal than it was by the dipping method. There seemed to be evidence that some other very important action caused the poor uniformity. The boron in the suspension was taken out of the tube that had set overnight so only small particles were left. The theory was that there would be a given amount of boron above the strip and, assuming a practically homogeneous mixture, it seemed logical that the coating left when the alcohol evaporated would be equal to the boron directly over the particular point in question. This did not turn out to be the case.
Some glycerine was added as a binder to see if it would help but in successive dippings an undesirable residue was left. No binder was needed for a fairly sturdy coating. The coating cannot be shaken nor jarred off. It can be rubbed off easily but it is very satisfactory from the standpoint of ruggedness for operational use.

When the surface had some boron on it there was a very distinct decrease in the evaporation time. Also, as the coating was built up there seemed to be a congregation somewhat like the growing of crystals. It was thought that this could be nullified by putting a sheet of cellophane over the surface and rolling it with a hard roller. The boron did not seem to stick to clean cellophane and this also had the advantage of making the surface harder. Needless to say the copper surface must be very true to obtain an even boron coating when using the cellophane and roller. Rolling inside of a tube would be very difficult. The use of a rubber roller was tried on the test strip but there were too many irregularities on the surface of the roller and it seemed ineffective. The irregularities of the coating were not expected to cause much change in the efficiency of the tube, therefore this smoothing attempt was ceased.

A 30-power binocular microscope was used to observe the surface. The motion of the boron particles
on the surface of the strips before evaporation was completed was studied after different methods of deposition were tried. It was observed that there was a motion similar to Brownian movement. If a mixture of boron and alcohol was dropped on the copper surface there was a definite line left where the wet surface ended, and if a small amount of glycerine were added, it concentrated at this boundary and there was no visible sign of it elsewhere on the coated surface.

As might be expected the best method found for coating the surface was to collect an amount of the suspended boron still left in suspension after a night's stand. This was syphoned into a tank and the alcohol evaporated so the liquid became more concentrated. The principle reason was to reduce the number of dippings. In the test runs it was found that 17 dippings made a very good coating.

After the square tube was made it was cleaned and a test run was made so the method selected could be tested. The tube was not absolutely square on the inside corners nor flat on the sides so it was not known whether or not it would coat evenly. After a few dippings it was decided to be satisfactory. The tube was placed in the bottom of the tank and the liquid run over the bottom side. The liquid was concentrated and not much deeper
than the thickness of the walls of the tube. The shallow depth was used so that the sides would not be coated also. Capillary action on the corners was important so square corners were not very desirable because they would dry last and give a thicker coating there.

The shoulders of the tube were attached and the tube coated by the foregoing method. The depth of the boron suspension was just slightly more than enough to cover the surface to be coated when the tube was flat on the bottom. The pan was rocked so that there was a flow of boron down the tube. The tube was then drained and laid on a block under a heat lamp. The sides of the tube were numbered and a count was kept of the number of dippings of each side. The test strip was coated after one complete dipping of the tube. Twenty-one dippings were made on each side in the course of two days, in which time the mixture concentrated. Small particles were seen inside the tube so a strong blast of air was directed down the tube to knock these off. Some success was obtained and no damage was done to the coating. The thickness of the coating was estimated to be two-thousandth of an inch thick. This conclusion was reached after a two-thousandth of an inch wire was laid on the test strip and viewed through the binocular microscope.
Vertical Position Coating. Adapters were made for both ends of the second tube. The bottom consisted of a plate about 1/4" thick with a copper tube soldered in a hole in the bottom, as shown in Fig. 7. This was clamped on the bottom end with "C" clamps. The top adapter (not shown) was made of a piece of scrap metal about one inch thick. A hole about the size of the tube was cut in it so that there would not be such a great danger of overflowing the tube. This was secured in the same manner as the bottom.

The boron was suspended in ethyl ether because it had a vapor pressure of about 442 mm at 20°C which was far above the next most volatile liquid. The reason for using a highly volatile liquid was to minimize the flowing of the liquid as the liquid level was lowered. The liquid evaporated before it had a chance to flow and make stream lines. The use of a highly volatile liquid also shortened the coating time. A hood was put over the can of ether and boron to minimize the escaping vapor.

A fan was placed so the blast of air would blow across the top of the tube to draw the fumes out and aid in the evaporation. To facilitate better air currents a glass "T" was put just below the copper tube on the bottom adapter and a rubber tube with a pinch-off clamp put on the branching arm as is shown in Fig. 7.
The pinch-off was opened after the level of the liquid was brought below it. The passage of air through this tube materially affected the evaporation rate of the ether.

There seems to be little doubt that the method used is workable but a satisfactory technique was not worked out. The fumes of the ether were such as to cause headache and nausea so further experiments other than those described were not undertaken.

From previous experiments with the evaporation of alcohol it was found that if the alcohol was allowed to evaporate successive layers of boron could be built up but if the liquid was not evaporated this was not possible. It is for this reason that rather elaborate pains were taken to be sure that evaporation did take place and at the greatest possible speed which would not cause stream lines to be formed. If a large volume of air was passed through the tube it was thought that an uneven coating would result. This was found to be the case when alcohol was used and air blown on the flat copper test plates was tried to speed up evaporation. It was also noted that if a slurry of boron in ether was caused to rotate fast in a beaker a heavy thickness of boron was left on the wall but if the speed of rotation was slowed the layer got thinner. The problem was
then to develop a technique which would enable the thick coating of boron to be left on the walls but not leave stream lines in the process.

Fast lowering of the movable ether boron container did not seem to have a very different effect than slowly lowering it. However it is felt that there is a solution to the problem with the apparatus used because the first coating was quite good but had a single small streak of poor coating. Perhaps due to poor cleaning with acid.

Cleaning Second Tube Surface. Concentrated nitric acid was poured down the tube to try to keep from oxidizing the soft solder which held the end shoulders. There were some black streaks which would not come off but they were not scraped off because it was thought that they would not affect the coating. This did not seem to be the case because it was here that the first coating was thin.

The first coating was wiped off by passing a not-too-clean rag down the tube and then an attempt was made to coat the tube without another acid cleaning. This was poor experimental practice but it was done for the following reasons: It was difficult to obtain a good surface by using concentrated nitric acid which seemed to be the best cleaning method under the conditions; and there were no clean rags readily available.
It was decided to try to use the surface obtained. The failure to get better results may be due to this error in reasoning because the first coating looked satisfactory. It was not the purpose of the experiment to exhaust all the possible experimental methods of coating boron. The purpose was, however, to prepare a coating of the same general thickness and uniformity as the first tube, which was used as the standard, but to be prepared in much less time and with less effort.

The final coating was applied by the same general method as the first tube coating but the size of the particles was not determined by letting the mixture stand. A slurry was used and only one dipping on each side was used. It will be admitted that the coating was rather crude but this was not necessarily undesirable as the standard tube coating was not crude and a comparison was desired.

12. **Electrical Effect of Boron on the Walls**

Boron is almost a non-conductor at room temperature so there was a possibility of poor positive ion neutralization with a solid coating. However there are two reasons why it should work: (1) Condensers have a dielectric between the plates and the tube is essentially a condenser; (2) There are many references to
the operation of boron coated counters.

13. **Amplifier Selection**

Proportional counters operate on the principle that there is a variation of pulse height with the number of ions initially formed. If the output pulse of the tube was distorted in the amplifier because of its size there may be errors induced in counting. For this reason a linear amplifier was needed; linear in the sense of equal amplification for pulses regardless of size. A flat response is not essential but a good response for high frequencies is necessary. An extensive search was made to find an amplifier suited to the needs of the proportional counter and information along with it to help in eliminating trouble. It was desirable that the amplifier not pass low frequencies to obviate AC hum.

Linear pulse amplifiers are a source of much trouble in design and construction. There are many warnings for the uninitiated to be wary of them. Elmore and Sands recommend the model 100 amplifier for most laboratory work. (5, p.165) There was a circuit in their book but not a layout and the latter is very important in the elimination of difficulties.

It is usually necessary to screen each individual stage from every other stage. The input stage
in particular has to be thoroughly shielded. This is ordinarily accomplished by building the stage in question inside a metal box. All leads connecting any one stage with other stages or supplying it with power must pass through shielded conductors. No portion of any stage can be permitted to "look" out into the room, since if a straight line can be drawn between any portion of the amplifier and any portion of the 60 cycle lighting circuit, excessive pickup will result. This is the familiar principle of electrostatic shielding. Multiple grounds should also be avoided. A grounded cable can be provided in the amplifier to which all grounded leads are attached. This grounded cable should be connected to the metal box at only one point, and the metal box should not be used as a conductor or as part of the circuit.

(10, p.186)

With the above in mind the amplifier and discriminator were laid out on a paper the size of the proposed chassis (10 x 17 inches). Each wire was drawn so that all leads in the first three stages were kept to a minimum and still have shielding possible. Due consideration was given for a neat looking job of layout and construction. Fig. 8 shows the circuit used for the amplifier, discriminator and a plug-in unit. The pre-amplifier was not used because it has a gain of less than
one but the amplifier is wired for it and there is room for it on the counter tube mounting. Some connectors for the preamplifier were ordered seven months and not delivered. A test was proposed to see if the preamplifier was of any particular value. This was to be accomplished by having two outputs on the tube mounting. At the time of this writing only one is completed.

The chassis was completely wired before the shields were put in between the first stages as shown in Fig. 9. The placement of the holes needed in the shields was found and cut. Many wires had to be disconnected to put in the shields but this seemed to be the surest way of getting good shielding. The amplifier was designed as a laboratory piece of equipment and the output may be taken with or without the discriminator.

The amplifier is designed so that a preamplifier of a gain of one hundred can be used with ionization chambers. There are five stages of amplification and two cathode followers in the amplifier. The flat response is obtained by a set of two feed-back loops of three tubes. Elmore and Sands has a complete discussion of the operation of this unit so it will be eliminated here. (5, pp.124-201)

The following is an excerpt from Elmore and Sands: (5, p.158) "The low-frequency response of a
pulse amplifier determines the shape of the output pulses. The network responsible for pulse shaping is ordinarily placed in the amplifier very near the coarse gain control. All other short time constants in the amplifier should be about 50 to 100 times longer than the single short time constant used for pulse shaping in order to avoid an appreciable undershoot of the output pulse. The maximum value of the clipping time need never be more than 50 to 100 times the rise time of the amplifier, and sometimes made as short as the rise time." The clipping time is defined as the time it takes for the amplifier to be able to take another pulse after the maximum has been reached. This assumes no overlapping of pulses.

14. Associated Electronic Equipment

Plug-in Units. The plug-in units for the amplifier are shown in Figs. 8, 10 and 11. The adapter plug for socket "B" is used when the preamplifier is bypassed. The shielded plug-ins for socket "A" are also shown in the same figures. For most of the testing the 100 μf condenser was used because of trouble with the pulse delay. The pulse delay, recommended and described in "Electronics" (5, p.168), was built to obtain a short time constant afforded by the foil. This should improve
the transient response of the line and give a certain amount of correction to its high-frequency, phase-delay characteristic. The resistances R-6 and R-7, in parallel (in the a-c sense) with the input attenuator of the amplifier, constitute the terminating impedance of the line. R-6 is made adjustable to enable an accurate termination of the line to be made. C-2, in conjunction with the various resistances in the circuit, introduces the proper exponential decay to the signal. The pulse delay was wound according to the direction in "Electronics" on a lathe run at low speed and connected as is shown in Fig. 11-B.

Voltage Discriminator and Pulse Shaper. In order to count only pulses due to alpha particles we must have a sorting device. This is done by an electronic pulse height discriminator as described in "Electronics". (5, pp.202-206) The variable resistance G is set at a desired position, and with the aid of A and J the bias can be read directly in volts. If it is set at 20 volts then only pulses larger than 20 volts will be passed by the discriminator and therefore counted. The circuit is so designed that the output pulses are all of the same amplitude. This is necessary for reliable scalar action. The amplifier had to put out a pulse of 4 volts before the discriminator would pass it, and the
amplifier becomes overloaded for output voltages over 50 volts with G set at the lowest triggering voltage. Larger voltage pulses in the counter tube could be used by using lower gain in the amplifier.

The output of the discriminator is always a square wave of 40 volts amplitude with a duration of time equal to that spent above the trigger voltage. The unit may be made to take a positive or negative pulse by the bias of the input grid. The output signal may never reach its full value if the input signal does not remain above the bias voltage for a sufficient length of time. For this reason it is desirable that narrow pulses, if used, should either be rectangular in shape or at least have a sufficiently long nearly flat top. (5, p.205)

Single Stage Amplifier. The scaling unit would not operate with the output of the discriminator so a single stage of amplification was built to drive the first stage. The circuit for this was obtained in the original article of Model 200 pulse counter in reference (7, pp.706-716). There was one change included in this circuit; this was the addition of the condenser in the output. The circuit is shown in Fig. 8 and the picture in Fig. 10. This amplifier has a gain of 100.

Testing of Amplifier. An audio signal generator was used as a signal generator for a square wave
FIG. 10

ADAPTER PLUG-IN FOR SOCKET "B"

PULSE DELAY

SHIELDED PLUG-IN FOR SOCKET "A"

SINGLE STAGE AMPLIFIER

T10-65N7

IN OUT 500V 8-0 2ND FIL 6.3V FIL
PINCH OFF

TIME DELAY LINE

FIG. II - A

FIG. II B
generator. The square wave was fed into the pulse amplifier and the output was noted. There did not seem to be any gain or signal in the output. On examination it was found that condenser 4 was grounded on both sides. This drew a large current and caused the resistor 43 to heat up and put a very low voltage on the first tubes. As soon as the wire grounding both sides of C-4 was disconnected (from pin 6 to ground) the first stage was blocking the signal. It was decided to put resistors 13 and 15 on the other side of 14. Upon inspection of the connection it was found to be very poor so this was corrected. This enabled the first two stages to operate correctly. It was then evident that tube 3 was blocking the signal. The tube was checked and found to be bad. This was the last difficulty encountered with the amplifier.

The pulse shaper had caused difficulty so a single condenser of value 100 μf was put in a shielded box. A square wave output of very good fidelity was found. This plug-in replaced the time delay.

Frequency Response. A video signal generator was used as a source of high frequency input to the amplifier as shown in Fig. 12. The output of the generator can be very accurately determined by the instrument. The output was kept at a constant 100 μv
and the output of the amplifier was noted as a function of the frequency as shown in Fig. 13. The band of amplification was from 10 kilocycles to about 3 megacycles with a maximum gain of $1.6 \times 10^4$ at 200 kilocycles.

A General Radio signal generator model 605B was used as a source of variable frequency oscillations. This instrument has a well calibrated output variable from one to about 100,000 $\mu$ volts. The reason for the qualifying statement will be discussed below.

It was decided that the frequency would be held constant while the input voltage of the amplifier was varied. This was done as follows: The selection dials of the signal generator were set so that the output was 10 kilocycles. The carrier wave was set at the correct position on the dial and the output set at one microvolt. The amplifier was put in operation and an alternating current probe from a Hewitt Packard vacuum tube voltmeter was connected to the output of the amplifier whose gain was turned up to maximum. The vernier output of the signal generator has a scale of ten so this was varied in steps of 1, 2, 4 and 7, so that the plot on a logarithmic scale would be somewhat evenly spaced.

The output of the amplifier remained fairly constant at 0.7 volts, which was accepted as the noise
Fig. 13

Fig. 14
level, as shown in Fig. 14, until the input to the amplifier was raised from zero to about 200 microvolts. As the input was raised above 200\(\mu\) volts the output increased until the last multiplier scale of the signal generator was needed to give an input pulse to the amplifier of from 10,000 to 100,000 \(\mu\) volts. When this multiplier was used there was noted a decrease in amplifier output for what should have been the same input signal. That is, the vernier set at 10 \(\mu\) volts and the multiplier set at 1,000 \(\mu\) volts should give the same output as the vernier set at 1 \(\mu\) volt and the multiplier set at 10,000 \(\mu\) volts. However the output of the amplifier was not the same for both dial settings so this discrepancy was investigated. There were two possible reasons for the decrease observed, one reason was that the signal generator was overdriving the amplifier, and the other reason was that the input signal was not the same for the two settings. The first possibility was dismissed when the output of the amplifier was increased, by advancing the vernier, above that previously noted as a maximum on the preceding multiplier. In all previous measurements there was no noticeable difference when the same output of the generator was obtained by the two different possible combinations of the dial settings.
To test the accuracy of these conclusions an oscilloscope was put on the output of the signal generator and the vernier was turned to 10 and the multiplier to 1,000 microvolts. The height of the signal on the screen was measured with a pair of calipers. The vernier was then set at one and the multiplier set at 10,000 and the signal was much less than the previous signal. The vernier had to be turned so the output read 5.5 times the multiplier of 10,000 before the output signal equalled the previous output of 10,000 µ volts on the screen. This meant that the last multiplier was not correct.

As a check the points using the 10,000 multiplier were recalculated using the multiplier setting of 10,000 to be 1,900 and because of the logarithmic nature of the vernier a new scale was started from this point. The point 1,900 was also found empirically by the following method. It was certain that the vernier was graduated correctly from the preceding work so it seemed that the multiplier was the source of error.

The curves were drawn without reference to the conflicting data and it was noticed that if the ones using the 10,000 multiplier were displaced to the left so that their lower ends matched the other curves at any one point, the rest of the curves matched and the curves extended upward similar to those of higher frequencies.
(See Fig. 14)

From the foregoing it should be evident that the general radio signal generator Type 605B serial number 1285 has an error in the multiplier calibration. The multiplication indicated as 10,000 microvolts is actually 1,900 microvolts.

The peak amplification frequency was noted at 200 kc and the threshold about 10 kc and 3 mc (megacycles). (See Fig. 13) The graphs show that the amplifier is linear in the sense that the amplification is not a function of the pulse height above the threshold for counting which is about 4 volts output.

Scaler. The scaling unit circuit used is well written in Higginbothams original article and will not be treated here. (7, pp.706-716) W. R. Jewell had the unit built for his Ph.D. thesis by R. P. Merritt. Only one of the two units built was used. The unit proved very satisfactory even though the first stage of the scaler had to be bypassed. Fig. 15 shows the assembled unit.

Power Supplies. A limiting accuracy was imposed by the power supplies which had quite an appreciable ripple. A 300 volt regulated power supply was not available so an unregulated one was used with an AC voltmeter on the amplifier output to take the gain data but for all other operations with the counter tubes a
285 volt regulated and somewhat filtered power supply was used for the amplifier. Two 3000 volt power supplies were used for the high voltage. One was regulated and the other not. Both of these instruments had ripple that could be seen on the output wave shape of the amplifier. One of the amplifiers is shown in Fig. 16 and its circuit in Fig. 16 A.
3000V DC REGULATED POWER SUPPLY

FIG. 16-A
Operation of the BF$_3$ Counter Tube

A BF$_3$ tube, shown in Fig. 19-A, was used to test the electronic equipment. It was connected as shown in the block diagram (Fig. 16-B). The pulse originated in the tube which was supplied with a high voltage from the 3000 volt power supply. The small signal was amplified about ten thousand times by the linear pulse amplifier. Part of the amplifier output was taken for the input to the...
oscilloscope to see the wave shape from the amplifier and to observe pulses. The other part of the amplifier output was used as the input for the discriminator. For most operations this was biased to give passage to all of the pulses. The output of the discriminator was not sufficient to drive the scaler, so an amplifier with a gain of 100 was put in between the two. The scaler had a built-in driver stage for the mechanical recorder. The 300 V power supply needed for the scaler was built into it so no lead is shown (Fig. 16 B) from the separate 300 volt supply. Although it is not shown, a 0.01 μF 5000 V test condenser keeps the direct current of the high voltage from the linear amplifier.

The filaments of the tubes were turned on for about three minutes before the plate potential was applied. The 300 V power supply was then turned on and pulses were seen on the oscilloscope. The power supply ripple was also noticed on the oscilloscope. The high voltage plate current was turned on with the voltage set at the lowest voltage possible. On one power supply this was zero but on the other it was about 600 V. Counts due to electrical noises were observed many times when the electrical system underwent changes but these were soon over and the system was stable. Counting started at about 2000 V with the 10 milli curie Ra-Be neutron
source about fifteen inches from the tube and paraffin between the source and the tube. 2550 operating voltage was printed on the tube so this was applied and the apparatus operated very well. To make sure that the tube was only counting neutrons, the source was taken away and a gamma source brought near. No increase in the small background counts was noticed.

The First Test with the Solid Boron Tube

The stop cocks in Fig. 17 were all opened for about ten minutes with the forepump on. It was found that the line to the argon tank would not remain vacuum tight at the gauge. The stop cock (2) to this line was closed and the valve on the cylinder opened to admit one pound of air pressure per square inch above atmospheric so that the transfer of gas would be from the inside of the line out. The stop cock (3) was closed and some argon and air mixture let in through (2). Care was taken so that the pressure on the line did not fall below atmospheric pressure when the valve was opened. The one pound per square inch of pressure was not allowed to get into the flask (1) because it was thought that this would tend to force the flask away from the ground glass seal (subsequent tests showed that 2 pounds per square inch of pressure were sufficient to do this). After the
flask was filled, stop cock (3) was again opened and the gas pumped out. This was repeated about four times to be sure all of the air was out of the system. The purpose of the argon intake situated below cock (3) was as follows: If something should go wrong and a high pressure allowed to develop into the evacuated system the shock wave might be great enough to break the entire manifold, but with the shock restricted below a stop cock the chance of damaging the whole system is reduced.

With the stop cock (2) closed and the others opened the system was pumped down for about ten minutes to get rid of all of the air in the alcohol flask (F2). This was then closed and the air taken out of the argon line. For the initial experiments dry ice was placed around the alcohol in an attempt to freeze out the water which was believed to be the main impurity in the 95% isopropyl alcohol. The reason for this precaution is that the oxygen in the water forms negative ions in a counter tube and this causes spurious counts.

The dry ice had to be discontinued because it lowered the vapor pressure to such a low point that enough vapor from the alcohol could not be obtained to give more than 2 mm of pressure. For later experiments ethyl alcohol was used as it has a higher vapor pressure and it could be obtained 100% pure. The ionization
potential was not found in the literature for isopropyl but is well known for ethyl alcohol. It is believed that it is about the same or at least less than the argon which is the important thing for a quenching gas in a tube filled with argon.

After care had been taken to remove air and water from the system it was pumped down to less than one micron and the pumps run for an hour. The uncertainty of the pressure is due to the fact that the batteries for the gauge were not sufficient to operate the ionization gauge.

Dry ice was put around the mercury trap before any pumping was done and left there until the pumping was completed. With (1), (2) and (3) closed (Fig. 17) the alcohol was admitted into the manifold for about ten minutes with valve (4) wide open. After this time (4) was closed and (2) opened until it was thought that there was some argon in the flask as indicated by a change in the pressure on the gauge as the valve was moved. (2) was closed and (3) opened a small amount until the total pressure in the system was about 20 cm, when it was closed. The system was allowed to stand for about 10 minutes and the high voltage applied to the tube. The wire was not gloved at this time because this was just a test run. The apparatus was assembled as shown in Fig. 18.
The potential on the counter was increased up to about 900 volts when the counter immediately began counting. Below this voltage there was no counting and as the potential was raised further there appeared on the oscilloscope exponential decay curves of a frequency of approximately 600 cycles per second. The oscilloscope input was taken from the amplifier output. As the potential was further increased, breakdown was attained at nearly 2000 volts. If the source of gamma rays and neutrons was removed the counting rate decreased very markedly (below 2000 volts). The counter did count gamma rays from a radium dial so it seemed that the counter was acting as a Geiger Müller counter and not a proportional counter. No solution of the problem of why the counter seemed to act as a geiger counter, without acting first as a proportional counter, was found the first day. At lower voltages than the seeming geiger region there was a very heavy exponential decay curve of random counting rate much slower than the rate at higher voltages and no explanation of this was evident at first. The system was pumped out but could not be pumped very low after the tests.
The Second Test

The next day the system was found to have increased slightly in pressure from the night before after all stop cocks were closed. The system pumped down easily and the isopropyl alcohol was replaced by ethyl alcohol, and no dry ice placed around it. The air was taken out of the alcohol flask just as it was done the previous day and the system pumped down to 20 microns and the diffusion pump started and left for about an hour. The stop cock (4) was opened and the increase of pressure noted. The pressure rose very slowly so a hand was put on the bottom of the flask to warm it up as it was very cold from evaporation. After about 5 mm pressure of alcohol was put in the manifold the flask was sealed off. (1), (2) and (3) had been turned off as was done previously). The argon flask was filled and the pressure increased to about 20 cm total.

Tests were repeated and the same results as obtained the day before were repeated. At this time the diffusion and fore pumps were stopped to lessen the noise and there seemed to be arcing in the counting tube that was a function of the voltage. This was very rhythmic and would present regular output pulses on the output of the amplifier. It was decided that the arcing was on the inside of the tube because the outside was examined and
no arcing noticed. There were two possibilities of arcing in the tube. One was leakage along the glass insulator due to dirt or moisture and the other was arcing through the gas from the high potential guide (5 in Fig. 4) to the end on which the insulator was soldered. It was reasoned that if the leak was along the insulator it would be a function of the applied voltage alone and not the gas pressure but if it was the other it would be a function of both the applied voltage and the pressure. At high pressure and very low pressure the starting potential should be greater than in between. This proved to be the case. The reason for this is explained by the operation of the Crookes tube. Another reason to suspect ionization was that the starting potential for the oscillation or discharge was greater than the extinction potential showing that there were ions that had to be neutralized which is the case in gas filled tubes.

It is now thought that the few counts, at the very few volts below that at which a sudden increase in counts takes place, are due to neutrons and the counter is then acting as a proportional counter. This was first interpreted as an unstable state of the counter because of the extremely narrow range of voltage in which it appeared (35 volts). It was passed over many times
without notice. The pulses due to these counts are quite large compared to the others.

**The Third Test**

The tube was taken apart and examined for spark probabilities. As was mentioned earlier the hole in one end plate was not rounded and this seemed to be the only possible source of arcing so it was put on a lathe and a large radius of curvature was put on it and the other end was rounded more to match. The holes in the end plates are one-half inch in diameter and the inside of the tube is about one inch square so there was just room enough to put a radius of curvature of about one quarter of an inch. The glass insulators were then cleaned and the tube assembled and filled in the same way as in test two. There was no evidence of sparking during the succeeding test. The voltage on the tube was increased to about 1100 V when counting started. These counts were random but very few. At 1250 V it was thought that neutrons were being counted. It was noted that at 1400 V the mechanical counter was counting very fast. The source was taken away and the counting decreased until just a small background was noted. A gamma ray source was brought near and the counting rate increased to a value less than before but large enough to indicate that the
tube was acting as a geiger counter.

When the counter was adjusted so that the tube seemed to count only neutrons a strange action was observed. When the neutron source was taken away the count decreased but if a gamma source, like a radium dial watch, was brought near, the background stopped; then after about three or four seconds it built up to a constant value independent of the placement of the watch as long as it was very close to the tube (6 inches). When the watch was removed, the counting stopped and then built up to the same background counting rate observed before the test. Due to the random nature of counting, no correlation was noted between the counting rate with the gamma source near the tube and far away. To date no reason for this strange action has been proposed. The action was not always reproducible but was observed many times.

The counter was tested with many different operating voltages and an attempt to get reproducible results was made but it was noticed that the starting potential for apparent neutron counting increased with time. This indicated a leak in the system which was later observed on the manometer. Neutron counting started at from 1250 V to 1500 V. The latter figure was the highest voltage used for neutron counting without
counting gamma rays and the voltage range for proportional counting was less than thirty volts. For all of the above tests the tube was isolated by stop cock (6). Because of the increased starting potential, the stop cock was opened and the threshold for neutron counting was immediately lowered to 1340 V and the pressure in the system was seen to rise by the indication of the manometer. The system was pumped out and left overnight.

The Fourth Test

There were two difficulties to be corrected before successful operation could be expected. Of course the most obvious trouble was the leak and the other was the very narrow region of proportionality. Research was conducted to see why the gas amplification should increase so rapidly. Korff (10, p.50) and Diven (3, p.22) showed that for low percentages of alcohol the amplification increased very rapidly with the applied voltage and that with the conditions in the tube similar to those in the preceding test there should be a proportional region of only about 40 volts. It was also found that by increasing the alcohol percentage to about half the total pressure, the region of proportionality would be over 100 volts for tube amplification of $10^2$ to $10^3$. An attempt was made to make the tube vacuum tight
and to test the new filling percentages. The tube was filled by the same method as was used in all of the other fillings but the alcohol pressure was increased to about 48 mm of mercury and the total pressure of 90 mm was used. The tube was connected to the high voltage and the test made. Counting started at about 1200 V and only neutron counting was observed until the potential was increased to 1350 V when Geiger counting was observed. The apparent 150 V plateau was not real because the starting potential increased with time and thus the starting potential for gamma counting increased also. Neutron detection was repeated at least ten times but the increase of starting potential indicated the leak had not been corrected.

Because the tube operated as expected, the construction of the second tube was started and glyptal was put on the leaking tube on all places where leaking was believed to be possible.

The Fifth Test

As near as possible the second tube was built just like the first tube. It was coated as described in the vertical method and then assembled. A "Y" adapter was made so both tubes could be filled at the same time and they would have exactly the same filling. This is shown
in the tandem setup in Fig. 19-B. The tubes were filled in the same manner as in test three with one exception (as far as is known), that is the argon was taken from a breathing oxygen bottle that had been cleaned out with carbon tetrachloride to eliminate the lubricating oil that had been in it. This bottle was evacuated and allowed to stand for two days when it was tested for vacuum and found to be very nearly the same as when sealed off. The tank was flushed with argon and pumped out three times before it was filled to a pressure equal to twice atmospheric.

The same wires and connections were used so that as nearly as possible the only difference in the tubes would be the boron wall coating. Black glyptal was also put on the second tube as a precaution against leaks. The high voltage was applied to the tubes one at a time and no counting was observed up to 3000 V from either tube. The BF$_3$ tube was connected to be sure the electrical system was operating correctly. There was no difference noticed in the counting of the BF$_3$ as compared to previous uses of the tube. The tubes were retested with no success, so the system was repumped and refilled. This did not seem to have any effect. Neither tube would count gamma rays or neutrons. There were observed "noise" counts after the potential was
raised above 900 V but these soon stopped after the variac was left in one position. These counts were not noticed in any significant amount when the $\text{BF}_3$ tube was used. No explanation for this has been found. The tubes were then repumped and filled with just argon and tested again but no counting that could be attributed to radiation was observed. There were only two known differences between the apparatus when counting due to radiation was observed and when counting due to radiation was not observed. The differences were: the gas was taken directly from the bottle in the first case and from an intermediate container in the second and the second difference was that glyptal was put on the counters. The system was pumped out and left for a day to rid the tubes of any volatile substances. The next day the tubes were pumped down for at least an hour and then isolated by closing the stop cock (6). The high pressure argon tank was connected to the system and the line from it flushed as mentioned earlier. The system was evacuated and the pump left on for at least an hour after no indication of pressure could be seen on the ionization gauge. The system was then filled and tested but no counting due to radiation was observed. The apparatus was very tight and left filled for about a month and no change in pressure was noted.
The Sixth Test

After much investigation of the literature on the discharge mechanism in counter tubes of this type it was decided that the source of trouble should not be in the filling gas. The only other possibilities were electrical connections in the only part of the electrical circuit that was not tested by operation of the BF$_3$ tube. After many tests of the individual parts of the circuit it was decided that if the BF$_3$ tube was put in parallel with the other tubes and counting observed then the electrical circuit would be all right. This was done and counting was observed. A voltmeter was connected across the resistor, R 1, in Fig. 6 to see if there was a voltage drop. This would indicate a leakage in the circuit. No voltage drop was detected so an oscilloscope was connected to either side of R 1. The wave shape of the high voltage power supply was seen but it was very small and believed to be due to the ripple in the power supply. The BF$_3$ tube was then put in series with the solid boron tube that had operated. This was done to see if a signal received at one end of the wire would be transmitted to the other and register a count. That is, if a pulse gets on the wire a count will result. This was found to be true and the counting observed was
no different from that when the tubes were in no way connected.

The Seventh Test

There remained one possibility not checked in the foregoing tests. It had been assumed that even if the counter tube had air at atmospheric pressure, at least corona discharge should start at 3,000 V across the electrodes. A check disqualified this assumption. The operating characteristics of a geiger tube tested by the author were checked to see at what potential that tube went into corona discharge. It was found that under atmospheric conditions the voltage was higher than 3,000 V and that if the fields were calculated by the use of equation (4) for the geiger tube and the solid boron tubes, the continuous discharge potential was over 3,000 V. It was decided to disconnect the tubes and blow air into the copper tubing connected to the counter tubes to make sure there was no obstruction in the line which would prevent obtaining the proper reduced pressure in the counter. There did not seem to be any obstruction in the tubes to the counters.

The tubes were then left to stand at atmospheric pressure for about a month while the vacuum pump was repaired. As an added precaution the geiger counter
The geiger counter was connected in parallel, in the electrical sense, with the solid boron counter tubes and the potential applied to them after the tubes had been filled in the usual manner. The geiger counter began counting at 1500 V with a total pressure of 12.8 cm of mercury when a uranium gamma source was brought near. There was noted a leak in the system and it was found that carbon tetrachloride which was used as a leak detector filled up the leak and the system pumped down to a good vacuum. This effect lasted about an hour and it enabled rough tests to be made. At a total pressure of 9.4 cm the starting voltage for geiger counting in the geiger tube was 1250 V. Castor oil was put on the rubber hoses and the leak stopped.

The geiger counter tube was electrically disconnected from the neutron counter tube and the potential difference between the electrodes increased until counting was observed at about 1200 V. About 30 V proportional region was observed with either power supply, (one was filtered and regulated and the other poorly filtered and not regulated). An explanation was sought for the narrow region of proportionality and the
following calculations give the reasoning used.

The Eighth Test

Calculations on the operation of the solid boron lined tube.

Consider an alpha particle given off in the disintegration of a B\textsuperscript{10} nucleus after the absorption of a neutron. The energy given the alpha particle will be on the average 1.6 Mev and 0.9 Mev will be given to the recoiling lithium ion (10, p.51). This amount of energy is less than the theoretical binding energy but the extra energy is assumed to be contained by the lithium which is in the excited state. Under favorable conditions the boron nucleus will be on the surface of the lining so all 1.6 Mev of energy goes into ionization of the gas if the pressure and geometry are favorable, but this will not always be the case. For the first calculations the most favorable conditions will be considered.

For argon the stopping power is 1.94 times that of air. See footnote in (15, p.221). The range of 1.6 Mev alpha particles in air at atmospheric pressure is 0.85 cm. It will now be assumed that either the pressure in the tube is at least one half atmospheric or the dimensions of the tube are large enough so there is a
large chance of the alpha particle spending its entire energy in the tube.

If twenty-five electron volts of energy (15, p.227) is expended for each ion pair formed then there will be

\[ \frac{1.6 \times 10^6}{25} = 6.4 \times 10^4 \text{ ion pairs} \quad (6) \]

formed by each alpha particle. If each of these ions have $1.6 \times 10^{-19}$ coulombs (electronic charge) and there was no cumulative ionization in the tube there would be a charge of

\[ (1.6 \times 10^{-19}) (6.4 \times 10^4) = 1.0 \times 10^{-14} \text{ coulombs} \quad (7) \]

collected on the wire of the counter.

The capacitance of the counter is assumed to be $10^{-11}$ farads. This is an approximation based on Korff (10, p.18). The pulse due to the collection of the ion pairs is then found to be

\[ V = \frac{Q}{C} = \frac{1 \times 10^{-14}}{10^{-11}} = 1 \times 10^{-3} \text{ volts}. \quad (8) \]

With a gain in the amplifier of $10^4$ the output would be 10 volts if there was no amplification in the counter tube. It is seen clearly that alpha particles could be detected if they spent all of their energy in the counter even without avalanche amplification.

The less favorable case will now be considered
where the ion does not spend all of its energy in the gas. The problem is as follows; there are two types of counts in the detector, those due to alpha particles which spend only a fraction of their energy in the gas and those due to gamma rays which spend only a fraction of their energy in the gas. The problem is different from that encountered in tubes filled with BF$_3$ because the alpha particles and lithium ions both contribute a large part of their energy to the production of ions in the gas. Thus the total number of ions formed per boron disintegration is considerably different in the two counters whereas the total number of ions formed by gamma rays is nearly the same. It then seems necessary to make sure that each alpha particle that gets into the gas, spends all of its remaining energy in the gas. Of course the gamma rays will also spend more energy in the gas if higher pressures are used.

If the alpha particle spends about half of its total energy in the counting volume, about half an atmosphere pressure would be needed (40 cm). There would then be about $3.2 \times 10^4$ ion pairs formed or $10^{-14}$ coulombs collected on the wire. This would give a voltage pulse of $10^{-3}$ volts. The pulse due to a gamma ray would be roughly
\[
\frac{(6) (2) (1.6 \times 10^{-19})}{10^{-11}} = 1.9 \times 10^{-7} \text{ volts.} \quad (9)
\]

For these to be detected it seems that there must be an amplification of $10^3$ or greater in the tube. Gamma rays were being detected so it would seem that the amplification went up very rapidly as the voltage increased. It was then decided to increase the pressure to about 40 cm and build a pre-amplifier with a gain of 100 so the tube amplification could be kept low. The pre-amplifier suggested by Elmore and Sands (5, p.166) for proportional counters of low amplification was built. The circuit and picture of the unit are shown in Fig. 20.

The increase in amplification introduced a considerable amount of noise that had to be eliminated. One source of noise was due to multiple ground wires from the pre-amplifier to the main amplifier. These were connected so that there was only one ground to the pre-amplifier chassis and one ground lead to the main amplifier. The ends of the tubes connected to the counter wire were found to be acting like receiving antennas for the varying fields in the room. Copper screens were put over the ends and the interference due to the carrier wave of one of the local radio stations was practically eliminated. It is believed that the residual pickup of the carrier wave was through the power supplies as all
of the apparatus other than these were very well shielded. This remaining noise was very infrequent so did not interfere with qualitative tests. With the increased amplification the cover had to be put on the main amplifier.

The solid boron tubes were tested individually and together. The results are tabulated below:

<table>
<thead>
<tr>
<th>Total Gas Pressure</th>
<th>Gas Filling</th>
<th>Starting Potential (neutron)</th>
<th>Starting Potential (geiger)</th>
<th>Counts Tube per minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 cm</td>
<td>50% argon 50% alcohol</td>
<td>1075 V</td>
<td>1200 V</td>
<td>460</td>
</tr>
<tr>
<td>8.1 cm</td>
<td>50% argon 50% alcohol</td>
<td>1075 V</td>
<td>1200 V</td>
<td>460 to 1 and 2</td>
</tr>
<tr>
<td>20 cm</td>
<td>21% alcohol 79% argon</td>
<td>1220 V</td>
<td>1300 V</td>
<td>472 to 1 and 2</td>
</tr>
<tr>
<td>20 cm</td>
<td>21% alcohol 79% argon</td>
<td>1260 V</td>
<td>1350 V</td>
<td>357</td>
</tr>
<tr>
<td>35 cm</td>
<td>12% alcohol 88% argon</td>
<td>1300 V</td>
<td>1480 V</td>
<td>337</td>
</tr>
<tr>
<td>51.6 cm</td>
<td>8% alcohol 92% argon</td>
<td>1420 V</td>
<td>1700 V</td>
<td>350</td>
</tr>
<tr>
<td>10 cm</td>
<td>100% argon</td>
<td>450 V</td>
<td>510 V</td>
<td>303</td>
</tr>
</tbody>
</table>

None of the strange happenings observed in some of the previous experiments were repeated. The tube operated consistently with the exception of the increased background because of the high amplification. For the
data taken the background was about ten counts per minute. Quantitative information could not be obtained because the stabilized power supply had to be rebuilt. The counting rate of tube 1 (the first built) was quite consistently about 350 counts per minute averaged over ten minute intervals at different pressures and gas fillings. The proportional counting voltage range (plateau) varied with the filling from 110 V to nearly 300 V. The increased range went with increased pressure. A uranium gamma source was brought near the tubes before and after each test to be sure the tube was not acting as a geiger counter.

The counting rate of tube 2 seemed to be slightly higher than tube 1 and the voltage range of the plateau was greater, but fewer tests were made on this tube as it was believed that the author was being exposed to too much radiation.

The BF₃ tube operated with the same counting rate when the pre-amplifier was used but the amplification of the main amplifier could be reduced. With six inches of paraffin surrounding the neutron source, and the BF₃ tube 27 inches from the source, 640 counts per minute were recorded for ten minutes. This included the background of about five counts per minute.
CONCLUSIONS

There does not seem to be any doubt that satisfactory neutron detectors can be made by coating the walls of the tubes with solid boron in the manner described in this thesis. The principle disadvantages seem to be the narrow region of proportionality compared to the BF$_3$ tube and higher amplifications are needed in the electronic amplifying circuit. The optimum operating conditions have not been investigated as it would take considerable time, but the possibility of building inexpensive neutron counter tubes of quite high efficiency is clearly evident. At first it was believed that these tubes were far more efficient than they apparently are. This was due to a high counting rate, when near the source of neutrons, that is now interpreted as pile-up counts due to high gamma ray flux. The counting volume of each tube is estimated to be about 8 cubic inches. The counting volume of the B$^{10}$ enriched BF$_3$ tube is about 48 cubic inches. A rough evaluation of the relative efficiency indicates that the solid boron tubes are about three times more efficient than the gaseous boron tube of equal counting volume and it should be remembered that the B$^{10}$ enriched gaseous tube is five times more efficient than normal BF$_3$ filled tubes.
BIBLIOGRAPHY


