A SCINTILLATION COUNTER FOR USE IN MEDICAL RESEARCH

and

THE STOPPING OF MESONS IN ABSORBERS AT LOW ALTITUDES

By

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The author of this thesis holds the following degree:

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Scope and contents of this thesis:

This thesis is made up of two parts.

Part A - describes the construction of a scintillation counter and its operation, as an instrument for use in medical research.

Part B - is a study of the stopping of mesons in various absorbers as a preliminary to the investigation of the meson decay process.

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PART A

A SCINTILLATION COUNTER FOR USE IN MEDICAL RESEARCH

I INTRODUCTION

Medical research has received a new tool in the last ten years in the application of radioactive isotopes which are readily produced in the atomic pile. However, for this purpose the radioisotope should be non-toxic and have non-toxic daughter products. It must localize only in the area to be studied, have a reasonably short half life and be manufactured economically in a fairly concentrated form (1). Of the radioactive tracers that fulfil the above mentioned requirements, eight day I^{131} is perhaps the most interesting. Its decay scheme (2,3) which is well established is shown in Figure 1. The beta component is absorbed by the surrounding tissue, hence only the gamma rays may be detected externally. For diagnosis it is imperative that small doses be given to the patient and therefore a very sensitive gamma detector is needed. This work describes a scintillation counter which in a large measure satisfies the above requirements.

II THE SCINTILLATION COUNTER

The scintillation counter (4) has several advantages over the geiger counter for the detection of gamma rays. Essentially it consists of a crystal which scintillates under irradiation by alpha, beta or gamma rays coupled with a photomultiplier tube (931, 1P21 or 5819) which detects the light flash through the photoelectric effect and amplifies it into a voltage pulse of from one to three volts. The scintillation counter is both rugged and extremely sensitive, its efficiency for gamma rays being roughly 20% (5) as compared to 1% (6) for the geiger counter. Moreover, the scintillation counter has negligible dead time and is therefore capable of recording very high counting rates. Unfortunately it has two disadvantages; the first is a large dark current and the second a variable pulse height from monoergic radiation. The dark current (7) is due to a combination of ohmic leakage in the tube, thermal emission and regenerative ionization effects, which appears as a large background counting rate. Figure 2 shows this dark current as a function of the dynode voltage. The variation in the pulse height is due to the statistical manner in which the secondary elections, multiplied by the dynodes of the photomultiplier tube, vary, and to the variation in the size of the light pulse produced in the crystal. This pulse height variation may cause the noise pulses to be of comparable amplitude to signal pulses. The dark current may be reduced by refrigerating the photomultiplier tube and by proper design of the circuit, while the variable pulse height may be controlled by a proper choice of dynode voltages. The light pulses from an anthracene crystal are independent of temperature while they decrease as the temperature falls in the case of a sodium iodide crystal. Hence refrigeration is advantageous in the case of an anthracene detector but detrimental in the detector using sodium iodide.

III THE PROBE

The survey monitor consisted of two parts, a probe which contained the detector photomultiplier tube and preamplifier, and the main amplifier. When designing the probe, it was felt that the qualities of total and directional sensitivity, selectivity, ruggedness and ease of operation were essential. These requirements are met with a type 1P21 photomultiplier tube and an anthracene crystal. Anthracene, because of its density, high light yield and crystalline structure is particularly suitable as a detector. Furthermore, the most intense wavelength it emits is that for which the 1P21 tube is most sensitive. Other crystals (8,9) were excluded because they posess undesirable features which outweigh their advantages. For example NaI(Tl) which is obtainable as large clear crystals, and which gives large light pulses was discarded because it is extremely hygroscopic.

Figure 3 is a full scale diagram of the probe that was finally adopted. This instrument was designed to scan small areas and to permit a comparison of the amount of radioactivity in adjacent areas. A lead collimator was used to give maximum sensitivity for gamma rays incident upon the crystal from the desired direction and at the same time to reduce the sensitivity of the detector for radiations coming from other directions. Considerations of weight prevented completely adequate shielding but the half inch of lead with which the crystal was surrounded reduced the intensity of the radiation incident upon the crystal from the side by a factor of 17. The probe was so designed that various apertures could be used by simply inserting the correct lead collimator. Furthermore, provision was made for the changing of the crystals, so that different ones could be used. A large output pulse was obtained by placing the crystal in direct contact with the envelope of the photomultiplier tube thus permitting more light to reach the photosensitive cathode. It was found necessary to cool the tube so an insulated, double walled canvas bag was placed around the probe: the space between the bag and probe being filled with dry ice. This decreased the thermal noise by a factor of ten and permitted the detection of weaker sources.

IV ELECTRONIC CIRCUITS

The apparatus consists of three units, the preamplifier, the main amplifier and the power supplies. The preamplifier, (Figure 4), mounted in the handle of the probe, consists of a single stage linear amplifier and a cathode follower, employing type 6AH6 tubes. A negative pulse from the photomultiplier tube is applied to the first stage where it is amplified, inverted and fed to the cathode follower as a positive pulse. The cathode follower serves to match the high impedance output of the amplifier to the low impedance coaxial cable. This prevents standing waves from being formed in the cable. No change in shape or polarity of the pulse occurs in the cathode follower, but since it has a gain of less than unity there is a reduction in its amplitude. In order to reduce the amplification of the noise from the photomultiplier tube a two microsecond time constant network (C2 R13) is incorporated into the grid circuit of the first stage of amplification. The noise pulses whose rise times are of the order of 10^{-9} seconds are smoothed out by the two microsecond network constant while the slower signal pulses are not much affected.

The main amplifier unit (Figure 5) consists of one stage of amplification, a discriminator unit and an univibrator counting rate meter. This circuit is similar to that used by H.E. Petch (10) hence only a brief explanation of it is required. The first stage amplifies and inverts the pulse received from the preamplifier. The resulting large negative pulse is fed to the discriminator which consists of a double diode type 6AL5. Pulse height discrimination is accomplished by applying a positive voltage to the cathode of the first diode. The second diode serves to prevent switching transients from the univibrator from being applied to other parts of the circuit.

The counting rate meter consists of a double triode type 6J6 connected such that the first half conducts while the second is cut off. A microammeter, shunted by a large condenser C15 is in series with the "normally off" triode. A negative pulse from the discriminator causes the first triode to be cut off and the second to conduct. This second triode conducts for about one microsecond, charges the condenser and the circuit returns to its original state. The condenser then discharges through the microammeter causing a deflection. The greater the counting rate, the greater the charge on the condenser and the greater the deflection of the meter. This permits the calibration of the meter to read the counting rate directly.

Two power supplies are used in the survey instrument. The first of these (Figure 6) is a conventional regulated power supply using two voltage regulator tubes in series placed across the output. This supplies 155 volts at 150 milliamperes to the preamplifier and main amplifier units. The second power supply, Figure 7, is of greater interest, and although it is discussed in the literature (11,12) a brief description of it is warranted here.

Coultman (4) has shown that an optimum signal-to-noise ratio in a photomultiplier tube is obtained by choosing the proper anode voltage. He has further shown that this voltage must be extremely stable in order to get reproducable results. For these reasons a stabilized power supply was designed which is capable of any output voltage between 500 volts and 1500 volts at 10 milliamperes, and which has a stabilization ratio of 0.1% with a change from 95 volts to 140 volts at the input. This power supply consists of the usual transformer rectifier and filter circuit with the addition of a stabilizing network. This network contains a series tube, an amplifier, and a source of reference voltage. The series tube is an 807 connected as a triode and acts as a variable resistance. If the output voltage decreases, the amplifier tube (type 6SJ7) has a lower voltage applied to its grid. Less plate current flows and less bias is therefore applied to the grid of the 807. This decreases the resistance of the 807 and the output rises to compensate. The amount of amplification is adjusted to the correct value by a screwdriven setting of resistor R43, and the output voltage is controlled by the grid resistor R44. The reference voltage for controlling the stabilization is furnished by the VR 150-30 in series with the cathode of the 6SJ7.

V APPLICATION

The probe which has been described has been used both to measure the total uptake of iodine in the thyroid gland of a patient and to explore nodules in the thyroid and other parts of the anatomy. This type of application is not new, but this instrument has proven to be more sensitive than most of those described in the literature (1,13).

The function of the thyroid gland is to convert the free iodine obtained in the patient's food and absorbed into the blood stream into protein bound iodine, which can be used by the tissues. Since radioactive iodine is accepted by the body on the same basis as normal iodine it can be very simply used as a tracer to follow the mechanism of iodine conversion through the detection of the beta and gamma radiation which it emits. In practice, the patient is given orally a glass of water containing 100 microcuries of radioactive iodine in the form of sodium iodide. Twenty-four hours later tests are made to discover the distribution of this iodine in the patient's body. A certain fraction will be found in the blood, some found in the thyroid and some will have been eliminated.

The doctor, for purposes of diagnosis, requires a knowledge of the conversion ratio, that is, the efficiency of the thyroid in converting free iodine into the protein bound form. This can be obtained by taking a blood sample and separating out the plasma. The plasma is divided into two equal portions, one of which is chemically treated to precipitate the protein. The protein and the untreated plasma are then dried in shallow sample dishes and their beta activities compared by means of an end window geiger counter, corrections being made of course for background counts. The method is time consuming since it requires several hours to dry the samples.

The probe was used on each patient to measure the relative pickup of the thyroid, that is the ratio of the activity of the thyroid to the activity it could have had if all of the iodine given the patient had been concentrated there. To do this, the probe with its widest aperture was placed 30 centimeters from the patient so that the crystal could "see" the whole of the thyroid gland and the activity measured in counts per minute. A second count was then taken with a 100 microcurie sample, prepared on the preceeding day, replacing the patient. Both counting rates were corrected for the background due to noise and cosmic radiation. The ratio of these corrected rates gives the percentage pickup of the thyroid directly. The relationship between the pickup and the conversion ratio is shown in Table I, in which each column refers to a different patient.

TABLE I COMPARISON OF TOTAL PICKUP AND CONVERSION RATIO

Percent Pickup	39	66	35	25	9.4	19	37	22	19	24	18.5	57	25	21	65	29	70	78	21	60
Conversion Ratio (%)	27	75	28	39	7	5	6	18	80	60	24	98	10	7	44	38	89	90	44	64

It is sufficient from the medical point of view to classify the patients into three groups. Those with conversion ratios in the range 10% to 35% are classified as normal, those below 10% as hypothyroid and those above 35% as hyperthyroid. On examination of Table I it is seen that there is rather good agreement between the two sets of data, particularly when it is considered that errors of the order of 20% are present in both measurements. Since it is much simpler to measure relative pickup than the conversion ratio, it would seem that the pickup measurement could be used as a reliable technique for the diagnosos of thyroid conditions in place of the more direct measurement of conversion ratio.

In a diseased thyroid there are often found hard nodules which may be either over or underactive and since an underactive nodule often indicates a carcinoma, the doctor is interested in identifying them. These nodules are studied by placing a lead collimator in front of the crystal and measuring the activities of small portions of the thyroid. This enables a comparison to be made between the activity of the nodule and that of the adjacent gland. Figure 8 (a) shows the results of such measurements on a thyroid containing a watery cyst. The figures represent the counting rates on the gland at the points indicated; the portion with a count of 41 being the cyst, an underactive nodule. A case where surgery has not completely removed the gland is illustrated in Figure 8(b). Here remaining tissue is indicated by higher counts. A large number of cases with nodules have been studied and the information obtained has been of value in indicating the treatment required.

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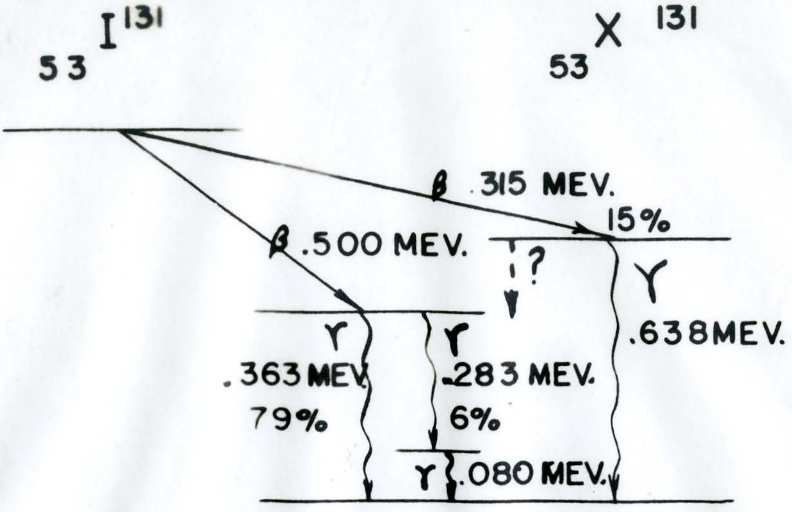
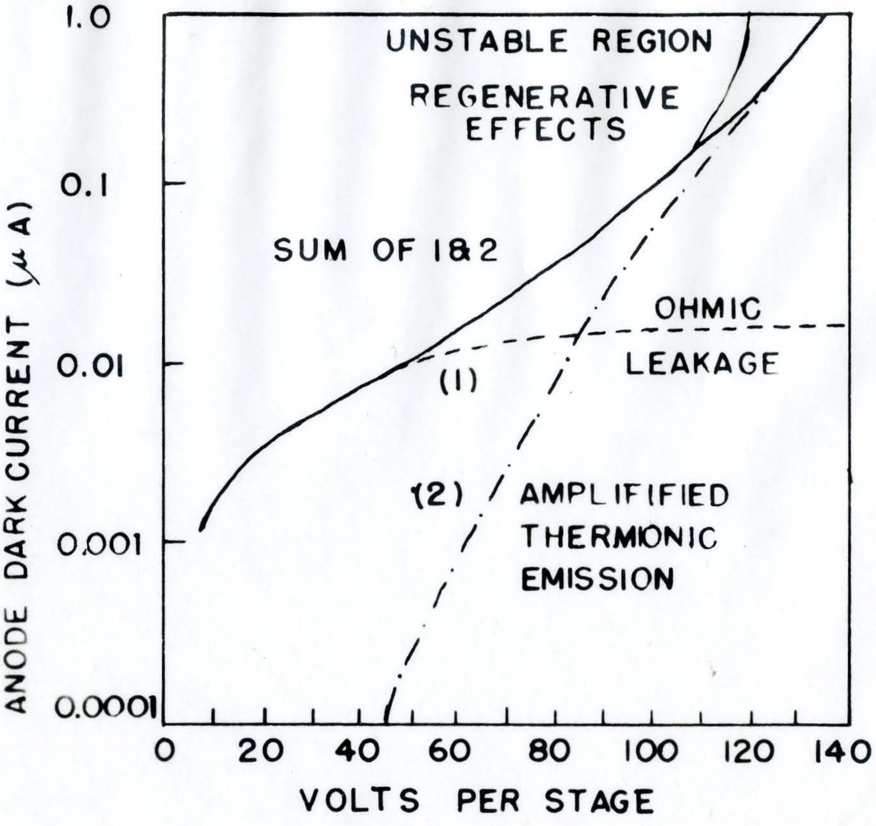


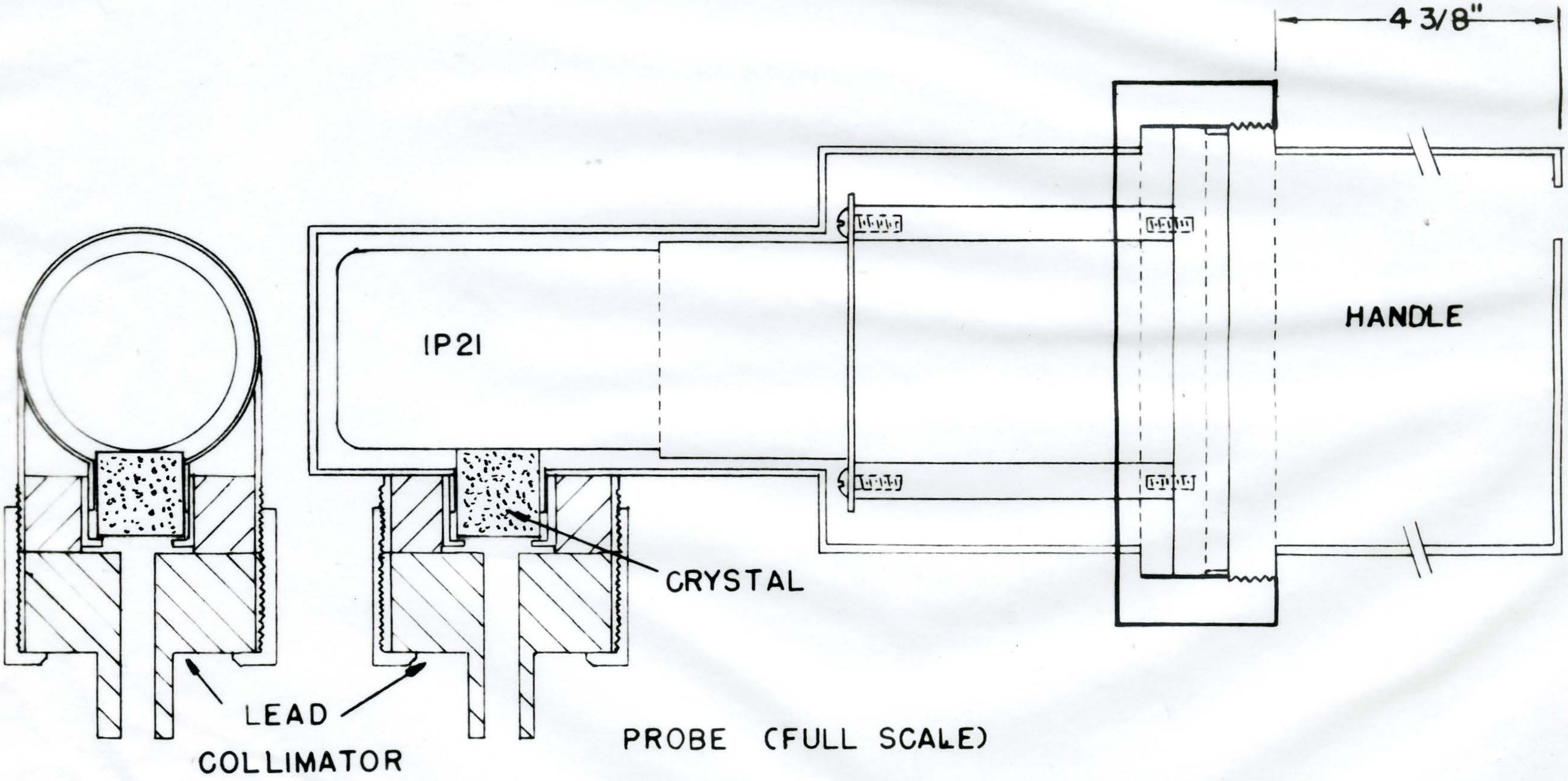
DECAY SCHEME I^{131} (1,2)

FIGURE 1



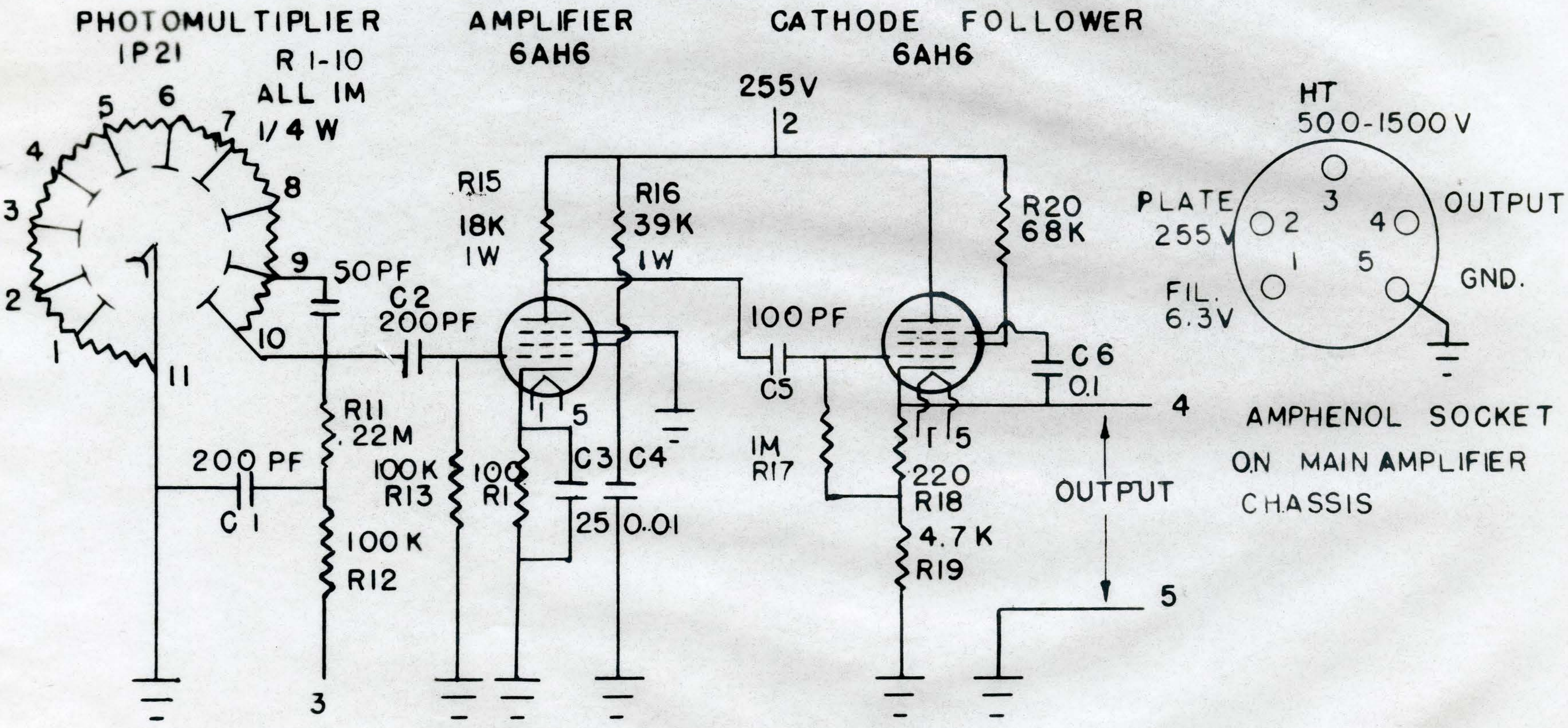
PHOTOMULTIPLIER DARK CURRENT

FIGURE 2



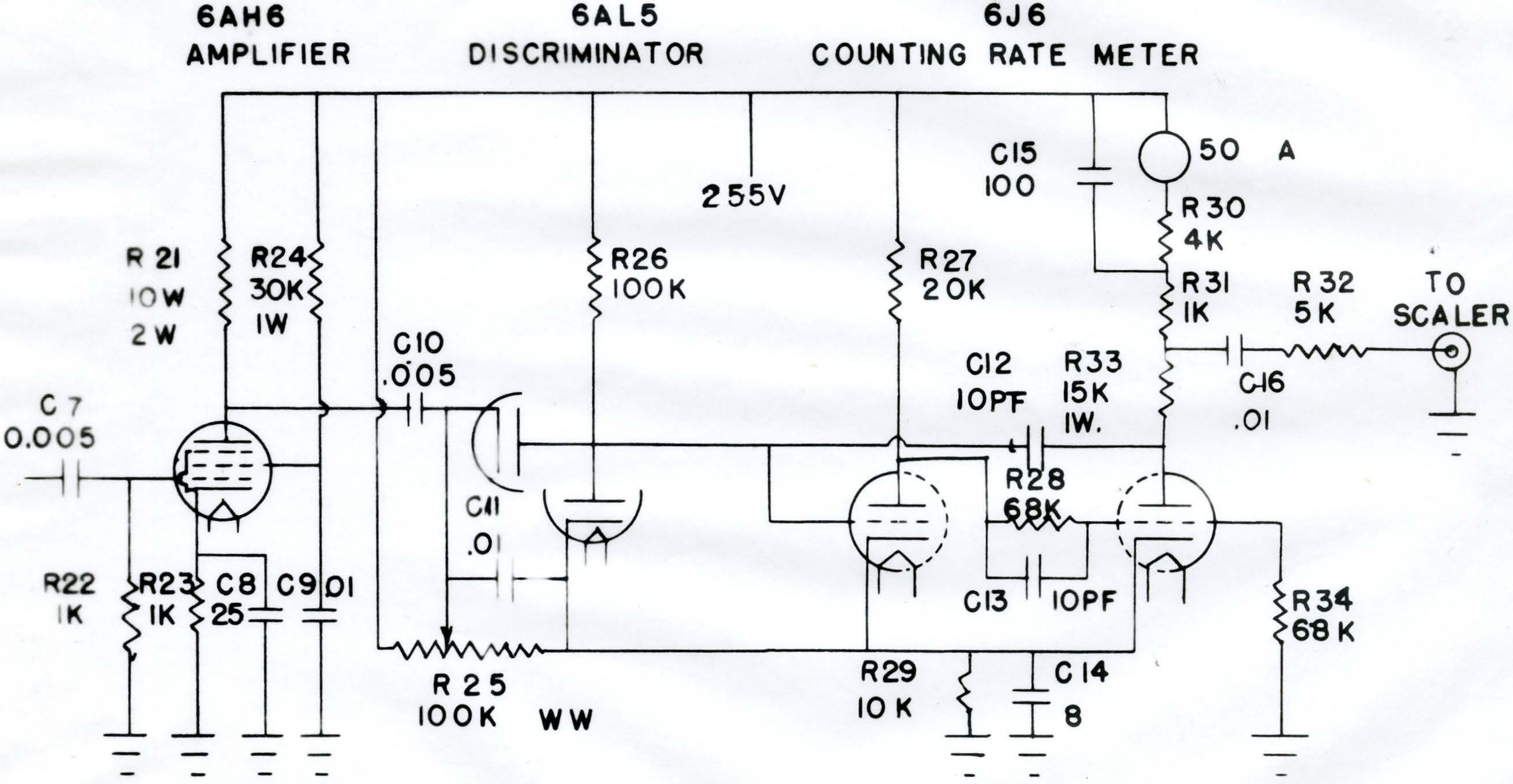
PROBE (FULL SCALE)

FIGURE 3



DETECTOR & PREAMPLIFIER

FIGURE 4



MAIN AMPLIFIER

FIGURE 5

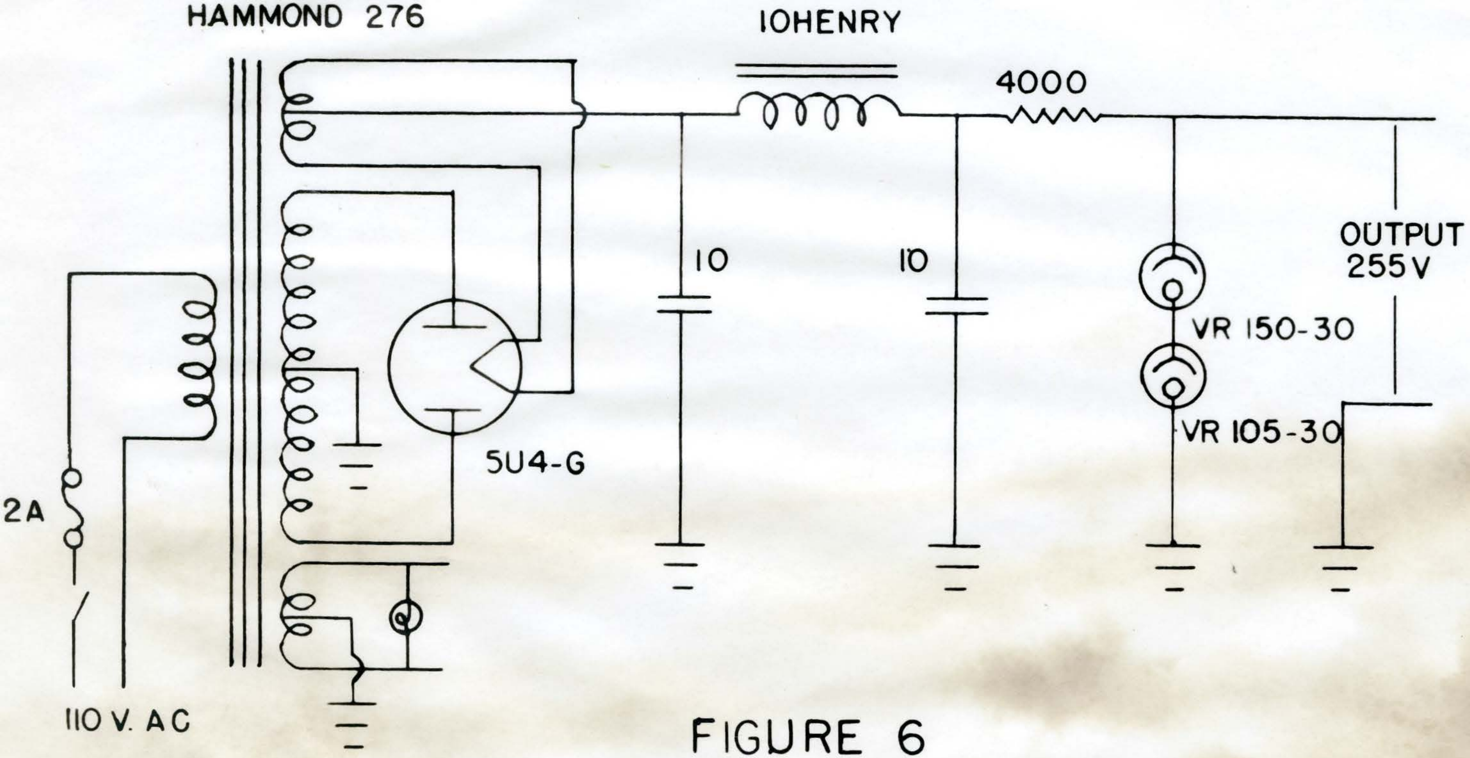

HAMMOND 276
10HENRY
4000
10
10
OUTPUT
255V
VR 150-30
VR 105-30
5U4-G
2A
110 V. AC

FIGURE 6

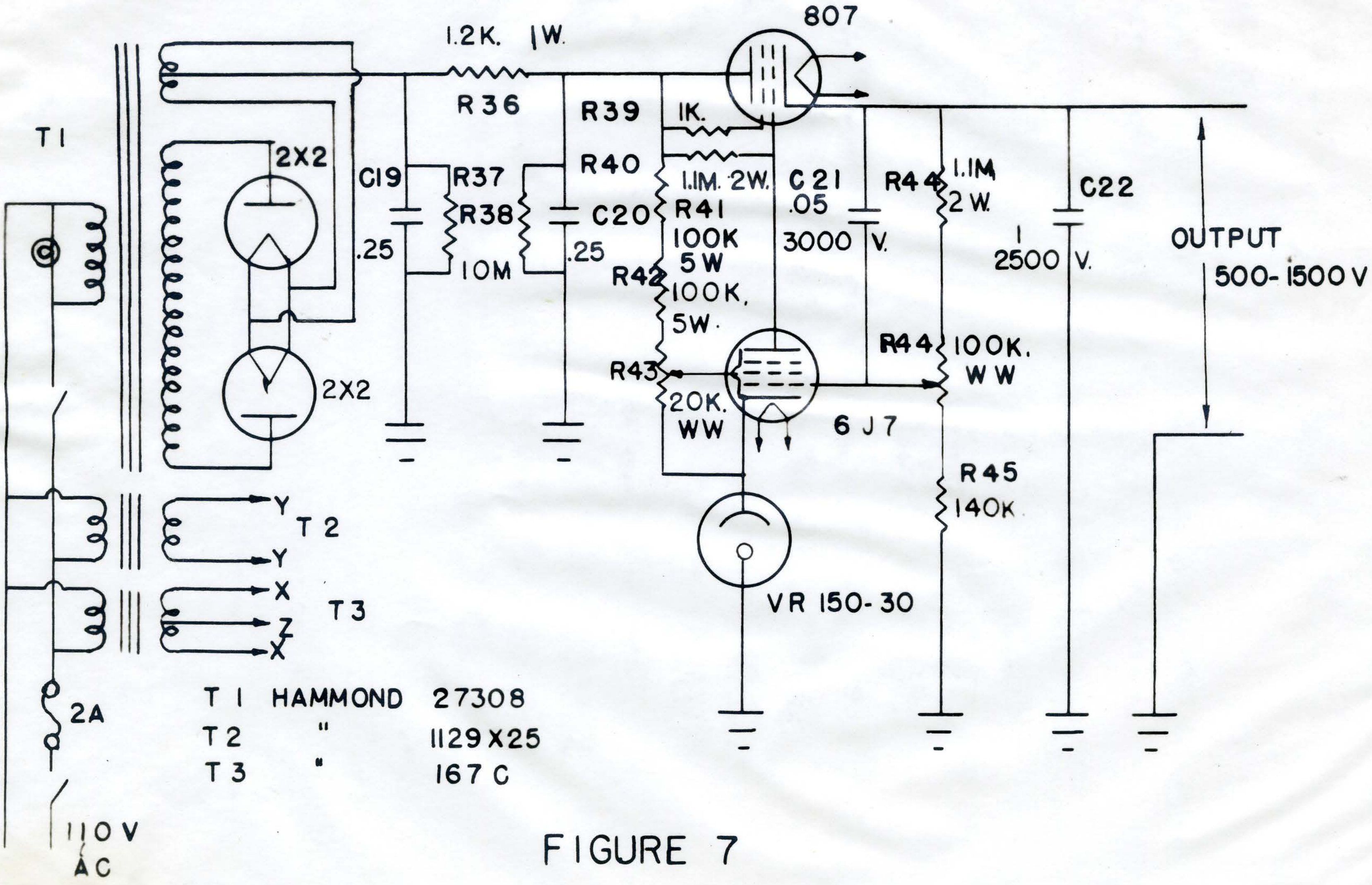

807
1.2K. 1W.
R36
R39
1K.
R40
1.1M. 2W.
T1
2X2
C19
.25
R37
R38
10M
C20
.25
R41
100K
5W
R42
100K,
5W.
R43
20K.
WW
C21
.05
3000 V.
R44
1.1M
2W.
C22
1
2500 V.
OUTPUT
500-1500V
R44
100K.
WW
6J7
2X2
R45
140K
VR 150-30
Y
T2
Y
X
T3
Z
X
2A
T1 HAMMOND 27308
T2 " 1129X25
T3 " 167C
110V
AC

FIGURE 7

PART B

THE STOPPING OF MESONS IN ABSORBERS AT LOW ALTITUDES

I INTRODUCTION

Cosmic radiation has been a source of constant investigation since it was first discovered in 1913 by Hess and Kolhoerster. Experiment has revealed this "radiation" to be composed of a variety of particles; protons, neutrons, electrons, photons and mesons. Only two of these, the electron and the meson are found in any quantity at sea level. Of these two particles, the meson has proven to be of the greatest interest from a theoretical as well as an experimental point of view. It is well known that the only meson component encountered at sea level is that of the mu meson. This particle has a mass of 215 electron masses, a charge of either plus or minus the electronic charge, and a mean lifetime of 2.15 microseconds (1)(2). Considerable study has been made of the mu meson for it was once believed that this particle "cemented" the nucleus together. Although later work proved this hypothesis to be incorrect (3)(4)(5), a great deal of study is still being devoted to it for there are still two very important but unsolved problems associated with it. The first of these is the determination of the mechanism of capture of the negative mu meson by the nucleus, and the second is the investigation of the products of positive mu meson decay.

Considerations of energy demand that when a negative meson is captured some particles be given off with a total energy equal to the rest energy of the captured meson. To date however, no such particles have been discovered (6). A positive mu meson on the other hand is slowed down by inelastic collisions and repelled by nuclear fields until it finally decays with a mean lifetime of 2.15 microseconds. It is known that an electron is ejected (7) and there is a strong belief that two neutrinos (8)(9) are also liberated. The negative mesons also decay but this decay is a function of the atomic number and is only appreciable for elements of low atomic number (3).

One of the most popular methods of studying the decay of the meson is to stop it in different absorbers and to detect the decay particle by means of delayed coincidences. Rasseti (2) first used this method to measure the mean lifetime of the meson. Koenig (10) and others have observed the stopping of mesons in different absorbers using the same method. It is the purpose of this work to investigate the stopping of mesons in absorbers of equal thickness and to draw conclusions as to whether the present experimental arrangement will record a sufficient number of stopped mesons in a reasonable time. If a greater thickness of absorber is necessary it must be honeycombed with geiger tubes in order to detect the decay electrons, for these particles have a range of only a few centimeters, even in carbon. Should a greater area of absorber be necessary, then a change in the geometry of the cosmic ray telescope must be made.

II THE APPARATUS

The electronics involved in the cosmic ray telescope have already been discussed (12). A description of the telescope itself is necessary however. The counter telescope is composed of a number of geiger tubes arranged in rows to form trays. These trays are then oriented so that particles passing through successive trays define a beam. The "aperture" and hence the size of the incident beam of mesons may be adjusted by means of the spacing of the trays of geiger tubes. Figure 1(a) shows a typical geiger counter whose plateau is shown in Figure 1(b). These tubes were manufactured at the university and behaved in a satisfactory manner over a period of many months. The filling consisted of the usual one part by volume of alcohol vapour and nine parts of dry argon at a pressure of 10 centimeters.

Figure 2 is a schematic diagram of the telescope drawn to 1/4 scale. It consists of two trays 15-3/4 inches long, each containing six geiger tubes. These trays, placed one above the other and separated by a distance of 11-1/2 inches defined the "aperture" of the telescope as shown by the dotted lines. A third tray 20-1/2 inches long and containing nine tubes was placed 2-1/2 inches below tray B. This is called "C" tray and it completely fills the beam defined by A and B trays. A one inch thickness of absorber was placed between B and C trays. This absorber consisted of aluminium, carbon, or iron as desired. Background counts were also taken with no absorber present in order to have a measure of the number of mesons that stop in the brass walls of the geiger tubes between the active volumes of B and C trays.

Six inches of lead was placed above A tray in order to screen out the soft (electronic) component and to act as a moderator in slowing the meson. Some electrons will be present in the meson beam however for they do accompany the mesons. These electrons are produced in the lower layers of the lead moderator and are impossible to remove. Koenig (10) has estimated that 94% of the particles below the moderator are mesons and that 6% are electrons.

The three trays are connected electronically to register the following events; (i) AB coincidences and (ii) AB-C anticoincidences, Figure (3). The AB coincidences are due to particles which penetrate both A and B trays within the dead time of either tray. The AB-C anticoincidences are caused by those particles which cause an AB coincidence but do not cause a discharge in any of the counters of C tray. This represents the number of stopped mesons. ABC events are not registered.

III SOURCES OF ERROR

There are several sources of error inherent in the telescope. One of these is due to spurious AB coincidences caused by two particles from outside the meson beam striking A and B trays respectively. This error is very difficult to eliminate unless a very complicated piece of apparatus is used. Since it is small this error is often ignored, or if not, it is included in the accidental count. The geometry is such that C tray completely fills the AB cone of incidence, hence there is no likelihood of ABC (triple coincidence) particles missing C tray due to poor geometry. There is however, a small probability of such a particle passing between the active volumes of C tray counters and thus registering as an AB-C event. Subtracting the AB-C background count from the AB-C value for an absorber removes this error.

Another source of error lies in C tray being struck by a stray particle at the same time that a true AB-C event occurs. The time allowed for such an occurrence is small, of the order of 0.001% of the total time permitted for a true AB-C anticoincidence.

The electronic component accompanying the meson is not likely to cause much difficulty because the range of the electron is much shorter than that of the meson. The decay electrons will not nullify the AB-C readings by triggering C tray because the decay particle is emitted, on the average, 2.15 microseconds after the stopping of the meson.

IV THE EXPERIMENT

The telescope was arranged as shown in Figure 2 and the electronics connected to it as in Figure 3. Several tests were made before the equipment was put into operation, and these tests were repeated during the experiment. The starting potential of the trays was checked at the beginning of the experiment and after six weeks of operation with excellent agreement. This indicated that the tubes were free from leaks and that the aging of the gas was not appreciable. The apparatus was allowed to operate overnight with the high tension to the geiger tubes turned off. Since there were no counts registered, it could be assumed that no spurious pulses were being developed in the electronics. Having made these preliminary tests, the telescope was placed in operation.

The apparatus was operated for a period of one week with no absorber between B and C trays in order to establish a value for the background count. This background count was taken at least once a week thereafter as a further check on the operation of the telescope as a whole. Good agreement was obtained throughout. A one inch thickness of absorber was then placed between trays B and C and the AB and AB-C counts recorded over a period of weeks. This procedure was repeated with each of the absorbers in turn until a mass of data was accumulated. As a final check on the operation of the equipment, short, 24 hour runs were made with each of the absorbers in turn as well as with no absorber. The number of AB and AB-C events fitted well with the values obtained during the three months of continuous operation, hence it was felt that all of the data was valid.

The accidental counting rate was obtained by displacing B tray until it was in a plane with A tray. This accidental rate is probably due to meson produced showers originating in the lead immediately above the tubes. The AB-C accidental rate is probably valid and due to shower particles having insufficient energy to penetrate the brass separating the active volumes of A and B trays from C tray.

VI DISCUSSION AND CONCLUSIONS

Of the two methods of studying meson absorption, the measurement of the change in the intensity of the meson beam when different absorbers are placed in it, and the anticoincidence technique described in Section Iv, the latter is the most efficient. This is readily seen from a consideration of the statistics involved. A much longer counting time is required in order to obtain a given accuracy using the change of intensity method than using the method of anticoincidences, consequently the anticoincidence technique was used. The counting rates with different absorbers over a period of three months are listed in Tables I and II.

TABLE I

ABSORBER	TOTALS AB	TOTALS AB-C	TIME (Hours)	COUNTS PER HOUR AB	COUNTS PER HOUR AB-C
Accidentals	277,487		239.5	1182 ± 72	
Background	1,873,035	162,198	483.4	3864 ± 114.5	332 ± 3
Carbon	831,057	82,259	217.3	3830 ± 85	379 ± 4
Aluminium	1,275,208	129,824	331.	3852 ± 60.6	393 ± 7
Iron	917,602	102,885	240.	3820 ± 54	428 ± 6

TABLE II

ABSORBER	COUNTS PER HOUR AB	COUNTS PER HOUR AB-C	CORRECTED VALUES AB	CORRECTED VALUES AB-C	RATIO $\frac{(AB-C)}{AB\ Av.}$ %
Accidentals	1182 ± 72				
Background	3864 ± 114.5	332 ± 3	2682 ± 186		
Carbon	3830 ± 85	379 ± 4	2648 ± 157	47 ± 7	1.77±0.09
Aluminium	3852 ± 60.6	393 ± 7	2670 ± 133	61 ± 10	2.29±0.11
Iron	3820 ± 54	428 ± 6	2638 ± 126	96 ± 9	3.61±0.04
Average			2660 ± 150		

The total number of AB and AB-C events as recorded in Table I consists of the sum of the counts obtained during twenty-four hour intervals. The value for each interval was then expressed in terms of the number of counts per hour and Chauvenet's criterion applied. Chauvenet's criterion (13) is commonly used in this type of work for it permits one to discard all those observations which have large deviations from the mean. In all, only six readings were found to be unsuitable and were rejected. Columns 4 and 5 of Table I list the AB and AB-C events in terms of counts per hour. The corrected AB and AB-C values are listed in Table II, columns 3 and 4. Subtracting the AB accidentals from the number of AB counts gives the true number of particles incident upon the absorber. Corrections are automatically made for AB-C errors when the AB-C background is subtracted. This is because the majority of errors embodied in the AB-C event contribute equally to the background rate; hence subtracting the background removes the errors. There will be an additional error due to scattering from the AB beam but this is so small (10) that it has no influence on the final result.

Column 5 of Table II shows the ratio of the number of stopped mesons to the total number incident upon the absorber expressed as a percentage. If the observations are to be of value in later experiments the (AB-C)/AB ratio must be as large as possible and must also be accurate. The deviations obtained using the present apparatus are shown. These are standard errors calculated in the usual manner (13). The results obtained with the apparatus as shown in Figure 2 seem to be sufficiently accurate to warrant its continued use.

It is unfortunate that time did not permit a study of the absorption of mesons in a fourth absorber, lead for example. This would have given sufficient points to plot an absorption curve. However, the relationship between the (AB-C)/AB ratio and the atomic number is linear and is expressed by the equation

$$R = 0.09Z + 1.2$$

where: R = the ratio $(AB-C)/AB$ expressed in %
Z = atomic number

The results of the experiment indicate that the accidental counting rate should be reduced. This could be done by using a system of triple coincidences to define the incident beam, for this would decrease the error caused by counts being missed due to the high counting rate of the present AB arrangement.

VI ACKNOWLEDGEMENTS

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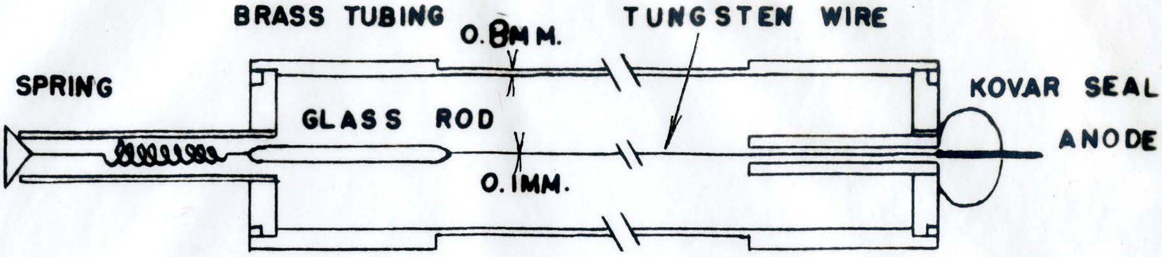
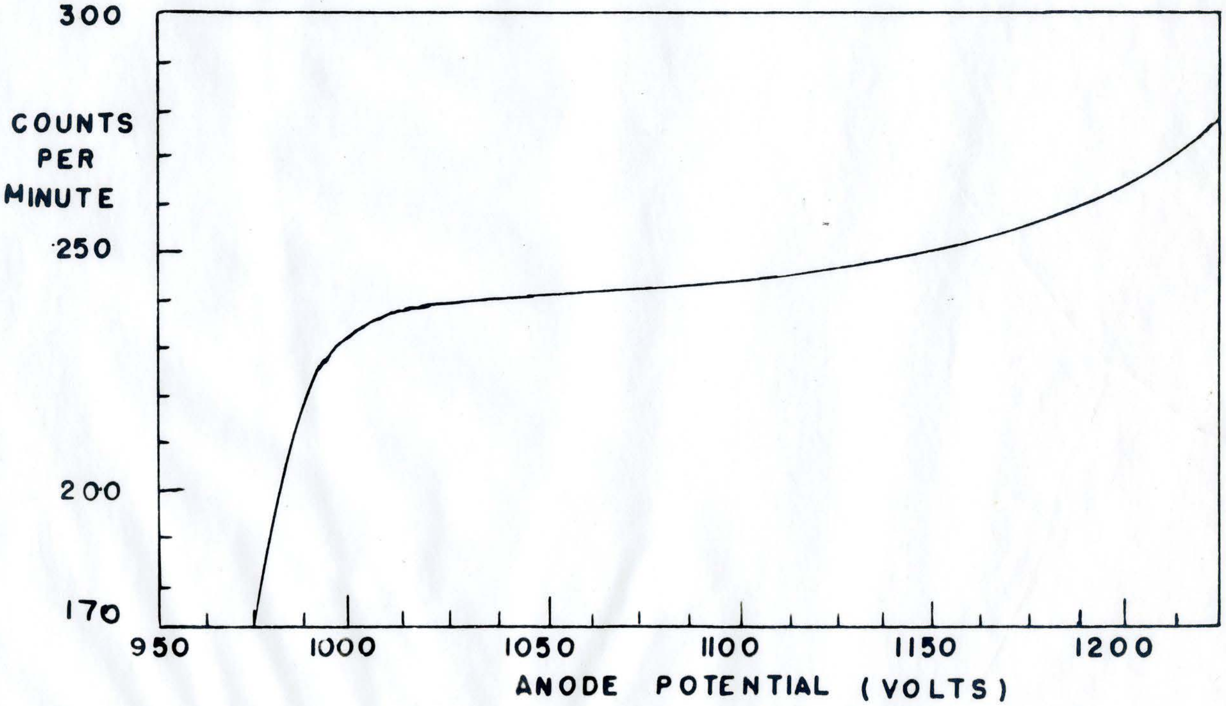


TYPICAL GEIGER TUBE

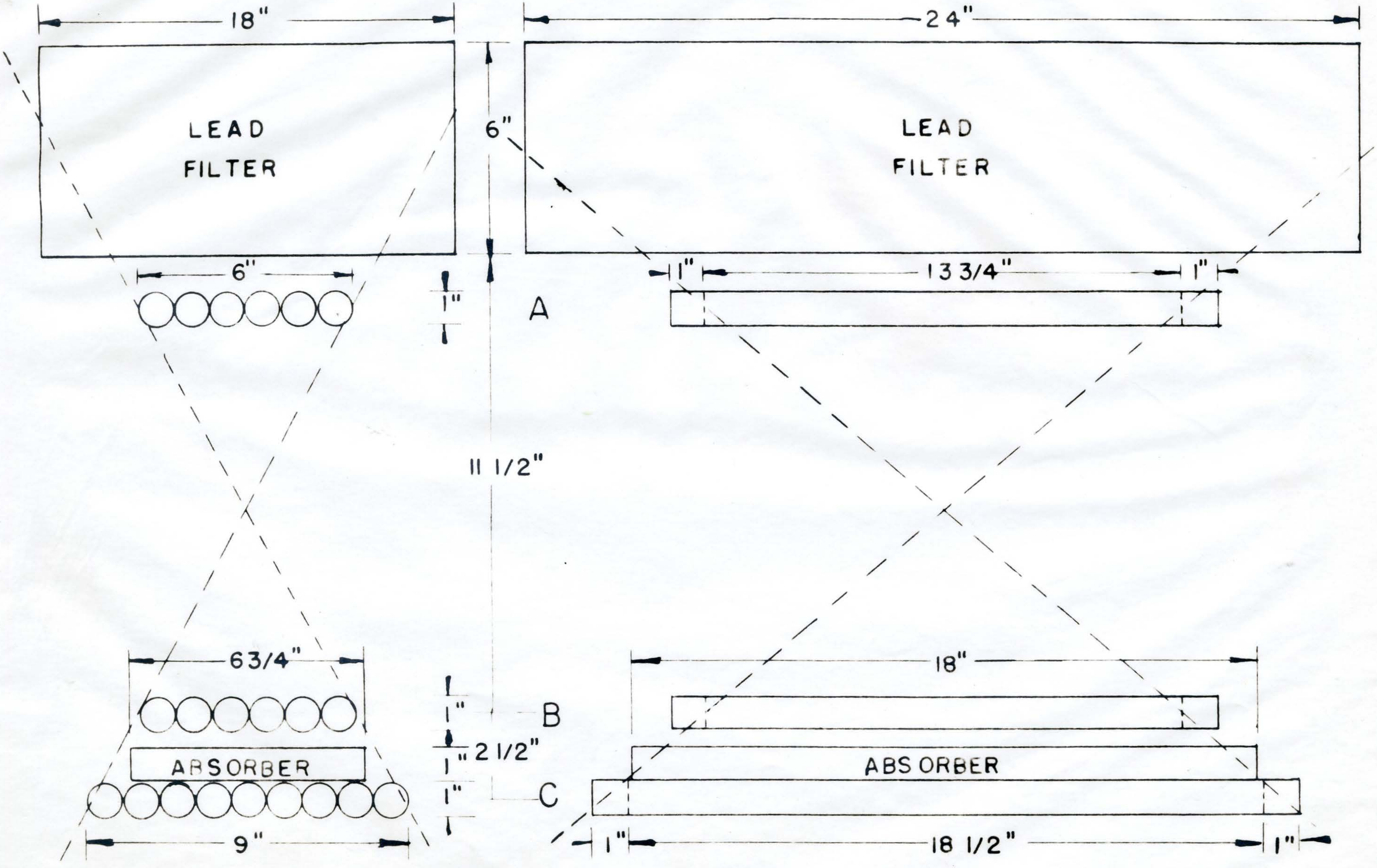
(a.)



TYPICAL PLATEAU

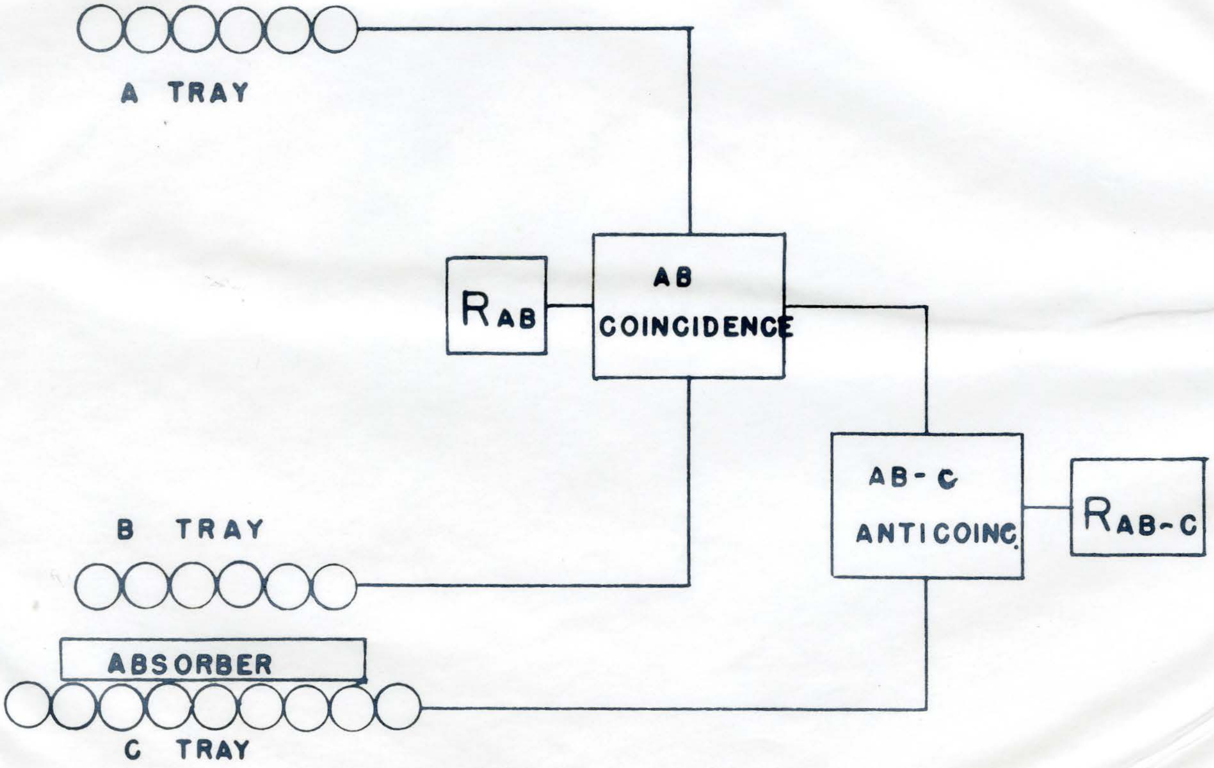
(b.)

FIGURE I.



ARRANGEMENT OF TELESCOPE TRAYS

FIGURE 2



SCHEMATIC DIAGRAM OF THE TELESCOPE

FIGURE 3