UNITED STATES NAVAL ACADEMY
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PHYSICS ★ CHEMISTRY ★ ELECTRICAL SCIENCES ★ ★

A Liquid Scintillation System For Use With a Cherenkov System to Investigate Interactions of High Energy Muons With Heavy Nucleii

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Physics Department, Research Report

1 June 1961 Report No. S-1

Science Laboratories
United States Naval Academy
Annapolis, Maryland

A LIQUID SCINTILLATION SYSTEM FOR USE WITH A CHERENKOV SYSTEM TO INVESTIGATE INTERACTIONS OF HIGH ENERGY MUONS WITH HEAVY NUCLEI

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This research was supported by
the Office of Naval Research
under contracts NR 015-909
and N onr - 2249 (04)

Research Report S-1
June 1961

F. A. Andrews
Head, Science Department

The results reported here are contained in a dissertation submitted in partial fulfillment of the requirements for the Degree of Master of Science at The Catholic University of America, Washington, D. C.

by

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June 1961

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ACKNOWLEDGEMENTS

The author wished to express his appreciation to Professor Clyde L. Cowan for suggesting the project and for his continued assistance and encouragement during its development. Thanks are also due to Professor Glenn E. Leydorf of the U. S. Naval Academy for his designs for some of the Electronic circuits and for many helpful suggestions. The following facilities provided money, equipment and laboratory space without which the project could not have been completed; U. S. Naval Academy, U. S. Naval Research Laboratory, Office of Naval Research, and the U. S. Naval Weapons Plant.

A large liquid scintillation detector has been developed for use in conjunction with a Cherenkov meson telescope to investigate the interaction with small energy transfer of high energy muons with heavy nucleii. The detector is in the form of a cubic plexiglass box and employs decalin activated with alpha-NPO and p-terphenyl as the scintillating material. The electronic equipment associated with the detector has been assembled and tested. An energy spectrum for local background and cosmic radiation has been determined.

I. INTRODUCTION

In recent years there has been an increasing amount of experiment with high energy particles. A few of these have been concerned with high energy mu-mesons.[1] J. de Pagter and R. D. Sard investigated the interactions of fast mu-mesons in lead with small energy transfer obtaining a cross section for the production of evaporation neutrons. The system which was developed and which will be described herein, when used in conjunction with a Cherenkov meson telescope, is capable of confirming the above experiment and investigating the same interaction for other heavy nucleii.

Although scintillation has been known for many years, some specific portions of the scintillation process are not yet completely understood. These portions will be mentioned briefly later in connection with the detector.

It is well known that when a charged particle moves through matter, it interacts with some of the atoms or molecules of the matter losing some of its energy to them. In most materials,

the acquired energy is dissipated as heat. In a scintillating material, however, a portion of this energy is converted into electro-magnetic radiation called a scintillation. The individual atoms (molecules) fall from "excited" energy state to ground by emitting one or more photons instead of losing this energy as heat.

In 1947 H. Kallman[2] first combined a scintillating crystal with a photomultiplier tube in order to convert the scintillation to an electrical pulse and amplify that pulse. After more amplification the pulse can be used to trigger a counting device, be presented on an oscilloscope or make some other record.

A scintillator will be useful only if it (1) transforms a large fraction of its acquired energy into radiated light, (2) is transparent to its own radiation and (3) the time for the energy to be converted to light is quite small (i.e., the scintillation is quite fast).[3] In certain instances, as in the present case, it is important that the scintillating material be available in large sizes. The use of organic solutions as scintillating materials was first investigated by Ageno et al.,[4] Kallman[5] and Reynolds et al.[6] They paved the way for liquid scintillators. Liquid scintillators are most useful because they are the fastest of all[7] and can be formed into any size and shape merely by pouring them into an appropriate vessel.

The advantage of the large volume liquid scintillator has been quite clearly demonstrated whenever the rate of occurrence of a particular event is small, as is the present case,

because of a small incident intensity[8] or a small cross section.[9] Some further properties which will be advantageous are: (1) The larger the volume, the higher is the probability that an incident neutron can be moderated and captured before it escapes at the boundary.[10] (2) The energy and hence the output at the meson "through" peak is approximately proportional to the vertical dimension. This second point may serve as a means to arrive at a quantitative energy calibration for the detector.

It is expected that the above points can all be utilized to good advantage when the detector is used with the Cherenkov counters. It might be noted that any muon which gives rise to a coincidence in the Cherenkov system will necessarily have traversed the scintillator and will hence yield an output at the scintillators "through" peak.

II THE DETECTOR

The detector includes a number of individual components which have been utilized in combination to comprise a system.

The vessel containing the liquid is a cubic tank twenty inches on a side constructed of one quarter inch plexiglass. The plexiglass was cut in square sheets and all edges were machined smooth to insure a good fit. After the squares were clamped together to form a box, the joints were sealed by applying ethylene dichloride ($CH_2Cl\ CH_2Cl$) at the connection using an eye dropper. This fused the plexiglass to make a good liquid tight seal which dried within an hour. Small holes with Pyrex glass stoppers in the top and on the side near the bottom of the tank provide for filling and draining.

The liquid scintillating material was an organic solution of p-terphenyl $[(C_6H_5)_2C_6H_4]$ and alpha-naphthyl-phenyl-oxazole $[(C_{10}H_7)(C_6H_5)(C_3H_2NO)]$, hereafter referred to as α-NPO, in decahydronaphthalene ($C_{10}H_{18}$) or decalin. Decalin was chosen in preference to some of the previously more widely used solvents such as toluene ($C_6H_5CH_3$) or xylene $[C_6H_4(CH_3)_2]$ because with decalin there is less fire hazard and less toxicity. Also, and most important, decalin is more transparent or has better transmission characteristics. M. Steinbach[11] has shown that in the region 3300 to 5000 $\AA$, commercial decalin has a slightly higher transmission characteristic than reagent grade toluene. This region is most important because the maximum

spectral response of the RCA 5819 photomultiplier tubes used in the detector is precisely 4400 Å. When decalin is purified by passing it through an Al_2O_3 adsorption column, its transmission characteristic is greatly enhanced. Hence the decalin was purified and its transmission tested relative to toluene by the Beckman Spectrophotometer method used by Steinboch.[12] The results showed this decalin to have a transmission characteristic as high as 200% that of toluene in part of the region 3300 to 5000 Å and to be greater than 120% in the whole region.

Current literature indicates that Oxygen quenches the flouresscence yield of a liquid scintillator while Argon enhances it. This effect was investigated for decalin by D. Ryan[13] and though some conclusions are still to be drawn, his data left no doubt that Argon should replace Oxygen or air as the atmosphere for decalin when decalin is used as a scintillator. Thus during all operations of purification and activation of the decalin and while filling the tank, Argon was bubbled through the decalin. Except for that amount which diffuses off the surface, Argon will remain in a container open to the atmosphere since it is heavier than air. This makes Argon easier to work with than Helium or Nitrogen both of which exhibit similar "enhancing" properties.[14]

Once the decalin was purified, it was necessary to "activate" it by dissolving in it one gram of α-NPO per liter and one gram of p-terphenyl per liter. These substances are the

activators, sometimes called wave length shifters, or solutes. This necessity arises because the flouresecence of decalin is in the ultraviolet whereas the maximum spectral response of the photomultiplier tubes used is in the visible region. The role of the activators is to absorb the exitation energy acquired by the decalin upon the passage of a charged particle and reemit this energy in the response region of the photomultiplier tube. The effect of the concentration of these two activators in decalin was investigated by F. Maciorowski[15] and it was concluded that the flouresecence efficiency is greatest with both solutes present and has a maximum near 4400 A°. It was also concluded that the flouresecence output approached a maximum value as the concentration of α-NPO was increased being within 10% of its maximum when the concentration was 1 gram/liter. Thus this concentration of α-NPO and p-terphenyl was chosen for the present experiment to most nearly approach optimum conditions. It might be mentioned that the part of the scintillation which is not yet understood is the mechanism by which the energy is transfered from the organic solvent to the activators. A number of good discussions of the possible mechan'sms involved can be found in the literature.[16]

The tank is viewed by twelve RCA 5819 two inch photo-multiplier tubes. The tubes are off-set from the decalin by a false bottom four inches in depth filled with distilled water. This eliminates the possibility of an event taking place very close to the face of the tubes and allows more tubes to see any event which takes place very near to the bottom of the tank.

Provision is made at the center of the false bottom to admit the lower Cherenkov generator. This will be discussed briefly later.

The high voltage divider network for the base of the photomultiplier tubes is shown in figure 2.

The high voltage power supply used with the photomultiplier tubes was the PP-948/UDR-9, a component of the AN/UDR-9 radiac detector. The AN/UDR-9 was manufactured by Beckman Instruments Incorporated.

The output signals from the photomultiplier tubes were connected in parallel. The signal was amplified by a Radiation Instrument Corporation Model 107P non-overloading linear amplifier, taken through a Hammer Electronic Company Model N601, single channel pulse height analyzer or differential discriminator as the input to a Nuclear-Chicago Model 151A decade scalar counter with timer attachment. The counter then records the events which take place in the scintillator in a desired energy region.

The photomultiplier tubes are optically sealed to the plexiglass surface by Dow Corning grease QC-2-0057. The tank is supported by a wooden frame constructed of two-by-fours. Built within this frame is a half inch plywood sheet which serves as a support for the photomultiplier tubes. The tank and tube are enclosed in a light tight box of one half inch plywood. Provision is made to shield the scintillator with lead and borax to keep out local background radiation and stray neutrons.

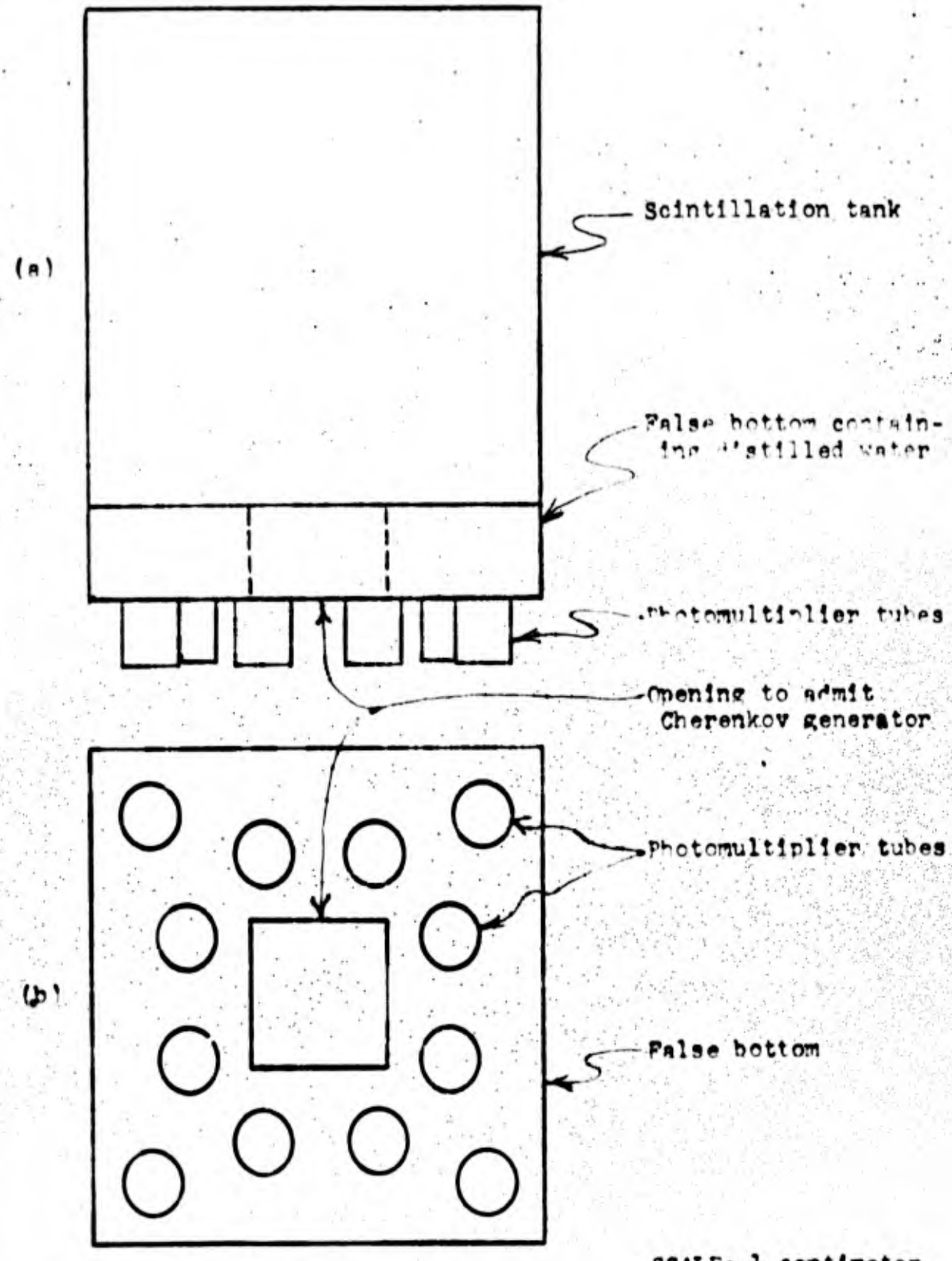

Figure 1. Geometrical arrangement (a) Side view (b) Bottom view.

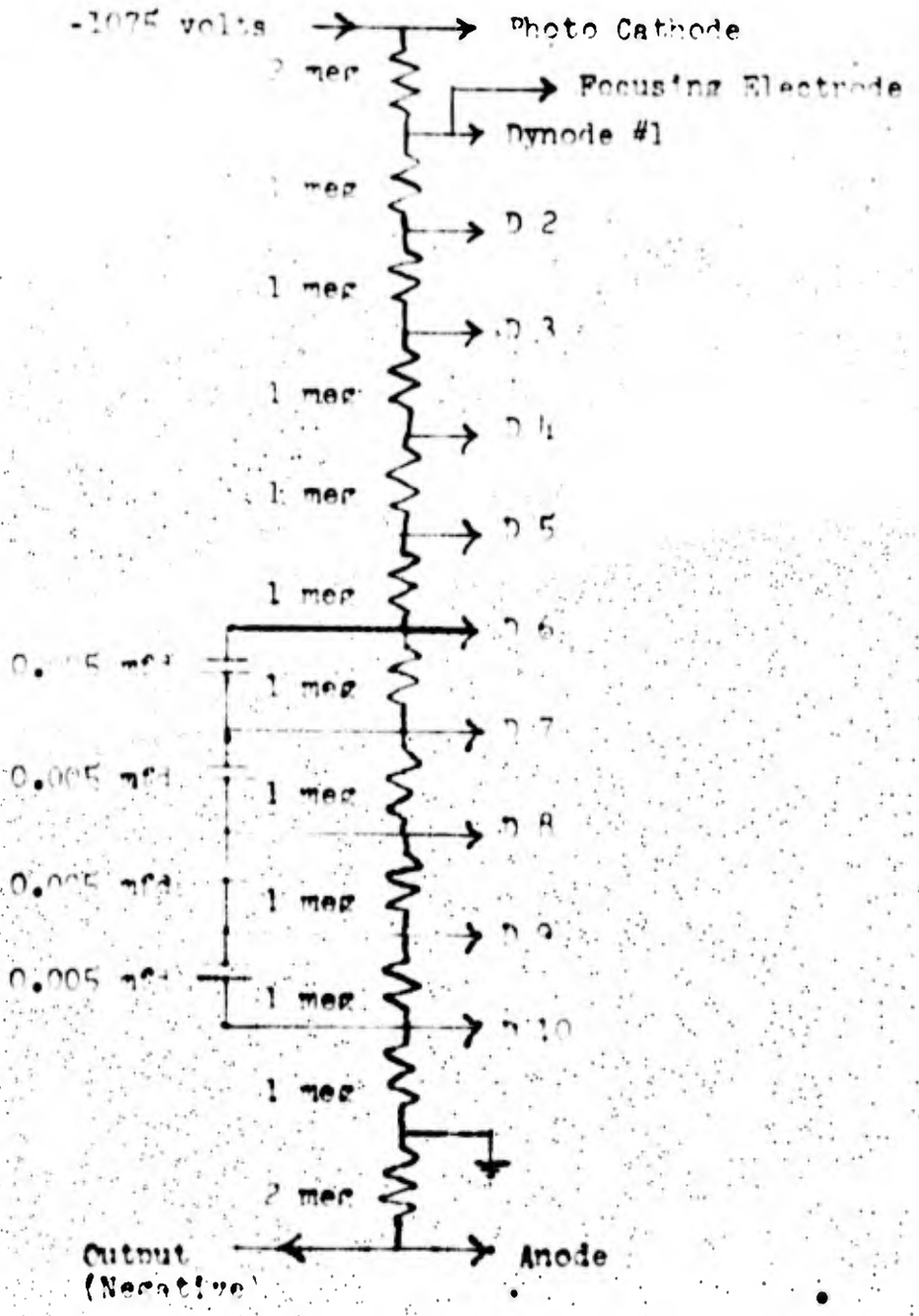

Figure 2. Voltage divider network for photomultiplier tube sockets. Variation of figure D, page 70 of DUMONT PHOTOMULTIPLIER TUBES, New Jersey, Allen B. Dumont Laboratories (2nd edition)

III OPERATION

All operations which were conducted were done so without shielding. The data gathered will be quite useful later if the scintillator is shielded and more research is carried out.

Before every run each photomultiplier tube was checked individually for gain by allowing its signal to trigger a Tektronix 545A Oscilloscope with type A plug-in unit and observing the pile up at the meson "through peak". The gains were balanced to that of the lowest gain tube by adjusting a variable resistor to lower the voltage across the tube. Each tube had a variable high resistance in series with its voltage divider network. This made possible the adjustment of the high voltage and hence the gain of each tube. This balancing was quite necessary in order that a through peak be observed when all tubes were operating together, for if the individual peaks are at different energies, the over all spectrum will be masked.

Runs to determine the energy spectrum were made at 1075 volts. The differential discriminator was set for a $\Delta E = 2.5$ volts. The number of counts per minute was recorded at 5 volt intervals to cover the whole spectrum. The electronic arrangement to balance the gains and determine the energy spectrum is shown in Figure 3.

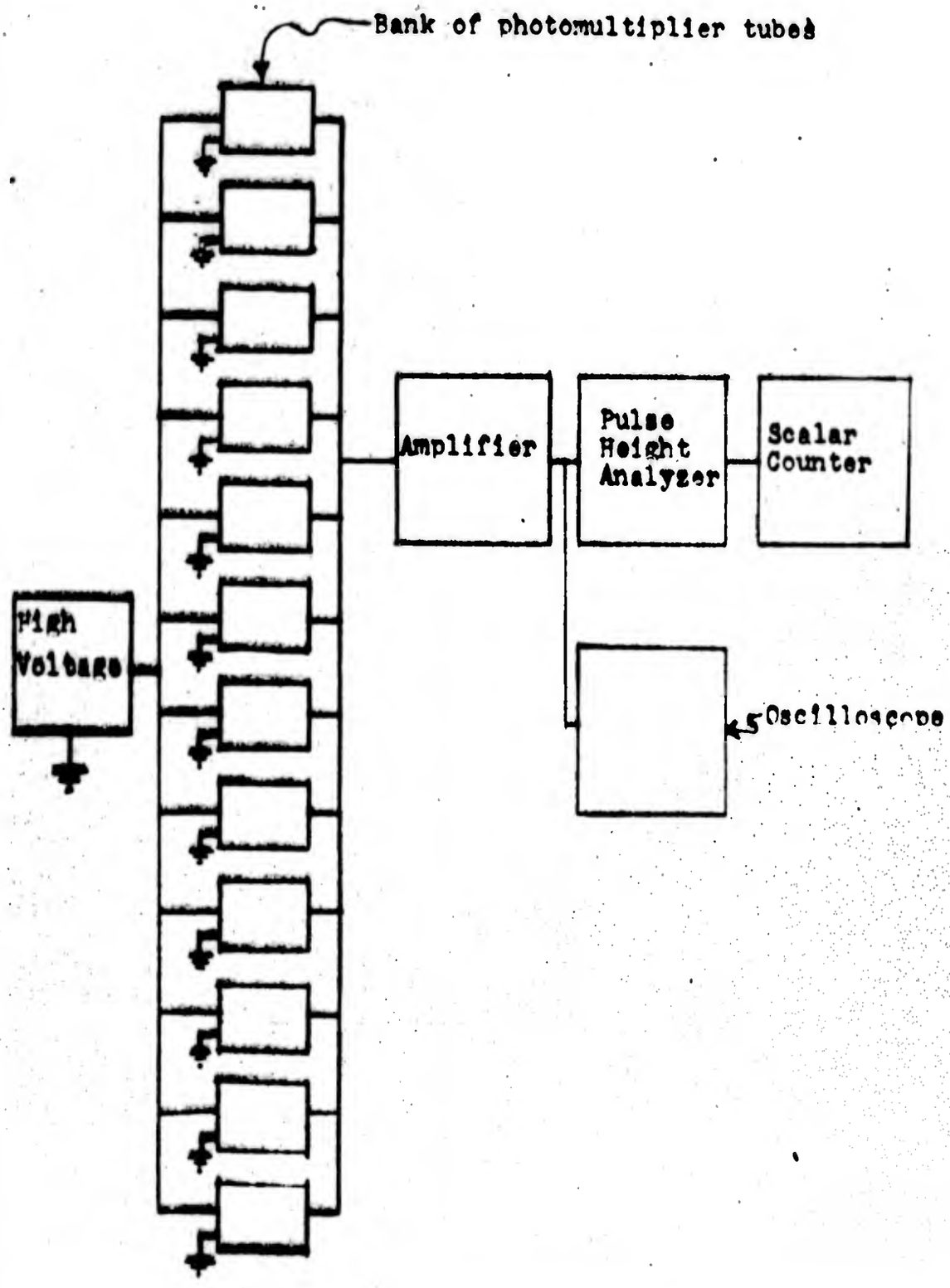

Figure 3. Arrangement of electronic equipment to determine the energy spectrum.

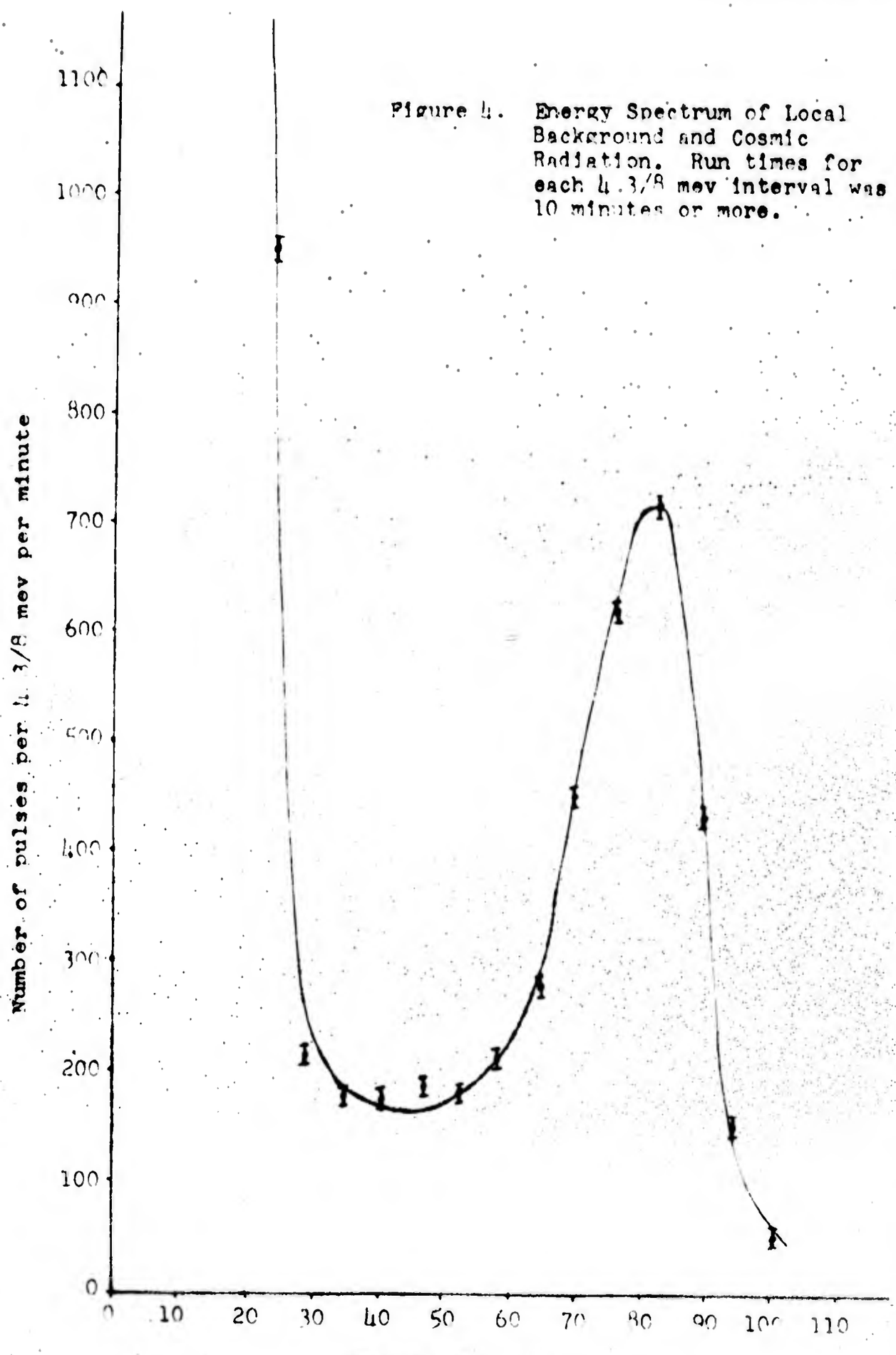

Figure 4. Energy Spectrum of Local Background and Cosmic Radiation. Run times for each 4 3/8 mev interval was 10 minutes or more.

IV DATA ANALYSIS

The peak in figure 4 near E=80 mev is that which would be expected from the geometry and agrees with Landau's distribution calculation. It is also in good agreement with many other experimental results.[17] This peak or pile up arises from the fact that a relativistic charged particle (a particle whose kinetic energy is greater than its rest energy), loses (approximately) a constant amount of energy per unit path length when traversing any material.[18]

In this detector the pile up particles were muons whose rest energy corresponds to approximately 102 mev. Relativistic muons will deposit approximately 4 mev per inch in decelin. Thus since the vertical dimension of the tank is twenty inches, particles traversing the tank will deposit on the order of 80 mev. The peak then corresponds to about 80 mev deposited in the tank. However, it corresponds to muons of 182 mev and greater since a muon must have had a minimum of 182 mev when it entered the tank in order to still be relativistic at the last part of its track.

Although it is beyond the scope of this paper to complete a detailed interpretation of this data in terms of meson flux, some points should be briefly discussed. It is known that the average number of cosmic rays at sea level is 0.83×10^{-2} per cm^2 per sec per steradian for the hard component and 1.14×10^{-2} per cm^2 per sec per steradian for the soft component.[19] Thus it might seem possible to calculate the number of particle detections which may be expected for this detector. A closer examination, however, reveals that although a consistent spherical area

could be calculated and would remain constant, a solid angle could not be defined which would remain constant throughout the spectrum. This is so because it is expected that most of the particles which cause the peak are vertical to traverse the whole tank and the solid angle for entry is quite small. Pulses at the lower energies could be caused by the soft component at any angle or a muon from the hard component at an angle off the vertical such that it traversed only part of the tank. It is felt then that these and other difficulties at lower energies, which will be mentioned shortly, make the problem of comparison of this data with known fluxes a vastly complicated one which should not be discussed in this paper.

The minimum in figure 4 is not quite as low as might be expected. Factors which could contribute to this are: (1) Muons from the hard component which traversed only part of the tank, (2) The difference in gains of the photomultiplier tubes (gains were balanced using an oscilloscope and pile ups could only be determined to within 10%), (3) Possible "knock on" electrons, (4) Small air showers, and (5) R.F. signal. This last point was quite a problem. The research was carried out on the third floor of Sampson Hall at the U.S. Naval Academy which is less than two miles from the transmitting antennas of NSS. This station broadcasts at a number of frequencies of very high amplitude. This signal was picked up and amplified in our equipment. Any or all of the last four factors could contribute and no doubt have contributed to spurious pulses. The large number of pulses at very low energies are due to local low

energy background radiation, noise originating in the photomultiplier tubes due to thermionic emission of electrons from the photo cathode, RF pick up and noise in the amplifier.

The data for figure 4 was the tenth run of the spectrum. All sets of data had their maxima near the same point. Some maxima were slightly greater than others but this can be attributed to the variation of cosmic ray flux at sea level due to changes in atmospheric pressure since the runs were made on different days.

Gains of the photomultiplier tubes were checked after each run by the same method they were balanced originally. Without exception it was found that they were still in balance.

V. OPERATION TO INVESTIGATE SMALL ENERGY TRANSFER INTERACTIONS OF HIGH ENERGY MUONS WITH HEAVY NUCLEI

J. de Pagter and R.D. Sard[20] were able to determine a cross section for evaporation neutron production by the interaction with small energy transfer of high energy muons in lead. T.D. Tuttle[21] has developed a Cherenkov meson telescope capable of selecting high energy muons from the hard component of normal sea level cosmic rays. This is done by a vertical arrangement of two cylinderical water Cherenkov generators viewed by photomultiplier tubes. When the outputs from the two tubes are properly amplified and counted in prompt coincidence, a count indicates a high energy charged particle has passed through both cylinders. Now 75% of all cosmic rays at sea level are penetrating and are mu mesons.[22] The soft component of cosmic rays is discriminated against because the experiment is to be carried out on the third floor of Sampson Hall which has six inches of concrete overhead. Also the threshold for Cherenkov radiation discriminates against the soft component. It is thus nearly 100% sure that the coincidence arose from the passage of a high energy muon through the two cylinders.

If the cylinders are arranged so as to bracket the scintillator as in figure 5 leaving room for the target as shown, a prompt coincidence will now indicate the passage of a high energy muon through the target. If this muon produced an evaporation neutron in the target, the neutron may enter the tank, be moderated and captured by the hydrogen within a certain time. The characteristic capture gamma radiation will give rise to a

scintillation and hence a pulse in the scintillators circuit. This pulse can be put in coincidence with the telescope coincidence pulse. (The telescope pulse must be delayed for the time necessary for the neutron to enter the scintillator, be moderated and captured.)

Unfortunately, none of the Cherenkov data available to date was gathered with the scintillation tank and target in place. Thus a good prediction cannot be made as to the flux of high energy muons which will pass through the target. A good assumption using the available data is that there will be on the order of 40 per hour. Using this value along with the experimental cross section of de Pa-ter and Sard[23] for the production of evaporation neutrons by high energy muons in lead of $(9.4 \pm 2.4) \times 10^{-28} cm^2$/nucleon, the calculated value of 6.83×10^{24} nucleons/cm^3 in lead and assuming 15 cm of lead for a target thickness, a rough calculation indicates that a count of 0.38 evaporation neutrons per hour due to small energy transfer of high energy muons can be expected with this detector. We would however expect our detector to yield a count of about 0.9 per hour, the difference being attributable to the neutron yield from real photons in cascade showers initiated by knock on electrons.[24]

It will also be possible to detect and measure the number of neutrons from each event.

Figure 6 shows the circuit which is in operation and is capable of detecting the proposed event.

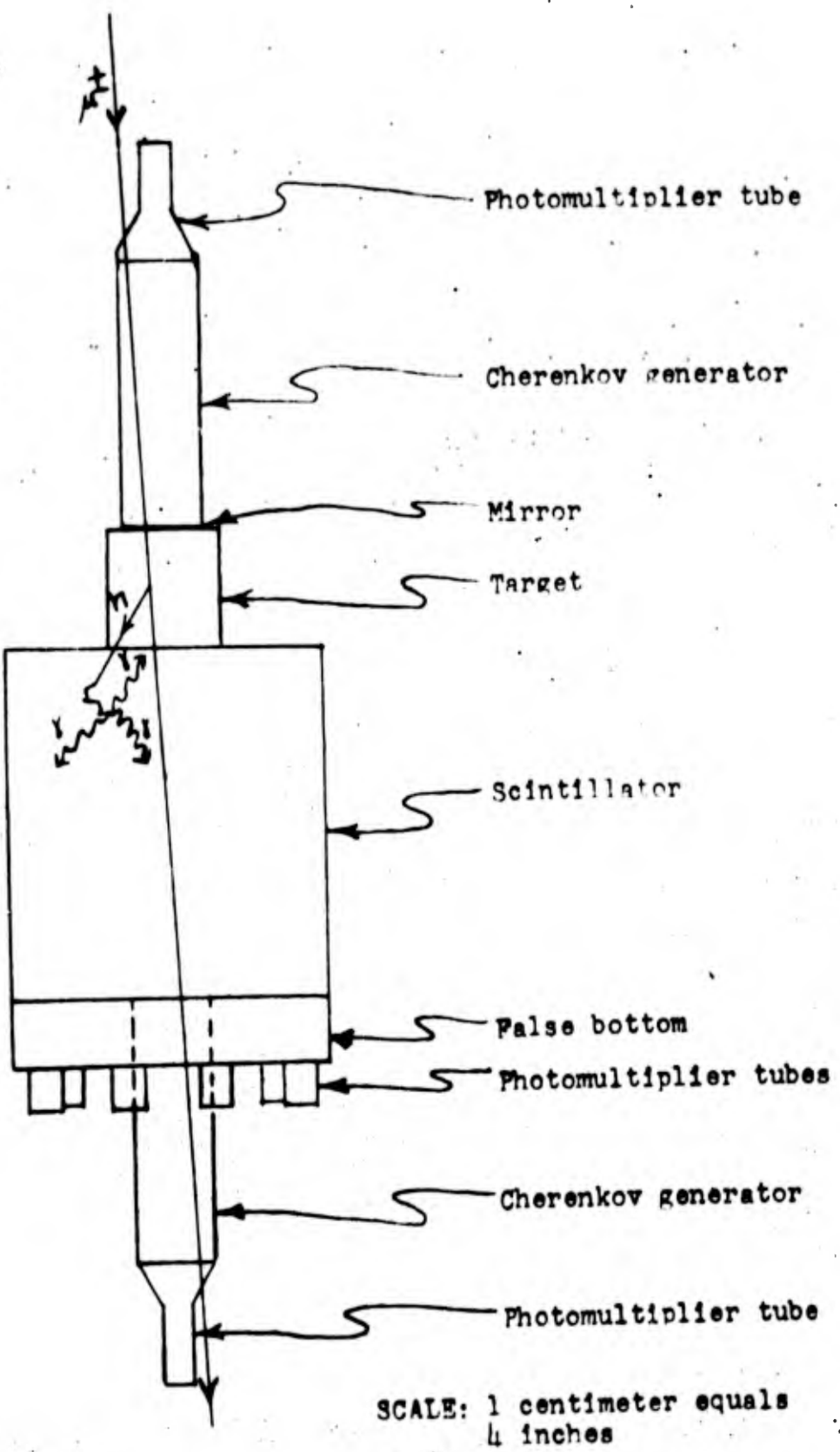

Figure 5. Geometrical Arrangement of Scintillator and Cherenkov counters and a diagram of the expected reaction.

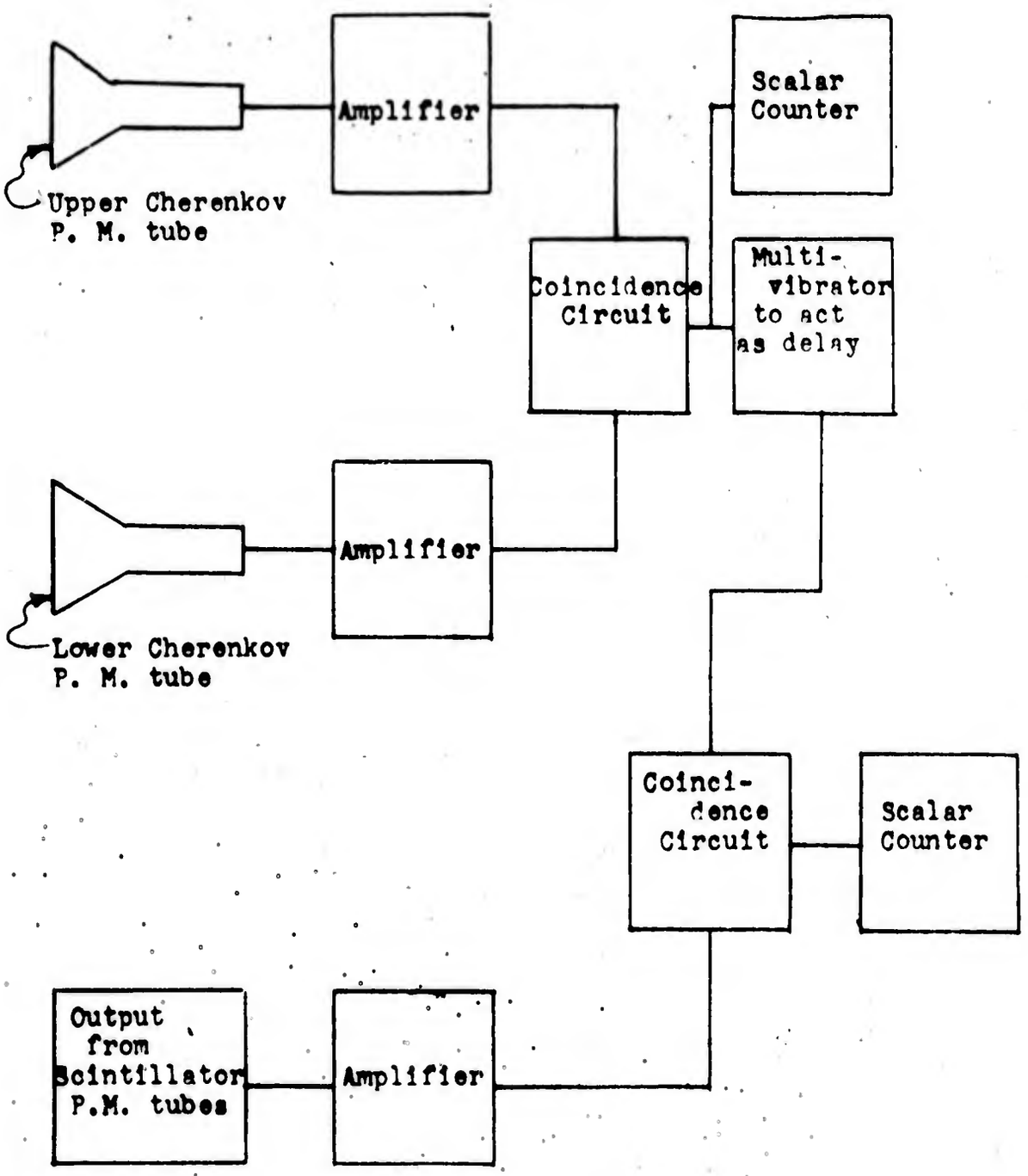

Figure 6. Block Diagram of Arrangement of Electronics to be used with the Scintillator and Cherenkov Generators.

It will of course be necessary to analyze the data from the above arrangement very closely to be absolutely certain that the events predicted actually took place. It is, for example, possible to show from energy and time considerations that a neutron is captured.[23] Reines, Cowan et al. have made use of the pair of pulses produced in a large liquid scintillator when a neutron enters and is captured to detect the neutron. They state "the first of each pair is due to recoil protons, gamma radiation entering the detector simultaneously with the neutron or other 'fiducial' event coincident with the entry of the neutron. The second is due to the gamma rays emitted by the nucleus which captures the neutron after it has been slowed down. The distinguishing parameters are the energy of the fiducial pulse, the energy of the capture gammas and the time delay between the two pulses." They further state the values of these parameters under given conditions and how they may be used to detect the neutron even in the presence of more copious radiation.

VI CONCLUSION

The Liquid Scintillation Counter has been shown to have many advantageous features as compared to other present-day counters. In addition to the ability to detect neutrons, the flexibility of size and shape and the speed of the scintillation have been discussed as properties which have been utilized in this detector.

In order to carry out the research suggested in the title, it may be necessary to shield the tank. This will be determined as the equipment is further developed. It is further suggested that the tank be painted white in order to insure that as much of the light as possible which originated in the tank finds its way into one of the photomultiplier tubes.

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