

A STUDY OF THE PROBLEMS INVOLVED IN THE  
DETECTION OF MU MESON PAIRS FROM  
THE MIT SYNCHROTRON

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A. JULIAN

1953

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THE MIT SYNCHROTRON

by

A. JULIAN

B.S., United States Naval Academy  
(1944)

SUBMITTED IN PARTIAL FULFILLMENT  
OF THE REQUIREMENTS FOR THE  
DEGREE OF MASTER OF  
SCIENCE

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TECHNOLOGY

June, 1953

Signature of Author.....  
Department of Physics, 23 May 1953

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Thesis Supervisor

Accepted by.....  
Chairman, Departmental Committee  
on Graduate Students

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A STUDY OF THE PROBLEMS INVOLVED  
IN THE DETECTION OF MU MESON PAIRS FROM  
THE MIT SYNCHROTRON

by

A. JULIAN

SUBMITTED TO THE DEPARTMENT OF PHYSICS  
ON 25 MAY 1953 IN PARTIAL FULFILLMENT  
OF THE REQUIREMENTS FOR THE DEGREE OF  
MASTER OF SCIENCE

In an attempt to relate the mu meson to the quanta of the nuclear force field, Wentzel has proposed a theory in which the pi meson is essentially a quantum state of a mu meson pair. Because of the anticipated low cross section for the process, and the low efficiency for detection of pair production, a study of the detection problem was needed before a meaningful experiment could be undertaken.

The general detector requirements have been analyzed, and a high efficiency detector manifold has been designed and constructed.

The detection efficiency, and expected counting rates for pair production by either the Wentzelian process, or an electromagnetic process, have been calculated for several target elements.

Response tests have been made of the fast 6BN6 coincidence circuit, and of the Model 402 distributed amplifiers, preliminary to their use in the experiment.

A preliminary set of experiments, with modified detector systems, has been conducted in the Synchrotron beam to resolve shielding, collimation, and background problems. From these experiments, an upper limit has been established for the Wentzel production cross section at  $2.5 \times 10^5$  times the electromagnetic cross section. This is about the same limit established by Martinelli and his co-workers at the University of California.

Final assembly and bench testing of the detector system is currently underway, in anticipation of an early run with the Synchrotron.

Thesis Supervisor.....Bernard T. Feld  
Professor of Physics





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## CHAPTER I

### INTRODUCTION TO THE PROBLEM

Experiment indicates that mu-mesons are not produced, singly, in nuclear interactions, although pi mesons can be produced, and with relatively high cross-sections. The appearance of the mu has always been traced to the decay of a parent pi meson. Moreover, the pi meson has been observed to interact strongly with nucleons, while insignificant nuclear interaction is known to occur with single mu mesons.

However, these observations do not necessarily mean that the mu meson is completely unrelated to the quanta of the nuclear force field. Wentzel has proposed a theory in which the pi meson is essentially a quantum state of a mu meson pair (muon--antimuon).<sup>1</sup> In this theory, the nuclear interaction, and creation, of a single mu meson is expected to be very small. However, Wentzel has suggested that a consequence of the excitation of the nuclear field would be an appreciable production of mu meson pairs (as compared, for instance, to single pi mesons).

It is to be observed that it should also be possible to create mu meson pairs, with photons of adequately high energy, by an electromagnetic process analagous to Dirac electron-pair production.<sup>2</sup> (Such an event assumes the mu to be a Dirac particle.)

---

<sup>1</sup>Wentzel, , P.R. 79, 710, (1950)

<sup>2</sup>Dirac, P.A.M., Quantum Theory.



CHAPTER I

INTRODUCTION TO THE THEORY

Experiment indicates that neutrinos are not produced singly, in nuclear interactions, although pi mesons can be produced, and with relatively high cross-sections. The appearance of the mu has always been traced to the decay of a parent pi meson. However, the pi meson has been observed to interact strongly with nucleons, while insignificant nuclear interaction is known to occur with single pi mesons.

However, these observations do not necessarily mean

that the pi meson is completely unrelated to the quanta of the nuclear force field. Fermi has proposed a theory in which the

pi meson is essentially a quantum state of a pi meson pair

(meson-antimeson).<sup>1</sup> In this theory, the nuclear interaction,

and creation, of a single pi meson is expected to be very small.

However, Fermi has suggested that a coincidence of the ex-

citation of the nuclear field would be an appreciable production

of pi meson pairs (as compared, for instance, to single pi mesons).

It is to be observed that it should also be possible to

create pi meson pairs, with photons of adequately high energy,

by an electromagnetic process analogous to pair electron-positron

production.<sup>2</sup> Such an event assumes the pi to be a Dirac parti-

cle.

<sup>1</sup>Wentzel,

<sup>2</sup>Dirac, P.A.M., Quantum Theory.

In order that an attempt to observe these processes be meaningful, a quantitative analysis of the detection problem was needed in view of the possibility that the Wentzelian cross-section may be very small.<sup>3</sup>

This paper presents such an analysis with emphasis on detector design. The various factors entering into detection efficiency are explored to indicate optimum geometries, and a new type of detector has been constructed to realize the optimum efficiency as closely as possible.

Meson electronics, already on hand, have been adapted, with some modifications, to this experiment. Data have been taken to establish the functioning of the electronics, and to resolve shielding and housing problems.

The calculation of expected counting rates has been carried forward in some detail for the electromagnetic process as well as the Wentzelian, in order to provide a good comparison of the relative weights of each at the quanta energies available in the MIT Synchrotron beam. Appropriate extrapolation to other Synchrotron energy spectra and intensities can easily be made.

Detection of either mode of production would be significant, and in particular the Wentzelian, which might reveal the respective roles of the pi and mu in nuclear interactions.

One previous attempt has been made to detect mu pairs-- by Mather, Martinelli, and Jarmis with the University of California 322 Mev Bremsstrahlung. Their experiment suffered from very high backgrounds, and detector blocking, due to high electron

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<sup>3</sup>Suggested by Dr. A. Wattenberg and Dr. B.T. Feld of the MIT Synchrotron Laboratory.

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fluxes, but they were able to assign an upper limit to the Wentzelian production cross-section as  $2 \times 10^5$  larger than the expected electromagnetic cross section.<sup>4</sup>

---

<sup>4</sup>Mather, Martinelli and Jarmie, UCRL 1166 W 7405-eng-48, University of California.

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## CHAPTER II

### DETECTION IN GENERAL

The proposed experiment involves the detection of mu meson pairs produced by the Bremsstrahlung of the MIT Synchrotron interacting with a suitable target.

With the existing electronics, detection of a single mu meson depends on a delayed coincidence between the meson pulse and the decay electron pulse. Detection of a pair of mesons will involve some type of final coincidence between the delayed coincidence pulses of each meson.

To measure the pair production, a certain basic geometry is envisioned. Figure 2-1, illustrates this geometry and the associated essential electronics in block diagram.

Desirable features for the measurement are as follows:

1. The separate meson signals must be in fast coincidence: a) to reduce the accidentals rate from the high flux of electrons and other particles at the detector positions; and b) to improve their cognizability.
2. For highest efficiency, all mesons with enough energy to leave the target and pass into either detector must be required to decay in the detector. The greatest meson range must lie within the meson detector dimensions. In other words, the detector should be as long as practicable.

## CHAPTER II DETECTION OF A SIGNAL

The proposed experiment involves the detection of an  
echo pulse produced by the backscattering of the MW energy  
from a target with a certain target.

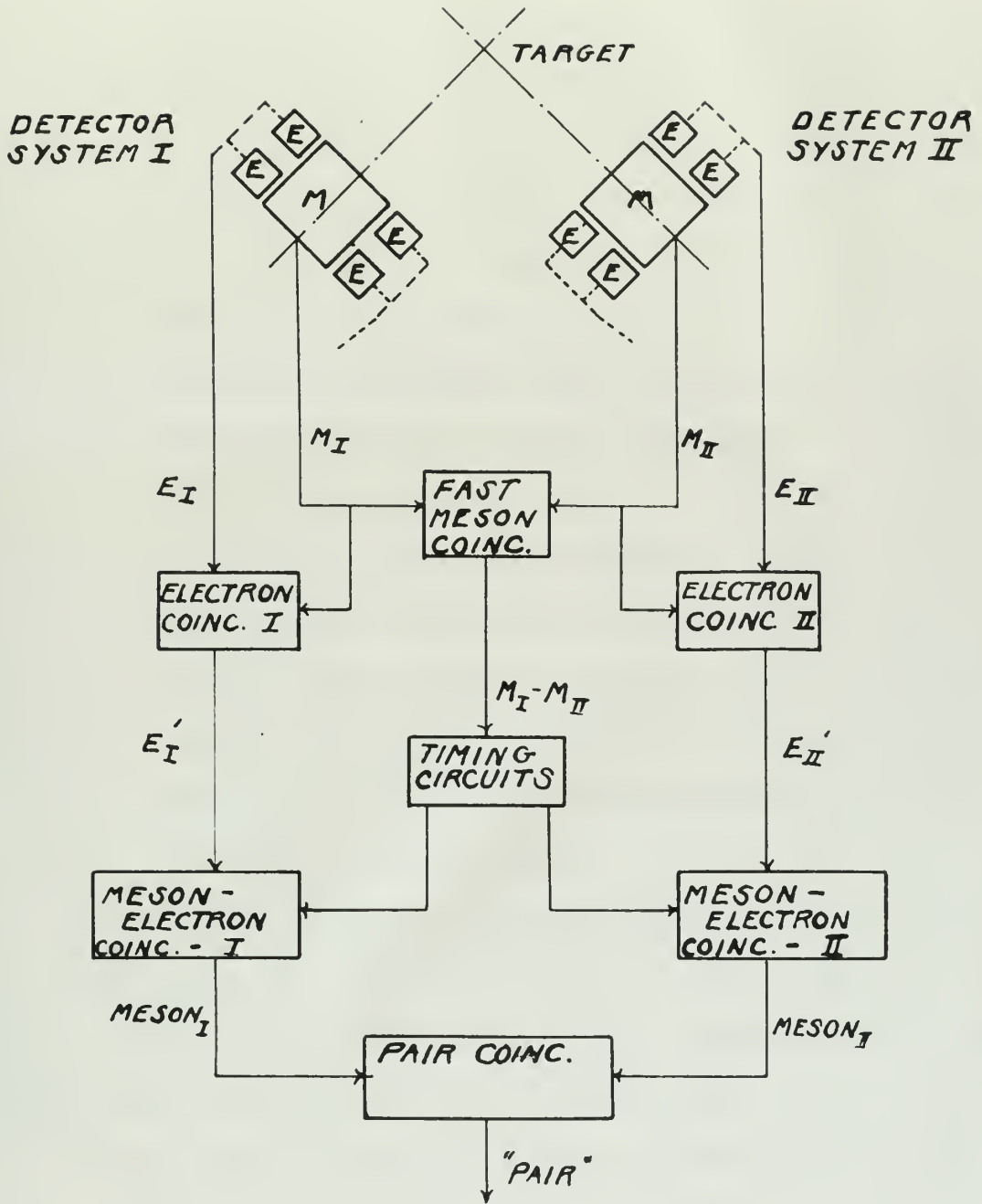
With the existing electronics, detection of a signal  
is based on a delayed coincidence between the echo  
pulse and the decay electron pulse. Detection of a signal  
is based on some type of final coincidence between the  
delayed coincidence pulses of each echo.

To measure the echo production, a certain pulse ge-  
ometry is employed. Figure 2-1, illustrates this geometry  
and the associated essential electronics in block diagram.

Essential features for the measurement are as follows:

1. The separate echo signals must be in fast co-  
incidence: a) to reduce the coincidence rate  
from the high flux of electrons and other  
particles at the detector position; and  
b) to improve their significance.
2. For highest efficiency, all echoes with enough  
energy to leave the target and pass into other  
detector must be required to pass in the  
detector. The greatest echo range must lie  
within the echo detector dimensions. In  
other words, the detector should be as long  
as practicable.

FIG. 2-1



TO SCALAR





3. The decay electron (mean life  $\approx 2$  microsec) must be observed in detectors physically separated from the meson detector to preclude ambiguity in meson and electron pulses in cases of very fast decay, and to negate the effects of phototube "after pulsing." It also appears desirable to require the electron to make coincidence between the meson and the separated electron-detector to keep accidentals rates down.
4. A delayed coincidence must be required between meson-coincidence pulse (1 above) and the electron coincidence pulse (3 above) to verify the identity of the particles. For single mu meson lifetime measurements the delayed coincidence will use timed gate techniques to provide decay time data.
5. A final coincidence is required between the individual delayed-coincidence meson pulses to establish the pair count.

An analysis of the basic requirements listed above shows that, apart from the electronics of the problem, the critical factor in determining success will be in the detector manifold use in the experiment. Experimental difficulties that have been encountered by previous workers (Martinelli et al<sup>5</sup>), and the requirements just mentioned, are, of course, a result of the anticipated very low cross section for mu pair production with the available quanta energy and intensities.

---

<sup>5</sup>Ibid.

3. The basic principle of the experiment is that

be observed in a detector which is positioned  
from the main detector to provide evidence in  
favor of the theory in cases of very low  
energy, and to reject the theory in cases of  
higher energy. It also requires a detector to  
verify the relation to make coincidences between  
the main and the separated electron-detector in  
very accidental cases.

4. A delayed coincidence will be required between  
electron-detectors (1 above) and the electron  
coincidence unit (2 above) to verify the identity  
of the particles. For single or weak lifetime  
measurements the delayed coincidence will use  
fixed gate techniques to provide good time data.

5. A final coincidence is required between the  
individual delay-coincidence counter units to  
verify the pair count.

An analysis of the basic requirements listed above  
must now be made from the standpoint of the problem, the  
critical factor in determining success will be in the ability  
to avoid use in the experiment. Experimental difficulties  
that have been encountered by previous workers (Klein) are  
of  $10^{-10}$  s, and the requirements just mentioned, etc. of course,  
a result of the anticipated very low cross section for an  
interaction with the available gamma energy and interaction.

These may, for emphasis, be grouped into three major categories:

- A. Small effective solid angles for the detection of the pair process. The detection efficiency decreases with the product of the solid angles of each system.
- B. Low efficiency of the decay electron detectors in detecting the meson decay in a tandem or side-by-side geometry with the meson detector.
- C. High fluxes of particles, other than mu's, producing high singles rates in the electron and meson counters. In Martinelli's experiment, the electron singles rates flooded his decay electron circuits and contributed heavily to his accidental rate. These rates probably were not only large angle pair-electrons and scattered-in electrons from the target, but also photoprotons, and pi mesons. In any event, as he pointed out, reduction of this cause of accidentals rate must begin with shielding of the electron detectors. And they must be shielded, not only from the target, but from showers produced by the beam (or its penumbra) in the shielding material and collimators.



These may, for example, be arranged into four major categories:

1. Small attractive forces acting for the detection of the hole nucleus. The detection efficiency decreases with the gradient of the hole and/or of mass system.
2. Low efficiency of the heavy electron detector in detecting the heavy hole in a random or side-by-side geometry with the electron detector.
3. High fluxes of particles other than alpha particles, produced by alpha rays in the detector and mean correction. In the detector's experiment, the electron alpha rays were flooded by heavy electron particles and contributed heavily to the experimental error. These rays probably were not only large angle alpha particles and scattered in directions from the source, but also isotropically, and of course, in any event, as he pointed out, reduction of this cause of background rate was begun with shielding of the electron detector. And this may also be achieved, not only from the target, but from source produced by the beam (or its neutrals) in the shielding material and collimator.



The problems indicated above are discussed in the following chapters:

Chapter III	Detector Design
Chapter IV	Detection Efficiency
Chapter V	Expected Yields and Counting Rates

The problem indicated above and discussed in the

following chapters:

- Chapter III Deletion Deletion
- Chapter IV Deletion Deletion
- Chapter V Deleted Fields and Counting Boxes

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CHAPTER III  
DETECTOR DESIGN

Single nuclear-reaction-product particles generally have a distribution in energy and solid angle. The counting rate from such a reaction is given by:

$$CR \propto \Delta\omega \cdot \Delta E \cdot F \quad \text{III-1}$$

where  $\Delta\omega$  is the fractional solid angle;

$\Delta E$  is the fractional spectrum energy;

$F$  is the fraction counted (an efficiency factor)

For pair detection, simultaneous events in physically separated and distinct detectors are involved. The counting rate from a pair production reaction is then given by:

$$CR_{\text{pair}} \propto \Delta\omega_1 \cdot \Delta\omega_2 \cdot \Delta E_1 \cdot \Delta E_2 \cdot F_1 \cdot F_2 \quad \text{III-2}$$

if there is no correlation in energy or angle between the two emitted particles!

Maximum counting rates result from maximizing the effective solid angle of each detector, both by decreasing detector distance, and increasing detector area. For example, a decrease in the effective detector-target distance from 35cm to 20cm, increases the solid angle factor for this two particle process by about 9. This particular improvement is so significant that special efforts were made to realize it. Further, to obtain as large a value as possible for  $\eta^6$  (discussed later)

---

<sup>6</sup>The factor  $\eta$  is the fraction of the total number of decay electrons, from mesons stopped in the inner detector, which are capable of being detected in the outer detector. See Chapter IV on Detection Efficiency for a discussion of  $\eta$ .

CHAPTER III  
DETECTION METHOD

Grain nuclear-reaction-product particles generally have a distribution in energy and solid angle. The counting rate from such a reaction is given by:

$$R \propto \Delta\omega \cdot \Delta E \cdot F \quad \text{III-1}$$

where  $\Delta\omega$  is the fractional solid angle;

$\Delta E$  is the fractional energy width;

$F$  is the fraction counted (an efficiency factor)

For pair detection, situations where the particles are separated and distinct detectors are involved. The counting rate from a pair production reaction is then given by:

$$R_{\text{pair}} \propto \Delta\omega_1 \Delta\omega_2 \Delta E_1 \Delta E_2 F_1 F_2 \quad \text{III-2}$$

if there is no correlation in energy or angle between the two emitted particles!

Maximum counting rates result from maximizing the

effective solid angle of each detector, both by decreasing

detector distance, and increasing detector area. For example,

a decrease in the effective detector-target distance from 100

to 50 cm, increases the solid angle factor for this two particle

process by about 2. This particular improvement is no longer

obtained if the detector is not large enough to realize it. However,

to obtain as large a value as possible for  $\eta^2$  (discussed later)

<sup>2</sup>The factor  $\eta^2$  is the fraction of the total number of decay electrons, from sources stopped in the inner detector, which are capable of being detected in the outer detector. See Chapter IV on detection efficiency for a discussion of  $\eta^2$ .



it is necessary that the decay electron detector have as large a solid angle as possible.

The latter consideration suggested a modification of the type of detector, first used at the MIT Synchrotron Laboratory by J.S. Clark, L.S. Osborne, and Y. Goldschmidt-Claremont in their meson experiments. The model is an inner-cylindrical detector, with a peripherally-contiguous outer cylinder; figure 3-1 illustrates this detector, which was used in the first experimental runs to line up the electronics. Such geometry is quite efficient for observing particles (decay electrons) in the outer detector which originate in the center detector.

The axial length of this design is determined by the upper limit of the mu energy spectrum that can be obtained with the maximum quanta energy available. This limit is reduced by the energy needed by the companion meson to just enter the second detector. The first modification, figure 3-2, shows the increase in length to this upper limit.

The basic design is purely cylindrical. The effective solid angle per detector, for this cylindrical geometry, can be taken as a crude estimate to be the solid angle subtended by the detector at mid-length. In other words, for a 30 cm long cylindrical system of diameter 4", with the detector face at 20 cm from the target, the effective solid angle is taken to be that subtended at the detector midpoint, 35 cm from the target. For this untapered cylinder, however, it is impossible to attain an effective detector distance of 20 cm because the

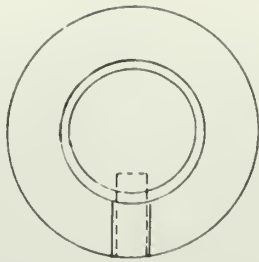
It is necessary that the detector system be able to detect  
a solid angle as possible.

The detector configuration suggested is modified in  
the type of detector, that is, it is a cylindrical  
array of 12 tubes, 1.5 inches long, and 1.5 inches  
diameter in their own experiments. The total is an  
cylindrical detector, with a hemispherically-convex  
exit; figure 3-1 illustrates this detector, which was  
used in the first experimental work on the reaction.  
Each geometry is quite different for observing particles  
(heavy electrons) in the outer detector which originates in  
the outer detector.

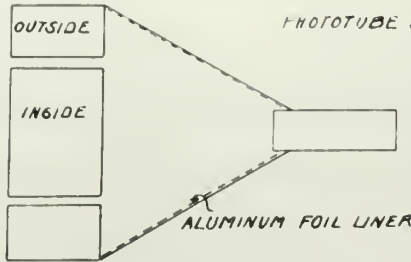
The axial length of the detector is determined by the  
upper limit of the energy spectrum that can be obtained with  
the sodium scintillation energy available. This limit is reached  
by the energy needed by the reaction to give rise to  
second detector. The first detector, figure 3-2, shows  
the increase in length to the upper limit.

The main design is a hemispherical detector. The effective  
solid angle is determined by the solid angle covered, and  
is less than a solid angle to be the solid angle subtended  
by the detector at all lengths. In other words, for a 30 cm  
long cylindrical system of diameter 4", with the detector face  
at 30 cm from the target, the effective solid angle is less  
to be less subtended by the detector diameter, 40 cm from the  
target. For this detector diameter, however, it is possible  
to obtain an effective detector diameter of 30 cm because the

FIG. 3-1



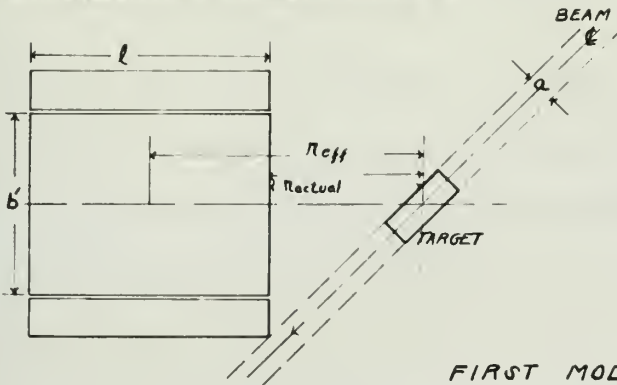
PHOTOTUBE 1P21



PHOTOTUBE 5B19

"CLARK" DETECTOR

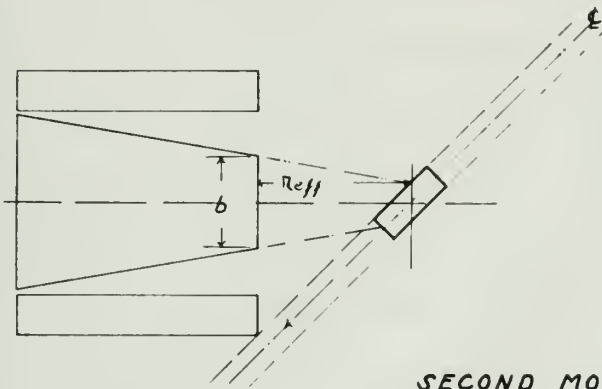
FIG 3-2



REQUIRING MINIMUM CLEARANCE,  $\frac{9}{2}$  FIXES THE MINIMUM  $r_{eff}$  AT  $45^\circ$ . SHIELDING WILL FURTHER INCREASE THE DISTANCE.

FIRST MODIFICATION

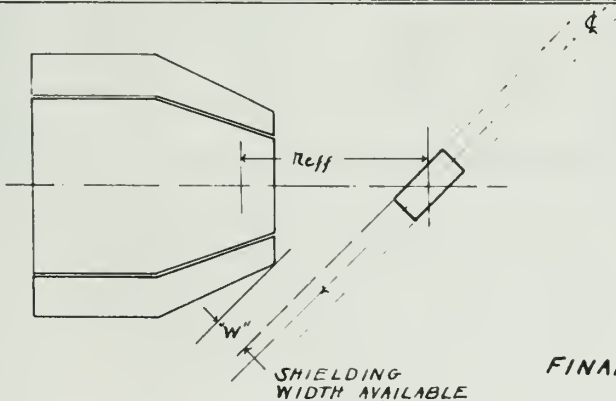
FIG 3-3



NOTE HOW FRUSTRUM CONSTRUCTION REDUCES  $r_{eff}$  TO  $r_{actual}$ . FOR " $b$ " = " $b'$ ", FIG 3-2, THE PHYSICAL DISTANCE OF THIS GEOMETRY IS GREATER THAN 3-2 FOR SAME CLEARANCE RESTRICTIONS, BUT WITH A NET DECREASE IN  $r_{eff}$ .

SECOND MODIFICATION

FIG 3-4



THE OUTER FRUSTRUM GEOMETRY ALLOWS FOR CLOSER ACTUAL DISTANCE AND INCREASE IN SHIELDING WIDTH, " $w$ ". A SLIGHT INCREASE IN  $r_{eff}$  FROM OPTIMUM, 3-3, IS ACCEPTED AS SPACE AND WEIGHT SAVINGS.

FINAL MODIFICATION

SHIELDING WIDTH AVAILABLE





edge of the detector system will be in the beam. Figure 3-2 demonstrates the requirements for minimum beam clearances, and the difficulty encountered with the rectangular cross section.

Forming the inner half of the inner detector as a conical frustrum of appropriate angle, effectively moves the detector towards the target by 15 cm, since the solid angle throughout is now that subtended at the face. Figure 3-3 illustrates such a detector with the resulting conditions imposed.<sup>7</sup> Note that, despite the decrease in the effective detector distance, the factor  $\eta$  has suffered in the critical forward section of the grouping because of the separation of the two detectors in this configuration.

A final modification to allow actual use of the system at 20 cm, and to preserve the factor  $\eta$  necessitated that the outer cylinder also be formed of conical frustums. Details of the final design geometry are shown in figure 3-4 and appended as Appendix A. The physical distance from the detector front-face to the target center is about 20 cm. To make  $r_{\text{eff}}$  equal to  $r_{\text{actual}}$ , the inner detector, in this case a continuous conical frustrum, would have had a base diameter of some 25 cm, and a volume of some 8 liters--the outer detectors in turn would be tremendous, an unwieldy and heavy apparatus requiring a large number of phototubes for reasonable photo efficiency and an immense amount of liquid. As a compromise, the frustrum extends to half length only, resulting in a reduction in weight and

---

<sup>7</sup>The scale of figure 3-3 is not the same as the scale of figure 3-2. Dimensions  $b$  and  $b'$ , the inner detector window diameter, are actually equal.

edge of the detector system will be in the beam. Figure 3-2

illustrates the procedure for minimum beam diameter.

and the diameter is equalized with the rectangular cross section.

Forming the inner half of the inner detector as a circular

frustum of appropriate angle, effectively moves the detector

towards the target by 10 cm, thus the solid angle throughout

is now just extended at the beam. Figure 3-3 illustrates such

a detector with the resulting conditions imposed. Note that,

despite the decrease in the effective detector distance, the

factor  $\gamma$  has suffered in the critical forward section of the

grouping because of the separation of the two detectors in this

continuation.

A final modification to allow actual use of the system

at 50 cm, and to preserve the factor  $\gamma$  necessitated that the

outer cylinder also be frustum of conical frustum. Details of

the final design geometry are shown in Figure 3-4 and appended

as Appendix A. The physical distance from the detector front-

face to the target center is about 50 cm. To make  $\gamma$  equal

to actual, the inner detector, in this case a conical

conical frustum, would have had a base diameter of some 25 cm,

and a volume of some 8 liters--the outer detector in turn would

be tremendous, an unwieldy and heavy apparatus requiring a large

number of phototubes for reasonable photo efficiency and an

excessive amount of liquid. As a consequence, the frustum extends

to half length only, resulting in a reduction in weight and

<sup>7</sup>The scale of Figure 3-3 is not the same as the scale of Figure 3-2. Dimensions b and b', the inner detector window diameter, are actually equal.



volume of liquid scintillator by about 45%, and reducing the number of phototubes required.

We do not gain the full increase of 9 in the solid angle factor  $\Delta \omega^2$ , mentioned in the early paragraphs of this Chapter. Instead, the actual net gain is about 6.5.

Another advantage to the outer frustrum design is that it permits heavier shielding of the system against electromagnetic production at small angles, without sacrificing the  $r_{\text{actual}}$  of 20 cm thus attained.

The sides and end window of the inner detector are made of 20 mil brass, as is the inner wall of the outer detector. The forward end plate, and the outer wall of the outer detector are made of 1/16" brass to give strength and rigidity to the entire structure. The back plates of both detectors are made of 3/8 inch brass. The interior of each is lined with 2 mil aluminum foil as a reflector. All seams were soft soldered at rolled joints, except for the back plate junction which was a combination butt-lap joint to the siding. The back plates contain the liquid filling and vent holes, and the plastic phototube mountings.

Six 5819 photomultipliers are used with each system: two, mounted parallel with the cylinder axis, in the inner detector; and four, mounted at 90° to each other on the circumferential center line of the outer detector back plate. Attached mounts of plexiglass hold the phototube to the back plates in such a way that the photocathode surface is at the surface of the back plate, and is separated from the scintillator

... of light ... and reducing the ... of ...

... gain ... in the ...  $\Delta \omega$  ... instead, the ...

Another advantage to the outer ... it ... of the ... the ... of ...

The ... of the inner detector ... of 50 ...

The ... of the outer detector ... of 1/8" brass to give strength and rigidity to the ...

The back plates of both detectors are made of 1/8" brass. The interior of each is lined with S.M.I. aluminum foil as a reflector. All ...

The ... are used with ... two, mounted ... in the lower ...

... of ... the ... of the ...



liquid by 1/16 inch of plexiglass and an optical contact of Dow-Corning "200 fluid," a viscous silicone. Some consideration was given to direct liquid contact with the phototubes, but sealing between the glass envelope and the brass has not been found reliable. It is for this reason that the full plastic envelope was used. Rubber "O" ring seals maintain the viscous oil reservoir between the tube and the plastic, and act as a mechanical clamp to hold the phototube in position. A small hole near the base of the flange of the plastic mounting allows for venting of surplus viscous oil during tube insertion. The simple contact seal between the back plate and the plexiglass tube-mounting provides the liquid seal for the cyclohexylbenzene containers. Figure 2, Appendix A shows details of the fitting and mounting.

Besides making possible the 20 cm target distance, the frustrum construction increased the photon collection efficiency for the liquid system because of the funneling of successive reflections toward the large end of the cones. Ray diagrams, figures 1 and 2, Appendix E illustrates this effect.

An order of magnitude calculation of the number of effective photons collected (those producing secondary electrons on the photo-cathode) per Mev lost in the liquid indicates an expected average of about 10 per Mev. A minimum ionizing electron at radial passage through the thinnest part of the outer detector will lose about 4 Mev, to produce an expected 40 effective (3 ev) photons in the outer detector.

liquid or gas of viscosity and an optical contrast of  
 100-1000. Some consideration is given to these liquids, but  
 not to the glass envelope and the pressure not  
 been found reliable. It is for this reason that the full  
 plastic envelope was used. Rubber "O" rings easily maintain  
 the vacuum of reservoir between the tube and the plastic,  
 and act as a mechanical clamp to hold the phototube in position.  
 A small hole near the base of the flange of the plastic mount-  
 ing allows for venting of surplus vacuum air during tube in-  
 sertion. The airtight contact seal between the back plate and  
 the phototube tube-mounting provides the liquid seal for the  
 cylindrical hydrogen cathode. Figure 2, Appendix A shows  
 details of the fitting and mounting.  
 Besides making possible the 20 cm target distance,  
 the further constriction increased the photon collection  
 efficiency for the liquid system because of the funneling of  
 successive reflections toward the large end of the cone.  
 Ray diagrams, Figures 1 and 2, Appendix E illustrate this  
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 An order of magnitude calculation of the number of  
 effective photons collected (those producing secondary elec-  
 trons on the photo-cathode) per MeV lost in the liquid indi-  
 cates an expected average of about 10 per MeV. A minimum  
 focusing electron at radial passage through the thinnest  
 part of the outer detector will lose about 4 MeV, to produce  
 an expected 40 effective (2.5 eV) photons in the outer detector.

See Appendix B for this calculation.

The detectors are to be mounted at  $45^{\circ}$  to the beam on each side, and at about 20 cm target to detector-face distance. A beam collimated to 1 inch width will be used. An arbitrary selection of 1 1/2 inches from the beam centerline was taken to be minimum approach distance for any housing material. The method of housing the detectors is shown in figure 3, Appendix A.



the equation for the wave function.

The solution can be written as  $\psi = e^{i(kx - \omega t)}$  for plane waves.

For a free particle, the energy is constant and equal to  $E = \hbar\omega$ .

The momentum is given by  $p = \hbar k$ .

The wave function for a free particle is  $\psi(x, t) = e^{i(kx - \omega t)}$ .

For a particle in a potential  $V(x)$ , the wave function satisfies the Schrödinger equation:

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V(x)\psi = E\psi$$

Figure 3. Energy levels.

The energy levels for a particle in a potential well are determined by the boundary conditions. For a rectangular well of width  $a$  and height  $V_0$ , the energy levels are given by:

$$E_n = V_0 \left( \frac{n\pi}{a} \right)^2 \frac{\hbar^2}{2m}$$

where  $n = 1, 2, 3, \dots$ . The corresponding wave functions are  $\psi_n(x) = \sqrt{\frac{2}{a}} \sin\left(\frac{n\pi x}{a}\right)$ .

The energy levels for a particle in a harmonic potential are given by:

$$E_n = \left(n + \frac{1}{2}\right) \hbar \omega$$

where  $\omega = \sqrt{k/m}$  is the angular frequency of the harmonic oscillator. The corresponding wave functions are given by Hermite polynomials.

The energy levels for a particle in a Coulomb potential are given by:

$$E_n = -\frac{13.6 \text{ eV}}{n^2}$$

where  $n = 1, 2, 3, \dots$ . The corresponding wave functions are given by Laguerre polynomials.

The energy levels for a particle in a parabolic potential are given by:

$$E_n = \left(n + \frac{1}{2}\right) \hbar \omega$$

where  $\omega = \sqrt{k/m}$  is the angular frequency of the harmonic oscillator. The corresponding wave functions are given by Hermite polynomials.



CHAPTER IV  
DETECTION EFFICIENCY

Equation III-2 must be analyzed in detail, and the correlation between the energy of the emitted particles taken into account.

The detection efficiency of a single detector is:

$$\varepsilon' = \Delta\omega \cdot \delta \cdot \eta \cdot \chi \quad \text{IV-1a}$$

where  $(\delta\eta\chi)$  is the factor F of equation III-1.

The detection efficiency for the pair of detectors is:

$$\varepsilon = 2(\Delta\omega)^2 \cdot \delta^2 \cdot \eta^2 \cdot \chi \cdot g \cdot f \quad \text{IV-1b}$$

where the additional factors 2, g, and f, take account of the characteristic physics of the process.<sup>8</sup>

g is a factor which results from the energy correlation between the emitted mesons for the pair process.

$(1-\delta)$  is the fraction of the meson decays which occur during the dead time of the counting circuit after the meson pulse. This dead-time comprises the electronic transit time, and fixed delays in the circuit.  $\delta^2$  is the fraction counted of the total pairs of decays after dead time.

$\chi$  is the factor relating to the competitive processes of decay and nuclear absorption for negative mu mesons.

$\eta$  is the fraction of the mesons which decay in a

---

<sup>8</sup>The factor 2 is a statistical one which arises in the following way: Since either meson can be counted in either detector, there are two combinations that will result in a successful detection. Meson 1 in detector 1; meson 2 in detector 2; or meson 1 in detector 2; meson 2 in detector 1.

SECTION IV

DETECTION EFFICIENCY

Equation III-2 must be analyzed in detail, and the correlation between the energy of the emitted particles must also be accounted.

The detection efficiency of a single detector is:

$$\epsilon' = \Delta\omega \cdot \delta \cdot \eta \cdot X \quad \text{IV-1a}$$

where  $(\delta \eta X)$  is the factor  $F$  of equation III-1.

The detection efficiency for the pair of detectors is:

$$\epsilon = \Delta(\omega)^2 \cdot \delta^2 \cdot \eta^2 \cdot X^2 \cdot G \cdot F \quad \text{IV-1b}$$

where the additional factors  $G, F,$  and  $F'$ , take account of the characteristic physics of the process.

$\epsilon$  is a factor which results from the energy correlation between the emitted beams for the pair process.

$(1-\delta)$  is the fraction of the meson decays which occur during the dead time of the counting circuit after the meson pulse. This dead-time includes the electronic transit time, and fixed delays in the circuit.  $\delta^2$  is the fraction counted of the total pairs of decays after dead time.

$X$  is the factor relating to the nonrelative processes of decay and nuclear absorption for negative  $\pi$  mesons.  $\eta$  is the fraction of the mesons which decay in a

The factor  $F$  is a statistical one which arises in the following way: Since either meson can be counted in either detector, there are two combinations that will result in a coincidence. Meson 1 in detector 1; meson 2 in detector 2; or meson 1 in detector 2; meson 2 in detector 1.

detector that form a detectable decay electron.

$f$  is a factor that gives the true angular distribution as compared to an uncorrelated spherically symmetric angular distribution.

The value of  $\mathcal{E}$  calculated will be a lower limit on the detection efficiency, based on the assumption of absolutely no correlation between the fractional solid angles  $\Delta\omega_1$  and  $\Delta\omega_2$ .

These factors are discussed below in detail.

#### Factor $\Delta\omega_1 \cdot \Delta\omega_2$

The solid angle product is a very critical part of the efficiency. The basic solid angle geometry is shown in Figure 4-1.

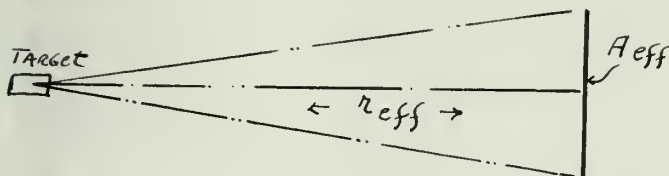


FIG. 4-1.

$A_{eff}$  is the effective detector aperture area.

$r_{eff}$  is the effective detector distance.

Some representative values of  $(\Delta\omega)^2$  for various  $A_{eff} \cdot r_{eff}$  combinations, which appear reasonable and attainable, are listed in Table .

Table 4-1 ( $\Delta\omega$  and  $(\Delta\omega)^2$ )

$A_{eff}/r_{eff}$	$\Delta\omega$	$\Delta\omega^2$
80.8/20	$1.61 \times 10^{-2}$	$2.57 \times 10^{-4}$
125.8/20	$2.51 \times 10^{-2}$	$6.25 \times 10^{-4}$
80.8/35	$.526 \times 10^{-2}$	$.275 \times 10^{-4}$
125.8/35	$.821 \times 10^{-2}$	$.67 \times 10^{-4}$

$A = 80.8$  cm is the 4 inch diameter

$A = 125.8$  cm<sup>2</sup> is the 5 inch diameter



... ..

... ..

... ..

... ..

The value of  $\epsilon$  ... ..

... ..

... ..

$\Delta \omega$

... ..

Factor  $\Delta \omega$ ,  $\Delta \omega$

The solid angle ... ..

... ..

Figure 4-1

... ..

... ..

... ..

... ..

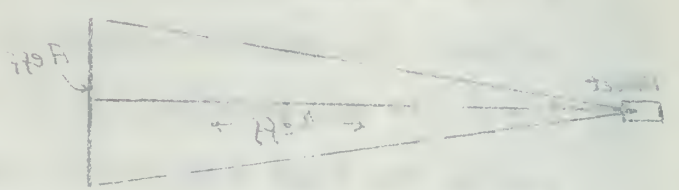


Fig 4-1

... ..

... ..

is ... ..

Table 4-1  $\Delta \omega$  and  $\Delta \omega$

$\Delta \omega$	$\Delta \omega$	$\Delta \omega$
$1.01 \times 10^{-4}$	$1.01 \times 10^{-4}$	$1.01 \times 10^{-4}$
$1.02 \times 10^{-4}$	$1.02 \times 10^{-4}$	$1.02 \times 10^{-4}$
$1.03 \times 10^{-4}$	$1.03 \times 10^{-4}$	$1.03 \times 10^{-4}$
$1.04 \times 10^{-4}$	$1.04 \times 10^{-4}$	$1.04 \times 10^{-4}$

$A = 40.0$  ... ..

$A = 100.0$  ... ..



Note that an increase in detector diameter by 1" increases the efficiency at either value of  $A_{\text{eff}}$  by a factor of about 2.4. Decreasing  $r_{\text{eff}}$  from 35 cm to 20 cm, holding  $A_{\text{eff}}$  constant, increases efficiency by a factor of about 9.

The path length of the decay electron becomes too large in general, and the factor  $\eta^2$  decreases, for a detector diameter of more than about 6 1/2 inches. Consequently this was the maximum diameter used in the inner detector, resulting in choosing an aperture diameter of 4 inches ( $A_{\text{eff}}=80.8 \text{ cm}^2$ ). The value of  $(\Delta\omega)^2$  for this  $A_{\text{eff}}-r_{\text{eff}}$  combination from Table 4-1 is  $2.57 \times 10^{-4}$ .

#### Factor $\delta^2$

The transit time of the circuit is negligibly short compared to the fixed delay time in the meson electronics. The meson coincidence pulse triggers the electron-meson gate after a 1/2 microsec fixed delay. The 1/2 microsec delay is used to preclude false coincidences in the gate circuit due to slowing of one or the other pulse in the discriminators. The fraction of all the mesons that decay in 1/2 microsec is:

$$(1 - \delta) = 1 - \exp\left(-\frac{t}{\tau}\right) \approx .21 \quad \text{IV-2a}$$

hence  $\delta^2$ , the fraction of the total that are observable in pairs, is

$$\delta^2 \approx .79^2 \approx .62 \quad \text{IV-2b}$$

Note that an improvement in  $\delta^2$  can be obtained by decreasing the fixed delay in the electronics to 1/4 microsec in lieu of 1/2 microsec. This results in an increase by a factor,

... factor of about 2. ...

The value of  $\delta^2$  ...

The value of  $\delta^2$  ...

Factor  $\delta^2$

The transit time of the circuit is negligibly short compared to the fixed delay time in the meson electronics. The meson coincidence pulse triggers the electron-meson gate after a 1/2 microsecond fixed delay. The 1/2 microsecond delay is used to provide false coincidences in the gate circuit due to ...

... of one or the other pulse in the discriminators. The fraction of all the mesons that decay in 1/2 microseconds is:

$$(1 - \delta) = 1 - \exp\left(-\frac{t}{\tau}\right) \approx 0.24 \quad \text{IV-2a}$$

Hence  $\delta^2$ , the fraction of the total that are observable in

$$\delta^2 \approx 0.057 \approx 5.7\% \quad \text{IV-2b}$$

Note that an improvement in  $\delta^2$  can be obtained by decreasing the fixed delay in the electronics to 1/4 microsecond in lieu of 1/2 microsecond. This results in an increase of a factor,

$$\frac{.79}{.62} = 1.27.$$

Factor  $\kappa$

The experiments of Ticho,<sup>9</sup> and Conversi et al,<sup>10</sup> have shown that the negative mu meson is frequently absorbed in high Z materials instead of decaying. For the purposes of this experiment, absorption of a negative mu meson will result in a lost pair count, since counting depends on the production and detection of the decay electrons.

For our absorber (the scintillator liquid) the average Z is about 4.

The results of Sigurgeirsson and Yamakawa<sup>11</sup> relative number of decay electrons per stopped meson--are statistically about the same for Be and C, both being approximately equal to unity. For our calculations, the factor  $\kappa$  is therefore taken to be 1.

Factor  $\eta$

The decay electrons have a distribution in energy, consequently a distribution in range, and thus some of them will not reach the outer detector. Due to the shape of the detector, the fraction that reaches the outer detector is a function of the position of the meson decay.

$\eta$  is the fraction of decay electrons produced in one of the inner detectors that reach the outer detector--and are

<sup>9</sup>Ticho, M.R., P.R. 74, (1337) 1948.

<sup>10</sup>Conversi, Pancini and Piccioni, P.R. 68, 232, 1945, P.R. 71, 209, 1947.

<sup>11</sup>Sigurgeirsson, T. and Yamakawa, K.A., Rev. Mod. Phys. 21, 124, 1949.



1954 - 1955

Factor X

The treatment of Factor X was carried out at all times under conditions which are described in the accompanying tables. It is noted that the results are generally consistent with those obtained in the experiments described in the preceding sections. The results are given in the following tables.

Table I

The results of the experiments are given in the following tables. The results are given in the following tables. The results are given in the following tables.

Table II

The results of the experiments are given in the following tables. The results are given in the following tables. The results are given in the following tables.

of the above experiments are given in the following tables. The results are given in the following tables. The results are given in the following tables.



observable--averaged over the entire detector.

The value of  $\eta$  is calculated in Appendix C. The basic considerations involving the calculation are given below.

The decay electron spectrum shows a most probable energy of about 30 Mev. Analytic forms for the spectrum energy have been formulated by Hubbard.<sup>12</sup>

The number of decay electrons of energy  $E$  in  $dE$  is  $f(E)$ :

$$f(E)dE = dE \frac{12 E^2}{W^4} (W-E + \frac{2}{9}\rho[4E-3W]) \quad \text{IV-3a}$$

Taking  $\rho$  here to be .25, a value nearly that recommended by Hubbard, and combining the bracket, leads to:

$$f(E)dE = dE \frac{12 E^2}{W^4} (.83W-.78E) \quad \text{IV-3b}$$

The bracket may be taken as  $.8(W-E)$ , whence,

$$f(E)dE = 9.6 \frac{E^2}{W^4} (W-E)dE \quad \text{IV-3c}$$

$W = \frac{m_e c^2}{2}$ ;  $W \approx \frac{110}{2} = 55$  Mev, the maximum kinetic energy that the electron may carry off from the decay.

A rigorous determination of the fraction of the decay electrons that leave the meson detector--with enough energy to produce a pulse in the electron detector--involves a complicated three-space-energy integration over the volume of the detector and throughout the spectrum.

A reasonable approximation has been made to the evaluation of  $\eta$ , taking into consideration the depth of penetration of the meson, and the electron spectrum. The detailed calculations (Appendix C) give for the value:

$$\eta = .609; \eta^2 = .37$$

<sup>12</sup> Hubbard, H.W., Thesis University of California, 10 March 1952, "Positron Spectrum from decay of mu mesons."

observed--averaged over the entire detector.

The value of  $\pi$  is calculated in Appendix C. The

basic considerations involving the calculation are given below.

The decay of electron positron pairs shows a most peculiar energy

of about 50 kev. Analytic forms for the electron energy have

been formulated by Hobbart.

The number of decay electrons of energy  $E$  in  $dE$  is  $f(E)dE$ :

IV-3a

$$f(E)dE = dE \frac{1.2 E^2}{W^2} (W-E + \frac{1}{2}(W-E-20))$$

Taking  $\rho$  here to be .25, a value nearly that recommended

by Hobbart, and combining the bracket, leads to:

IV-3b

$$f(E)dE = dE \frac{1.2 E^2}{W^2} (.824 - .782E)$$

The bracket may be taken as  $(W-E)$ , whence,

IV-3c

$$f(E)dE = 0.8 \frac{E^2}{W^2} (W-E)dE$$

$\frac{W}{2} = \frac{m_0 c^2}{2} \approx 110 = 55 \text{ kev}$ , the maximum kinetic

energy that the electron may carry off from the decay.

A rigorous determination of the fraction of the decay

electrons that leave the main detector--with enough energy to

produce a pulse in the electron detector--involves a compli-

cated curve-square-energy integration over the values of the

detector and throughout the spectrum.

A reasonable approximation has been made to the main-

tion of  $\pi$ , taking into consideration the death of penetration

of the meson, and the electron spectrum. The detailed calcul-

ations (Appendix C) give for the value:

$$\pi = .505; \pi^2 = .255$$

14  
Hobbart, W. W., Thesis University of California, 1950  
1952, "Electron Spectrum from Decay of  $\pi$  Mesons."



## Factor g

Factor  $g$  is the fraction of the total pair production of mesons accepted in the detector system, as a function of the distribution of the available kinetic energy. The energy distribution is such that an unequal division of energy is much more probable than an equal division.

If the division of kinetic energy is such that one meson carries off enough energy to stop at the back wall of one very long detector, and decay, the other meson may not get out of the target. The pair is not counted. For a short detector, the high energy particle of the pair may pass through the detector without stopping and decaying--the result is again a lost count.

Graph IV-1, Appendix E, energy distribution of meson pairs, extrapolated from similar distributions for the electron pair kinematics, has been plotted as a piecewise linear approximation, symmetric about the fraction one-half.<sup>13</sup>

Superimposed on these approximate curves are the energy acceptance limits imposed by: the target thickness to the exiting mu; the absorber thickness; and the meson detector front window thickness. As a not entirely arbitrary choice of these parameters, consider a target of thickness one inch transverse to the beam, with 1/4 inch of lead absorber, and a window of .02 inch brass. The limits of energy acceptance are determined by:  $[E_{\gamma} - 2m_{\mu}c^2]$  minus the energy loss in

$$[\sqrt{2}'' \text{ target} + \frac{1}{4}'' \text{ Pb} + .02'' \text{ brass}] = T_0 - T_L$$

<sup>13</sup> Heitler, W., Quantum Theory of Radiation.

factor in the location of the local peak production of energy accepted in the detector system, as a function of the distribution of the available kinetic energy. The energy distribution is such that an unequal division of energy is more probable than an equal division.

If the division of kinetic energy is such that one season carries off enough energy to stop at the back wall of the very long detector, and other, the other season may not get out of the target. The half is not counted. For a short detector, the high energy particles of the tail may pass through the detector without evoking and heating--the result is again a lost count.

Figure IV-1, Appendix B, energy distribution of season pairs, extrapolated from kinetic energy distributions for the detector pair. This distribution, has been plotted as a function of their kinetic energy, symmetric about the reaction one-half.

Interpolated on these exponential curves are the energy responses in the target for the target thickness to the width of the detector thickness; and the season detector front window thickness. As a not exactly arbitrary choice of these parameters, consider a target of thickness one inch immersed in the beam, with 1/4 inch of lead absorber, and a window of .02 inch brass. The limits of energy response are

$$\text{determined by: } [E - 2m_0c^2] \text{ minus the energy loss in } \left[ \frac{1}{2} \rho d + .02 \text{ brass} \right] = T_0 - T_1$$



For each value of  $k_{\max}$  ( $E_{\max}$ ), the acceptance limits are at  $T_l$ ,  $T_0 - T_l$ ; the fraction of the total area under the distribution curve bounded by  $T_l$  and  $T_0 - T_l$  is the maximum fraction of the total mu pair spectrum that is observable in the whole solid angle.

Note that at lower photon energies the acceptance fraction becomes very small. The combination: cross-section; number of photons in the energy range; and acceptance fraction in the energy range, probably tends to make the likelihood of an observation of a pair from either group (those from photons in the highest energy region, as opposed to those from photons in an intermediate or low region) about equal, other factors remaining unchanged.

Taking an average over the range of  $k$ , we have:

$$g \approx .75$$

IV-5

#### Factor f

To conserve momentum and energy for pair production from a single nucleon, the mesons will tend to be emitted in the forward direction. Since only the forward hemisphere is involved, the factor  $f$  is about 4, and probably greater. (See discussion on upper limit efficiency, latter part of this section.)

$$f \approx 4$$

IV-6

The lower limit of the total detection efficiency factor then becomes:

$$\epsilon = 2 \cdot \Delta\omega^2 \cdot d^2 \cdot \eta^2 \cdot \chi \cdot g \cdot f$$

$$\epsilon = 2 \times 2.57 \times 10^{-4} \times .62 \times 1 \times .37 \times .75 \times 4$$

$$\epsilon = 3.53 \times 10^{-4}$$

IV-7

The ratio value of  $\epsilon_{max}$  is the maximum  
 ratio of  $\epsilon$  to  $\epsilon_0$  in the reaction of the total wave  
 and the dispersion curve is shown by  $\epsilon = \epsilon_0 - \epsilon_1$  is  
 the maximum reaction of the total wave reaction that is  
 observable in the whole field angle.

When the total wave angle is small the dispersion  
 curve is almost linear. The dispersion curve is  
 almost linear in the energy range and the reaction  
 is also energy range, probably there is some  
 in the reaction of a part from other parts (from  
 in the highest energy region, as opposed to those from  
 in an intermediate or low region) about equal, other factors  
 remaining unchanged.

Taking an average over the range of  $k$ , we have:  
 $\epsilon \approx \epsilon_0$   
 $\epsilon \approx \epsilon_0$

Factor 2

To determine constant and energy for pair production  
 from a single photon, the reason will tend to be related to  
 the lowest dispersion. Since only the lowest dispersion is  
 involved, the factor  $\epsilon$  is about 4, and probably greater. (see  
 discussion on space-time efficiency, lower part of this section).

The lower limit of the total dispersion efficiency factor  
 then becomes:

$$\epsilon = \epsilon_0 \cdot \Delta \omega^2 \cdot h^2 \cdot n^2 \cdot x \cdot g \cdot f$$

$$\epsilon = 1 = 2.0 \times 10^{-4} \cdot 1.5 \times 10^4 \cdot 1.5 \times 10^4 \cdot 1.5 \times 10^4 \cdot 1.5 \times 10^4 \cdot 1.5 \times 10^4 \cdot 1.5 \times 10^4$$

$$\epsilon = 2.0 \times 10^{-4}$$

II-7

The use of this lower limit efficiency is a reasonable approach to the problem of the Wentzel production, since we have no knowledge of the correlative effects of the assumed meson field.

However, for the electromagnetic production discussed in the later parts of Chapter V following, an increase in the expected counting rate figures may be obtained. The yield calculations for the electromagnetic process are made assuming a completely incoherent process, (linear Z dependence).

If calculation can show a Z dependence of the type:

$Z + Z^2 \times$  (Form factor), that is, with additional coherent production over the nucleus, the expected counting rate values will be increased. In this case there is a strong forward correlation of the mu pairs; 1) from the theoretical cross-section (Heitler) for Dirac particle pair production; and, 2) from the coherence in the forward direction. Both of these will make the factor  $f$  greater than 4 for particle detection at forward angles.



The use of this lower limit affords a reasonable  
 approach to the problem of the correct production, and we  
 have no knowledge of the relative effects of the assumed  
 reason listed.

However, for the electromagnetic production discussed  
 in the later parts of Chapter 4 following, an increase in the  
 expected counting rate figures will be obtained. The yield  
 calculation for the electromagnetic process was made assum-  
 ing a completely incoherent process, linear dependence.

If calculation can show a dependence of the type:  

$$A + B \cos^2 \theta$$
 (form factor), then in, with additional coherent  
 production over the nucleus, the expected counting rate  
 values will be increased. In this case there is a strong  
 forward correlation of the nucleus;  $B$  from the theoretical  
 cross-section (Heitler) for the particle pair production;  
 and,  $B$  from the coherence in the forward direction. Both of  
 these will make the factor  $B$  greater than  $A$  for particles  
 detected at forward angles.



## CHAPTER V

## EXPECTED YIELDS

Introduction: In order to calculate the counting rate to be expected, one needs a knowledge of the cross section. Lacking a knowledge of the cross section all one can do is express the Counting rate as a function of the integral of the cross section over the energy range available. If a CR is observed, experiments at different energies could give the energy dependence of the cross section. In this section, the general expression for the counting rate as a function of the integral cross section is developed.

The yield of the pair production process can be written in differential form as:

$$d^2Y = d\phi(E) N \sigma(E) dx \quad V-1$$

where  $d^2Y$  is the yield, in meson pairs per unit target length, per unit quantum energy interval, per mouse.<sup>14</sup>

$d\phi(E)$  is the number of quanta having energy between  $E$  and  $E + dE$  over the entire target area, per mouse.

---

<sup>14</sup>

The "mouse" unit is a Laboratory unit of integrated intensity. The beam is monitored in an ionization chamber at the collimator face. Charge accumulated in the chamber is discharged after  $7 \times 10^7$  e.q. (See S.M. Thesis H. Ratz.) Note that even though the collimation to one inch absorbs some of the quanta produced in the Synchrotron target, the rate, e.q. per mouse at the target position will still be  $q$ , since the ionization chamber is on the target side of the wall. The collimation effect will be to increase the running time per mouse.

EXPERIMENTAL RESULTS

Introduction: In order to determine the operating rate to be expected, the knowledge of the cross section is essential. The knowledge of the cross section will not be complete unless the dependence of the cross section on the energy of the incident particles is known. It is the purpose of this report to present the results of the measurements of the cross section for the reaction  $\text{p} + \text{p} \rightarrow \text{p} + \text{p} + \text{p}$  as a function of the incident proton energy in the range 0.5 to 1.5 Mev. The results are shown in Figure 1. The error in the cross section is about 10%.

The yield of the pair production process can be written

in differential form as:

$$d^2Y = d\phi(\epsilon) N d\epsilon dx \quad V-1$$

where  $d^2Y$  is the yield, in number pairs per unit target

length, per unit positive energy interval, per

source.

$d\phi(\epsilon)$  is the number of pairs having energy

between  $\epsilon$  and  $\epsilon + d\epsilon$  over the entire target

area, per source.

The "source" used in a laboratory will be integrated in-  
tensity. The beam is monitored in an ionization chamber at the  
collimator face. Data accumulated in the chamber is displayed  
after  $10^4$  e.p. (see S.K. Tamm, R. Metz.) Note that even  
though the collimator is one inch above the source of the protons  
produced in the synchrotron target, the rate, e.p. per area of  
the target position will still be  $d$ , since the ionization chamber  
is on the target side of the wall. The collection effect will be  
to increase the counting rate per source.

$N$  is the number of target atoms per  $\text{cm}^3$ .

$\sigma(E)$  is the cross section for meson pair production at energy  $E$ , per target atom.

The number of quanta per mouse in the energy interval  $E$  to  $E + dE$ ,  $d\phi(E)$ , is a function of the target length:

$$d\phi(E) = d\phi_0(E) e^{-\mu x} \quad \text{V-2}$$

whence, 
$$dY = N\sigma(E) d\phi_0 \int_0^l e^{-\mu x} dx \quad \text{V-3}$$

where  $dY$  is the yield in meson pairs per unit quantum energy interval in target length  $l$ <sup>15</sup>

and 
$$dY = N\sigma d\phi_0 \left( \frac{1 - e^{-\mu l}}{\mu} \right) \quad \text{V-5}$$

or 
$$dY = N\sigma d\phi_0 l_{\text{eff}} \quad \text{V-5}$$

where  $l_{\text{eff}}$  is the effective target length, values of which<sup>16</sup> for several elements are tabulated in Table 5-1

Table 5-1 - Effective Target Length (cm)

Be	9.23	Al	7.01
C	8.96	Cu	2.48

Now  $d\phi_0 = \frac{\text{Target area}}{\text{Beam area}} \times \alpha \frac{dE}{E} = \alpha' d(\ln E) \quad \text{V-6}$

<sup>15</sup> Collimation determines the useful target length to be 4 inches.

<sup>16</sup> The figures in Table 5-1 are calculated, taking  $\mu$  equal to the asymptotic pair limit coefficient.<sup>17</sup> Graph V-1, Appendix E, Linear absorption coefficient for the elements listed in Table 5-1 shows that this assumption is reasonably valid at the energies under consideration.

<sup>17</sup> Fermi, E., Nuclear Physics.



is the number of target atoms per unit area.  $\sigma(E)$  is the cross section for neutron capture.  $\phi(E)$  is the neutron flux, per target atom.

The number of neutrons per second in the energy interval  $E$  to  $E + \Delta E$ ,  $\Delta$  is a function of the target length: 
$$q\phi(E) = N\sigma(E)\phi_0(E)e^{-\mu x}$$
 where,  $q\phi$  is the yield in neutrons per unit quantum energy interval in target length  $x$ .

$$q\phi = N\sigma\phi_0 \left( \frac{1 - e^{-\mu x}}{\mu} \right)$$

$$q\phi = N\sigma\phi_0 \text{eff}$$

where  $\text{eff}$  is the effective target length, values of which are listed in Table 3-1 and tabulated in Table 3-1.

Target Length (cm)	Effective Target Length (cm)	Table 3-1	
1.01	0.91	0.91	0.91
2.02	1.82	1.82	1.82

$$\phi_0 = \frac{\text{Target Area}}{\text{Beam Area}} \times \alpha' \sigma(E) = \alpha' \sigma(E)$$

Calculation determines the useful target length to be... The length in Table 3-1 and calculated... values listed in Table... under consideration.



where  $\alpha = 7 \times 10^7$  equivalent quanta (e.q.) per mouse  
in the MIT beam;

$\frac{dE}{E}$  is the energy spectrum of the Bremsstrahlung;<sup>18</sup>

$\alpha'$  is the e.q. per mouse, corrected for the actual  
area, and is equal to:

$$\alpha' = \frac{2}{\pi} \times 7 \times 10^7 \text{ e.q. per mouse}$$

therefore  $Y = N l_{\text{eff}} \alpha' \int_{E_{\text{MIN}}}^{E_{\text{MAX}}} \sigma(E) d(\ln E)$

$$\text{or } Y = N l_{\text{eff}} \alpha' I \quad (\text{events per mouse})^{19} \quad V-7$$

The limits of integration are somewhat variable: The  
upper limit is a function of the Synchrotron, with a probable  
maximum of 340 Mev. The absolute lower limit is the threshold  
energy for the pair process (215 Mev). The practical lower  
limit is a function of target and absorber material and thick-  
ness.<sup>20</sup>

The observable yield (Counting Rate) is then:

$$CR = \epsilon Y = \epsilon N l_{\text{eff}} \alpha' I \quad V-8$$

The expected counting rate, in counts per mouse, is  
tabulated in Table 5-2 for the four elements C, Be, Al and Cu,  
as a function of the integral I. (The integral has the  
dimensions,  $\text{cm}^2$ .)

<sup>18</sup>

The spectrum has been theoretically predicted, and ex-  
perimentally verified, as actually being about:  $.87 \times \frac{dE}{E}$ .

<sup>19</sup>

To determine the rate, "events per equivalent quanta,"  
divide the rate "events per mouse" by  $\frac{2}{\pi} \times 7 \times 10^7$ .

<sup>20</sup>

To reduce background, it was found necessary to put 1/4  
inch of lead in front of the detector--see Chapter VII.

...  $\alpha = 7 \times 10^7$  ...

... in the ...

...  $\alpha$  is ...

... and ...

$$\alpha' = \frac{2}{\pi} \int_{E_{min}}^{E_{max}} \alpha(E) d(E) \quad \alpha' = 2 \times 10^7 \text{ e.s.u. per second}$$

...  $Y = 2 \times 10^7 \alpha'$  ...

The limits of integration are somewhat variable: The upper limit is a function of the frequency, with a possible maximum of 200 Mc. The lower limit is the frequency which for the given process (100 Mc). The physical limit is a function of energy and absorption coefficient and is of course, on

The absorption coefficient (constant) is then:

$$\alpha = \epsilon \mu \alpha' \quad \alpha = 8 \times 10^7$$

The expected limiting value, in constant per second, is tabulated in Table 2-2 for the four elements O, Na, Al and Fe, as a function of the frequency. The constant per second is

The quantity has been theoretically predicted, and experimentally verified, as roughly being about:  $5 \times 10^7$ .

To determine the value, "average per wavelength" would be  $10^7$  per second, or  $10^7 \times 10^7 = 10^{14}$ .

It is also pointed out, it was found necessary to use a loss of land in front of the detector--the detector Y1.

Table 5-2 Expected counting rate (counts per mouse)

Be	- 1.783 x 10 <sup>28</sup> I	Al	- .66 x 10 <sup>28</sup> I
C	- 1.126 x 10 <sup>28</sup> I	Cu	- .718 x 10 <sup>28</sup> I

The practical upper limit for the length of a run was taken to be about 10<sup>5</sup> mice.<sup>21</sup> So unless the integrated cross section, I, is of the order of 10<sup>-33</sup> cm<sup>2</sup>, or greater, it is probable that no pair production will be detectable.

If a few 10<sup>5</sup> mouse runs are completed with no counting established, it will be possible to fix the upper limit of the Wentzelian cross section at near 10<sup>-33</sup>, an improvement over Martinelli's limit by about 10<sup>6</sup>.

The expectation counting rate for electromagnetic mu pair production can be calculated by substituting the theoretical cross section in the above relationships.

P.V.C. Hough<sup>22</sup> has developed formulae based on the Bethe-Heitler<sup>23</sup> equations for electron pair production which are represented to give better fit to experimental data than the latter. In particular, for symmetrical division of the kinetic energy, his equations give:

$$\frac{\sigma_{\text{pair}}}{\sigma_0} = \frac{.785 \sigma_0}{.085 \cdot \frac{1}{137} \left( \frac{Ze^2}{mc^2} \right)^2} \quad V-9$$

At energies very slightly above threshold, Hough's best power law approximation gives:

<sup>21</sup>This limit is set by considerations of the backgrounds observed in the preliminary study--see Chapter VII.

<sup>22</sup>Hough, P.V.C., P.R. 73, 1 February 1948.

<sup>23</sup>Ibid.



41 - $1.0 \times 10^{22}$	8e - $1.0 \times 10^{22}$
40 - $1.0 \times 10^{22}$	0 - $1.0 \times 10^{22}$

The practical upper limit for the length of a run was found to be about  $10^6$  msec. Unless the integrated cross section,  $I$ , is of the order of  $10^{-22}$  cm<sup>2</sup>, or greater, it is probable that in pair production will be detectable.

If a few  $10^6$  msec runs are completed with no counting established, it will be possible to fix the upper limit of the Venturian cross section at near  $10^{-22}$ , an improvement over Martinelli's limit of about  $10^0$ .

The expected counting rate for electromagnetic pair production can be calculated by substituting the theoretical cross section in the above relationships.

V.V.C. Booth has developed formulae based on the Bethe-Heitler equations for electron pair production which are intended to give better fit to experimental data than the latter. In particular, for symmetrical division of the kinetic energy, the equations give:

$$P-V \quad \frac{dN_{pair}}{dE} = \frac{1}{137} \left( \frac{Z^2}{m^2 c^2} \right) \left( \frac{E^2}{m^2 c^4} - 1 \right)^{1/2}$$

at energies very slightly above threshold, Booth's best power law approximation gives:

<sup>21</sup>This limit is set by consideration of the background observed in the preliminary study--see Chapter V.II. Booth, P.V.C., J.E.S. 78, 1 February 1968.



$$\sigma_0 = \frac{1}{3} (k-2)^3 \left(\frac{2}{k}\right)^3 \text{ in units of } \frac{1}{137} \left(\frac{Ze^2}{mc^2}\right)^2 \quad \text{V-10}$$

$$k = \frac{h\nu}{mc^2}; (k \ll 1)$$

which equation is 12% low at  $k = 3$ , with increasing error as  $k$  becomes much greater than 1.

Extrapolating the equations to the mu pair process by introducing the meson mass, gives:

$$\sigma_{\mu \text{ pair}} = .785 \left[ \frac{1}{3} (k-2)^3 \left(\frac{2}{k}\right)^3 \right] \text{ in units of } \frac{1}{137} \left(\frac{Ze^2}{m_{\mu}c^2}\right)^2 \quad \text{V-11}$$

From the mass ratio alone, this hypothetical cross section is down at once by a factor of about  $4 \times 10^4$  from the electron pair cross section. Moreover, the square  $Z$  dependence implies a coherence which is probably not valid for the meson production. It is probably more realistic, and does not change the order of magnitude, to take the  $Z$  dependence as linear.<sup>24</sup>

The expected counting rate is:

$$CR = \epsilon N \text{ less } \alpha' I' \quad \text{V-12}$$

where  $I' = C \int \sigma d(\ln E)$  can now be evaluated;

$$I' = C \int_{k_{\min}}^{k_{\max}} (k-2)^3 \left(\frac{2}{k}\right)^3 \frac{dk}{k} \quad \text{V-13}$$

$I' = \frac{I}{C}$  (Graph V-2, Appendix D) is a numeric and has the values tabulated in Table V-2, Appendix D, where the integration is carried out by graphical methods for various combinations of the upper and lower limits. A practicable

24

Table V-1, Appendix D, tabulates the electromagnetic cross section (per Rought with linear  $Z$  dependence) as a function of quantum energy.

7-10

$$V_0 = \frac{1}{3} (k-2)^2 \left( \frac{2k}{k-1} \right)^3$$

$$k = \frac{2k}{k-1} \quad (k > 1)$$

The exact solution is given by  $V_0 = \frac{1}{3} (k-2)^2 \left( \frac{2k}{k-1} \right)^3$ . The exact solution is given by  $V_0 = \frac{1}{3} (k-2)^2 \left( \frac{2k}{k-1} \right)^3$ .

7-11

$$V_0 = \frac{1}{3} (k-2)^2 \left( \frac{2k}{k-1} \right)^3$$

The exact solution is given by  $V_0 = \frac{1}{3} (k-2)^2 \left( \frac{2k}{k-1} \right)^3$ . The exact solution is given by  $V_0 = \frac{1}{3} (k-2)^2 \left( \frac{2k}{k-1} \right)^3$ .

7-12

$$V_0 = \frac{1}{3} (k-2)^2 \left( \frac{2k}{k-1} \right)^3$$

7-13

$$V_0 = \frac{1}{3} (k-2)^2 \left( \frac{2k}{k-1} \right)^3$$

The exact solution is given by  $V_0 = \frac{1}{3} (k-2)^2 \left( \frac{2k}{k-1} \right)^3$ . The exact solution is given by  $V_0 = \frac{1}{3} (k-2)^2 \left( \frac{2k}{k-1} \right)^3$ .

The exact solution is given by  $V_0 = \frac{1}{3} (k-2)^2 \left( \frac{2k}{k-1} \right)^3$ . The exact solution is given by  $V_0 = \frac{1}{3} (k-2)^2 \left( \frac{2k}{k-1} \right)^3$ .

lower limit, to discount energy loss in the target and the absorber is about 240 Mev.

For  $E_{\max} = 340$  Mev. ( $k_{\max} = 3.18$ ), and  $E_{\min} = 240$  Mev. ( $k_{\min} = 2.25$ ),  $I''$  corrected for the 12% low error inherent in the Hough formulae, at  $k = 3$ , is about .06.

The constant C, here is: (See Table 5-3)

$$C = \frac{.785}{137} \left( \frac{e^2}{m_{\mu} c^2} \right)^2 Z \quad V-14$$

Table 5-3 Constant C (Equation V-14) in  $\text{cm}^2$

Be	- $4.12 \times 10^{-32}$	Al	- $1.34 \times 10^{-31}$
C	- $6.18 \times 10^{-32}$	Cu	- $2.99 \times 10^{-31}$

The expectation counting rate is:

$$CR = (\epsilon N l_{\text{eff}} \alpha') CI'' \text{ (counts per mouse)} \quad V-15$$

where the factor  $(\epsilon N l_{\text{eff}} \alpha')$  is the coefficient of  $I$  in Table 5-2.

Values for this expectation counting rate are tabulated in Table V-4, for these four elements, for various limits of the integral  $I''$ .

For the particular case of Beryllium between limits of 340 Mev and 240 Mev, the rate is:

$$CR_{\text{BE}} = 4.46 \times 10^{-5} \text{ (counts per mouse)}$$

a rate which is of the same order of magnitude as that which we could expect from Wentzelian pair production with an integrated cross section,  $I$ , of about  $2.5 \times 10^{-33} \text{ cm}^2$ . For runs of  $10^5$  mice, both the Wentzelian rate for this cross section, and



lower limit, to illustrate energy loss in the target and the  
scattered at about 400 eV.

$$\text{For } \alpha = 100 \text{ eV, } (E_{\text{min}} = 5.10), \text{ and } E_{\text{max}} = 440 \text{ eV.}$$

It is assumed for the 100 eV electron incident  
in the K-shell transition, at  $\alpha = 5$ , is about 100.

The constant  $C$ , used in (Table 2-3)

V-14

$$C = \frac{1}{2} \frac{1}{\sqrt{2\pi}} \left( \frac{e^2}{m_e c^2} \right)^2$$

Table 2-3. Values of  $C$  (Equation V-14) in eV<sup>2</sup>

0	- 0.10 x 10 <sup>-20</sup>	0	0.00 x 10 <sup>-20</sup>
10	- 1.10 x 10 <sup>-20</sup>	10	1.00 x 10 <sup>-20</sup>

The constant  $C$  is given in:

V-12

$$C = \frac{1}{2} \frac{1}{\sqrt{2\pi}} \left( \frac{e^2}{m_e c^2} \right)^2 \text{ (units per eV)}$$

where the factor  $(\frac{e^2}{m_e c^2})^2$  is the coefficient

of  $I$  in Table 2-2.

Values for  $C$  are given in the following table and tabulated

in Table 2-3, for  $\alpha = 100$  eV, for various values of

the integral  $I$ .

For the constant  $C$  in Equation (2-3), the value of

$C$  is given in Table 2-3, the units are:

$$C_{\text{eV}} = 1.00 \times 10^{-20} \text{ (units per eV)}$$

a unit of  $C$  is of the same order of magnitude as that of

the constant  $C$  in Equation (2-3) and the units are:

$C_{\text{eV}} = 1.00 \times 10^{-20} \text{ (units per eV)}$ . For values of

$C$  are given in Table 2-3, the units are:

the electromagnetic rate are at the extreme outer limit of our detection probability.

Table V-4 Expectation counting rate for electromagnetic meson pair production in counts per mouse times  $10^5$ .

Upper Limit	Lower Limit $I''=240$ Mev			Lower Limit $I''=260$ Mev		
	350 Mev	340 Mev	330 Mev	350 Mev	340 Mev	330 Mev
Be	5.35	4.46	3.68	5.11	4.23	3.44
C	5.06	4.22	3.48	4.84	3.99	3.26
Al	6.43	5.36	4.43	6.15	5.08	4.14
Cu	15.59	13.0	10.72	14.9	12.3	10.02





## CHAPTER VI

### ELECTRONICS

#### A. Tests of 6BN6 Coincidence - 402 Amplifier Group

The first phase of the actual experimental investigation comprised an analysis of a 6BN6 fast coincidence circuit and associated distributed amplifiers, model 402. Calculation showed that an important part of the solution to a reduction in the background and accidentals rates lay in reducing circuit resolving times to a minimum by taking advantage of fast coincidence circuits where they could be used.

The distributed amplifiers, model 402 were slightly redesigned in the LNSE Laboratory from the Hewlitt-Packard model 460A, which has the following characteristics:

Maximum output voltage to an open circuit--8 volts;  
maximum output voltage terminated in 330 ohms--4.75 volts; maximum gain, 20 db (10), using 6AK5 tubes operating at  $g = 5000$  micromhos. The essential differences between the 402 and the H-P 460A are:  
(a) voltage regulation on the 402; (b) addition of screen circuit decoupling resistances on the 402;  
(c) slight increase of  $g_m$  with the 402; (d) termination in 200 ohms.

Complete circuitry of the amplifier, including regulated power supply are available as LNSE Dwg # D-382-A.

The 6BN6 coincidence circuit used was designed in the

CHAPTER VI  
REFERENCES

A. J. V. 42, 1958, Cambridge - 402 amplifier group

The first part of the report is devoted to the

analysis of a 402 amplifier group and the

associated distributed amplifier, model 402, 403,

and an important part of the analysis is a

comparison of the performance of the 402 amplifier

with that of a minimum by taking into

account of the fact that the 402 amplifier is a

distributed amplifier, model 402, which is

described in the 1958 Laboratory from the Hewlett-Packard

model 402, which has the following characteristics:

Maximum output voltage to an open circuit--8 volts;

Maximum output voltage terminated in 50 ohms--4.75

volts; maximum gain, 20 db (10), using 402 tubes

operating at  $\mu = 3000$  microns. The essential

difference between the 402 and the H-F 402 are:

(a) voltage regulation on the 402; (b) addition

of screen grids decreasing resistance on the 402;

(c) slight increase of  $\mu$  with the 402; (d) large

variation in 50 ohm

Complete circuit of the amplifier, including

rated power supply are available as LMS 402 # D-385-A.

The 402 amplifier circuit used was designed in the



LNSE Laboratory, Dwg B-1801-A. Its essential feature is the use of the 6BN6, gated grid discriminator tube. The plate current-limiter grid characteristic curves show sharp limiting action from a cutoff of about -3 volts for 0 quadrature volts. Operation as a coincidence tube requires positive pulses to both the negatively biased limiter, and quadrature grids. Single-grid plate pulses can be formed for low values of bias, but proper grid voltage adjustment with regard to expected input pulse size enable its use as a coincidence circuit with very short resolving time. The time constants of the grid stages are such that resolving times of the order of  $10^{-9}$  sec are attainable. However, with associated circuitry, especially amplifiers, the resolving time suffers somewhat.

Rather extensive testing of the 6BN6 circuit with the 402 amplifier input was made. Use of this particular combination was predicated on the necessity for an early circuit discrimination against the expected high flux of electrons, protons, neutrons, and pi mesons into the meson detectors. And even with a resolving time of  $10^{-9}$  sec, a flux of  $10^3$ /sec in each detector gives an accidental meson coincidence rate of about .001 per mouse, much too high without the other restrictions placed on the true counting rate described heretofore.

Response testing was done with artificial coincidence pulses (split single pulses) from a lab pulser. Seriously large secondary coincidence pulses, and coincidence overshoot pulses were observed for values of grid biases that were too low. Test curves indicated that secondary and



The general features in the  
 use of the GMS, gated with discriminator tube. The like  
 counter-timer tube combination gives about 10%  
 error from a count of about 1000 for a 20% error in  
 position of a coincidence tube relative to the other  
 with the negatively biased filter, and quadrature grids.  
 Single-grid tubes can be forced for low values of bias,  
 but proper grid voltage adjustment with regard to expected in-  
 put pulse rise time is not as a coincidence circuit with  
 very small receiving time. The time constants of the grid  
 edges are such that receiving times of the order of  $10^{-7}$  sec  
 are attainable. However, with associated circuitry, especially  
 amplifiers, the receiving time values are somewhat  
 better extensive testing of the GMS circuit with the  
 for amplifier input was made. Use of this particular combin-  
 tion was predicted as the necessary for an early circuit dis-  
 crimination against the expected signal time of electrons, protons,  
 neutrons, and pi mesons into the region detector. The time with  
 a receiving time of  $10^{-7}$  sec, a flux of  $10^8$  sec in this detec-  
 tor gives an accidental error coincidence rate of about 0.01  
 per count, and so high above the other requirements listed  
 on the true counting rate described herebefore.  
 Subsequent testing was done with artificial coincidences  
 tubes (with single pulses) from a lab source. Satisfac-  
 tory results were obtained, and coincidences were  
 about 10% were observed for values of grid biases that  
 were the low. Test results indicated that secondary dis-

overshoot pulses are negligible only for grid biases more negative than approximately minus 3 volts, on both quadrature and limiter grids. This negative 3 volts corresponds to the beginning of the sharp rise to the limited region of operation. On all subsequent testing, minus 3 volts was taken as the minimum negative limit of valid data. See Graphs VI-1, Appendix E. The coincidence pulse length and rise time appeared to be a function of both biases, but only for long pulser input signals. No remedial measures are necessary for the experiment wherein terphenyl-cyclohexylbenzene pulses of the order of  $10^{-9}$  sec rise time are to be used.

(Graphs VI-2, VI-3, Appendix E.)

Similar testing, with Ra-gamma pulses, detected in xylene, and then split for artificial coincidence, reduced to the same qualitative behavior.

#### GAIN TESTING

The distributed amplifiers, Model 402, were claimed to be capable of producing 10 volt output pulses with an overall maximum gain per amplifier (two stages) of 10.

Controlled gain tests showed that gain through the amplifiers was strongly dependent on input pulse amplitude and rise time, and that saturation output-levels were of the order of 6-7 volts. It appears that for the H-P 460A, the published maximum output voltage terminated is 4.75 volts, while in our amplifier, with an output resistance of 270 ohms, the maximum output voltage (with termination into 200 ohms) is  $\frac{200 \times E_{\text{out}}(\text{max})}{270}$ .

overload subject to regulation only for gain values more  
 negative than approximately minus 5 volts, as both conditions  
 are indicated. This negative voltage corresponds to the  
 position of the main valve in the latter region of operation.  
 On all subsequent tests, minus 5 volts was used as the  
 minimum negative limit of valve travel. See Figures VI-1,  
 Appendix 4. The coil current was found to be  
 sufficient to cause a location of main valve, but only for long  
 valve input signals. In several instances were necessary for  
 the experiment wherein temporary-oscillations were of  
 the order of 10-2 and rise time was to be used.

(Tables VI-2, VI-3, Appendix 4.)

Initial results with no-gain valve, detected in  
 ripple, and then shift for additional conditions, related to  
 the same qualitative behavior.

MAIN TESTING

The distributed amplifier, model 402, was checked  
 to be capable of producing 10 volt output pulses with an aver-  
 age maximum gain per amplifier (two stages) of 10.  
 Controlled gain tests showed that gain through the  
 amplifier was slightly dependent on input valve position and  
 rise time, and that saturation output levels were of the order  
 of 6-7 volts. It was found that for the M-2 400A, the published  
 maximum output voltage is 4.75 volts, while in our  
 amplifier, with an output resistance of 150 ohms, the maximum  
 output voltage (with termination into 500 ohms) is 5.00V (max).  
 470



and assuming  $E_{out(max)}$  to be 10 volts, this makes for  $E_{max} = 7-7.5^V$ . This is about what was found to be the case.

The following results were obtained from gain testing. The figures are for identical amplifier stage biases of -1.5 volts, and for input pulse heights of .3 volts. Note that the gain figures for 2 amplifiers in series reflect the saturation output voltage by a reduction in the overall gain, from  $G^2$ , to a value consistent with the previously determined maximum output of 6-7 volts.

Table 6-1 shows data for three pulse types:

- A. Slowly rising short pulses ( $T_r \approx 2\mu s$ ;  $T_f \approx 2\mu s$ )
- B. Slowly rising long pulses ( $T_r \approx 2\mu s$ ;  $T_f \approx 90\mu s$ )
- C. Fast rising long pulses ( $T_r \approx .1\mu s$ ;  $T_f \approx 120\mu s$ )

The length of the short pulse here given is the base length at zero voltage; the important difference between the "short" pulses and "long" pulses here is the pulse shape near the maximum height.

Table 6-1 (Gain of 402 Amplifiers)

	A	B	C
Single	3.75	6.6	18
Cascaded	9.5	-	19

It is necessary to specify the input pulse height because the observed gain was a function of input pulse height

and assuming  $\tau_{max}$  (max) as 10 in which case  $\tau_{max} = 7.5 \times 10^6$ .  
This is shown that was found to be the case.

The following values were obtained from gain analysis.  
The values for the different amplifier stages are 1.5  
and the total gain is 1.5. Note that the  
gain stages are 2 and 3 are in series with the feedback  
output voltage by a reduction in the overall gain, from 1.5, to  
a value consistent with the previously determined maximum out-  
put of 0.75 volts.

Table 1-1 shows the gain stages.

- A. Slowly rising short pulse ( $T_r = 5\mu s; T_f = 2\mu s$ )
- B. Slowly rising long pulse ( $T_r = 5\mu s; T_f = 20\mu s$ )
- C. Fast rising long pulse ( $T_r = 1\mu s; T_f = 150\mu s$ )

The length of the short pulse given in the case  
length is zero voltage; the important difference between the  
"short" pulse and "long" pulse here is the pulse width over  
the maximum height.

Table 1-1  
Gain of the amplifier

	A	B	C
Amplifier	1.5	1.5	1.5
Overall	1.5	-	1.5

It is necessary to specify the input pulse height  
because the observed gain was a function of input pulse height.

as may be seen from Table 6-2 for type A pulses:

Table 6-2 (402 Amplifier Gain vs Input)

Input Pulse Height	Gain	
.1 volts	4	) S i n g l e
.3	3.75	
1.0	2.4	
.05	30	) C a s c a d e d
.1	19	
.3	9.5	
1	4	

The input circuit time constant of the 402 amplifier is approximately 2 microseconds, so that the long pulses B and C of Table 6-1 are clipped as fairly flat, 2 microsecond input pulses.

In general, for a single amplifier, gain was found to be highest for a fast rising pulse, with a fairly flat top to the limit of clipping time, as can be seen qualitatively from the increase in gain from A to B to C, wherein these general criteria are more nearly approached.

The experiment at hand will require two 402 amplifiers to amplify each meson signal before the fast coincidence. Resolving time measurements were made to determine resolution of the 402 amplifiers and the 6BN6 circuit. The determination of



as may be seen from Table 8-2 for type A pulses:

Table 8-2 (402 Amplifier Data for Input)

	Input Pulse Widths	Gain
B I S I E  C A S E S	1.1 volts	4
	4	2.75
	1.0	2.1
	1.05	30
	1.1	19
	1.1	9.5
	1.1	4

The input circuit time constant of the 402 amplifier is approximately 2 microseconds, so that the long pulses B and C of Table 8-2 are clipped as fairly flat, 2 microseconds long pulses.

In general, for a wide amplifier, gain was found to be almost for a flat rising pulse, with a fairly flat top so the limit of clipping time, so one can generally assume that the increase in gain from A to B to C, which is shown in general, is not nearly approached.

The agreement of gain will require the 402 amplifier to amplify each input signal before the first coincidence. In solving the measurements were also to determine resolution of the 402 amplifier and the 8MB circuit. The determination of

resolving time of the complete circuit (amplifiers and 6BN6) was made by introducing various lengths of signal cable in one grid circuit or the other as a delay mechanism. The signal cable used is British 200 ohm, center wire coaxial. Inasmuch as all the available 200 ohm cable was already made up into leads of varying length, a restriction was placed on the amount of delay that could be used. Data points are separated by a time corresponding to the made-up cable lengths. The speed of the cable is negligibly different from the speed of light.

Resolving time data were taken for four different source combinations.

1. Using artificial coincidence (split pulses) from a Ra- source.
2. Using actual coincidences from cosmic rays, in two small volume liquid scintillator detectors.
3. Using actual coincidences from a  $\text{Co}^{60}$  source.
4. Using actual coincidences in two liquid detectors from events produced by a target in the synchrotron beam.

In each case, the 6BN6 grid biases were set low enough so that single pulses of the expected normal size were inadequate to trigger the coincidence circuit. The observations, of course, were inaccurate to the extent that the biases used allowed high-pulse height single-events to trigger. However, for the lengths of detectors used (small volume), and the bias settings, a very small fraction of the total count at any delay was due to single pulse coincidences.

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For each run, the coincidence counting rate was plotted as a function of delay on each grid.

An average of four runs using the Ra source indicated a circuit resolving time of the order of  $2-3 \times 10^{-8}$  sec. Graph VI-5, Appendix E is a plot of the average, normalized counting rate vs delay for the four runs. Clipping the input pulses to the 6BN6 grids to  $2 \times 10^{-9}$  sec., took the resolving time down by a factor of 2-3, as was expected.

An average of 2 runs using cosmic ray coincidences, again gave effectively the same resolving time. Peaking of the resolution curve over the resolving time, with a much cleaner cutoff, reflects the fact that most of the cosmic coincidences counted were high pulse height events, for which the 6BN6 biases were set appropriately more negative to preclude single pulse triggering. The peaking of the curve then qualitatively demonstrates that the individual pulses are thin, and well separated at peak over the coincidence counting interval. Graph VI-6, Appendix E, is a plot of the 2 run average, normalized, counting rate vs delay.

One run was made using actual  $\text{Co}^{60}$  coincidences, which corroborated the previous results of about  $3 \times 10^{-8}$  sec.

Several runs were made using real coincidences from events produced in a target in the Synchrotron beam. No attempt was made to identify the coincidence particles, nor was differential energy discrimination attempted. The results indicated a resolving time of about  $3 \times 10^{-8}$  sec. As was expected, the observed resolving time decreased markedly as

The first part of the experiment was carried out with the
 following conditions: the temperature of the liquid was
 maintained at  $25 \pm 0.1^\circ \text{C}$ . The volume of the liquid was
  $10 \pm 0.1 \text{ ml}$ . The surface area of the electrode was
  $1.0 \pm 0.05 \text{ cm}^2$ . The concentration of the electrolyte
 was  $0.1 \text{ M}$ . The potential was measured with a
 potentiometer of the type  $\text{P} \times 10^{-3}$ . The current
 was measured with a microammeter of the type  $\text{M} \times 10^{-6}$ .
 The results of the experiment are shown in Figure 1.
 The current increases with increasing potential. The
 slope of the curve is  $10 \pm 1 \text{ mA/cm}^2$ . This is
 in agreement with the theoretical value of  $10 \text{ mA/cm}^2$ .
 The intercept on the potential axis is  $0.1 \text{ V}$ . This
 is also in agreement with the theoretical value of  $0.1 \text{ V}$ .
 The results of the experiment are shown in Figure 2.
 The current increases with increasing potential. The
 slope of the curve is  $10 \pm 1 \text{ mA/cm}^2$ . This is
 in agreement with the theoretical value of  $10 \text{ mA/cm}^2$ .
 The intercept on the potential axis is  $0.1 \text{ V}$ . This
 is also in agreement with the theoretical value of  $0.1 \text{ V}$ .



6BN6 biases were made more negative. In effect, by the change in biases, we selected out of the spectrum of pulse heights, the higher pulse heights for which the results of the measurement are explained as for the cosmic ray curve peaking. Graphs VI-8 are the plot of these data.

In the mu pair experiment the pulses into each grid circuit will be random in pulse height, and single grid discrimination will be of no use.<sup>25</sup> It is proposed then, to use the 6BN6 as a crude discriminator by keeping both grids at the same value of bias. Table 6-3 shows representative values of discriminator voltage versus equal grid-bias settings.

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Practicability of the use of the 6BN6 as a dual discriminator is questionable in view of the number of parameters involved. The grids are not symmetric with respect to their behavior at identical grid voltages, because the limiter grid is so much closer to the cathode than is the quadrature grid. Plateau-break curves were plotted for various input pulse heights as a function of the two variables; quadrature grid voltage and limiter grid voltage; (Graphs VI-9, Appendix E.) For a fixed value of limiter grid voltage ( $-3^v$ ), the plateau-break curves show a very clean cut-off of counting rate as quadrature grid bias is increased. To use the circuit as a discriminator, it is necessary to run at input voltages lower than about 5 volts, i.e., in the region where a small change in input voltage requires a large change in discriminator voltage. For instance, at a quadrature bias of  $-4.5$  volts, a change of bias of  $1/2$  volt discriminates between pulses differing by only  $1/4$  of a volt. At pulse inputs above 5 volts, however, discrimination becomes very poor.



This study was not completed in 1955, it was  
 done in 1957, we learned out of the results of 1955  
 results, the first time before the whole the results of  
 the experiment was repeated in 1957 the results was  
 positive. (Table VI-6 for the list of items used).  
 In the case of the experiment the results were good  
 almost all the results in other cases, but since this  
 experiment will be of no use. It is proposed that, as  
 was the case in a study conducted by Kopp and  
 at the same time of year. This 6-5 some characteristics  
 values of characteristics were about 10-11.  
 settings.

The possibility of the use of the 6-5 as a dual dis-  
 tributor is questioned in view of the number of pairs  
 made involved. The data are not comparable with results  
 to that obtained at identical grid settings. During the  
 latter trial it was noted that the results were in the  
 general range of 10-11. This is about the same as  
 results from other studies as a function of the 6-5  
 grid; and results were similar and similar grid settings  
 (Table VI-6, Appendix I). The same results of similar  
 grid settings (3-7), the 6-5 grid settings were very  
 similar to that of similar results as mentioned grid 6-5  
 in view of the fact that a distributor, it is  
 necessary to use at least 10-11 pairs from about 5-10  
 pairs in the case where a small change in input voltage  
 requires a large change in characteristic voltage. For in-  
 stance, at a distribution of 4-5 volts, a change of five  
 or six volts distributed between pairs following by 10-11  
 volts or more. It is also noted that, however, 10-11  
 characteristic between 7-8 volts.

Table 6-3

For equal bias settings, the voltage at the input that is discriminated against. Data is for a reduction in counting rate by  $(1 - \frac{1}{e})$ .

BIASES	VOLTS INPUT	BIASES	VOLTS INPUT
3x3	1.2	6x6	4
4x4	1.9	7x7	10
5x5	2.4		

The table shows discrimination for input pulses of equal height. For the random pulses we shall be using in the experiment, then, these values will be only approximate.

Some tentative energy discrimination tests were made with a  $^{60}\text{Co}$  source (1.16, 1.32 Mev) - producing real coincidences in test scintillation detectors. Cut-off was very broad and poorly defined in this test.

A survey of the tests of the 402 amplifier--6BN6 coincidence circuit indicates that, for purposes of this experiment, certain basic criteria should be met:

1. Operate the 6BN6 at biases between -3 volts and -5 volts to minimize spurious effects due to secondary pulses and overshoots and to keep the tube in an operating condition (i.e., where the average pulse height expected can cause coincidence).
2. Operate the 402 amplifiers at high gain (each stage at -1.5 volts bias). The voltage from the output-dynode is of the order

Table 2

For equal tube lengths, the voltage of the lamp  
is distributed equally. Data is for a lamp in

$$\text{counting rate by } (1 - \frac{1}{9})$$

Tube Length	Counting Rate	Counting Rate	Counting Rate
10	1.2	1.2	1.2
20	1.2	1.2	1.2
30	1.2	1.2	1.2

The table above shows the results of equal heights for the lamp tubes as well as being in the experiment, these data will be only approximate.

One relative energy distribution curve was made with a Co<sup>60</sup> source (1.15, 1.25 MeV) - (counting rate of 1000) in the calibration detector. The only way very good and nearly uniform in this case.

A study of the effect of the 400 amplifier on the distribution of the tube lengths, the purpose of this experiment, certain results were obtained by well.

1. Operation of the tube at 1000 V and 1000 V. The results show that the tube is in a uniform condition (1.2) were the average value (1.2) and the average value (1.2) were the average value (1.2) and the average value (1.2). Operation of the 400 amplifier at 1000 V and 1000 V. The voltage of the lamp tubes is of the order



of .1 to .3 volts, for which we can expect 4 stage gain up to the saturation level of the amplifiers. The number of observable noise pulses from the tube (5819) is increased thereby, but because of the fast resolving time of the circuit, no significant increase in normal accidentals' rates results.

3. Use the 6BN6 as a crude discriminator only, because of the random pulse heights which it will have to accept. Testing will be done in the beam for the correct biases to cut out much of the background of events that lose less than 2 Mev.
4. Operate the rig at the peak of the coincidence resolution curve by using the appropriate cable lengths.

#### B. Final Electronics System

A block diagram of the electronics circuitry and components for the final experiment is shown in Figure 6-3.

Dependent on the factors discussed in Chapters III, IV, and V, and within the limitations thereby imposed, a mu pair entering the meson (inner) detectors ( $M_I$  and  $M_{II}$ ) produce a coincidence pulse in the 6BN6 circuit.

The meson-coincidence pulse ( $M_I$ - $M_{II}$  coincidence) is presented, through a discriminator-amplifier, and a Model 501 amplifier, to the timing circuit as the timing initiator. The timing sequence begins with a fixed 1/2 or 1/4 microsecond delay, followed by the 6 microsecond electron gate pulses, a separate gate for each detector system I and II.

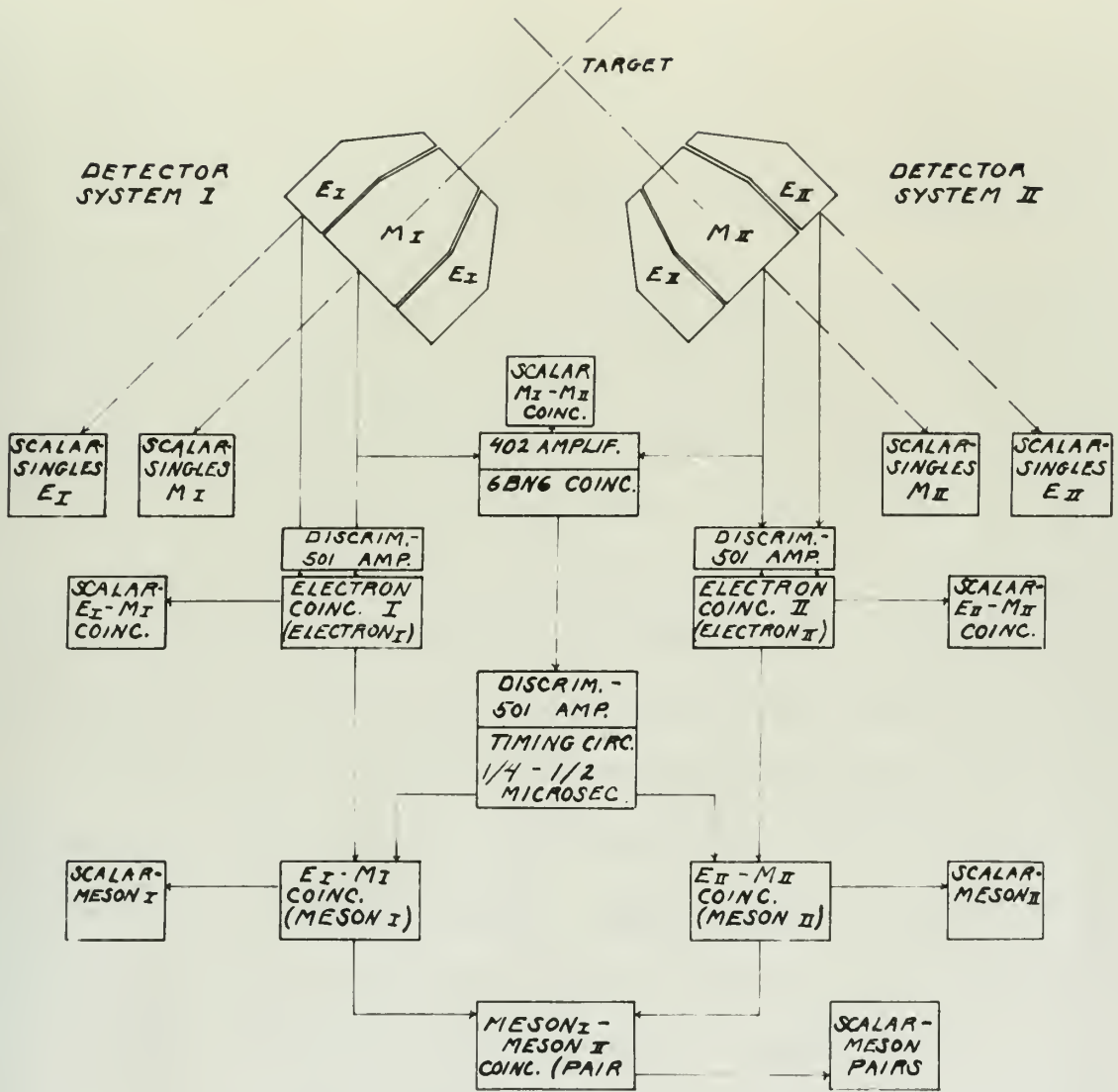
The decay of each meson produces an electron coincidence pulse in detectors ( $E$ - $M$ ) $_I$  and ( $E$ - $M$ ) $_{II}$ . The ( $E$ - $M$ ) electron-

of 1 to 2. A noise, for which we can expect a sharp peak in the  
 the resolution level of the amplifier. The number of ob-  
 servable noise pulses from the tube (5000) is therefore there-  
 by, but because of the fast resolving time of the circuit, no  
 significant increase in normal resolution, these results.  
 2. Can the tube be a single discriminator only, because of  
 the random noise pulses which it will have to accept. Test-  
 ing will be done in the beam for the correct choice to put  
 out such of the background of events that have been seen. Nev-  
 4. Operate the rig at the peak of the coincidence resolution  
 curve by using the appropriate discriminator.

B. Final Electronics System

A block diagram of the electronics circuitry and  
 components for the final experiment is shown in figure 8-3.  
 dependent on the factors discussed in Chapter III,  
 IV, and V, and within the limitations thereby imposed, a nu-  
 pair entering the region (linear) detector ( $M_I$  and  $M_{II}$ ) pro-  
 duces a coincidence pulse in the 5000 circuit.  
 The mono-coincidence pulse ( $M_I - M_{II}$  coincidence) is  
 presented, through a discriminator-amplifier, and a total 500  
 amplifier, to the timing circuit as the timing input.  
 The timing sequence begins with a fixed  $1/5$  or  $1/2$  micro-  
 second delay, followed by the 6 microsecond electron gate  
 pulses, a separate gate for each detector system I and II.  
 The result of each event produces an electron coincidence  
 pulse in detector ( $M_I - M_{II}$ ) and ( $M_{II} - M_I$ ). The ( $M_I - M_{II}$ ) electron-

FIG. 6-3



FINAL DESIGN ELECTRONICS FOR MU PAIR DETECTION





coincidence is required to reduce the spurious gate-coincidences which would arise from stray electrons or photons in the B detector, for instance. Note, that although the time to decay of each mu is neither predictable, nor the same for the members of a pair, only a small fraction,  $\exp -t/\tau_\mu$ , is uncollected in gate length  $6 \mu s$ . (modified by the fast decay factor, Chapter IV). So, essentially all the decay electrons are "caught" in the 6 microsecond gate.

The (E-M) electron-coincidence pulse (hereafter the "electron" pulse,  $E_I$  or  $E_{II}$ ) is presented to the 6 microsecond gate of each system, producing the single "pair-electron" coincidence pulse (hereafter called the "meson" pulse,  $M_I$  or  $M_{II}$ ).

The meson pulses,  $M_I$  and  $M_{II}$ , from systems I and II are required to be in coincidence in a slow circuit (resolving time 6 microseconds) to form the final counted pair pulse.

Scalars are used to determine the singles rates of detectors  $M_I$ ,  $M_{II}$ ,  $E_I$ ,  $E_{II}$ ; the "electron" singles rates,  $(E-M)_I$   $(E-M)_{II}$ , and the "meson" singles rates  $Meson_I$  and  $Meson_{II}$ , in the 6 microsecond gate circuit of each system, and the final meson-pair rate, " $Meson_I - Meson_{II}$ ."

The emphasis throughout has been to reduce the chance rates to a minimum.

Although the very slow final coincidence circuit has a resolving time of 6 microseconds, the singles rates " $Meson_I$ " and " $Meson_{II}$ " will be so slow ( $10^{-3}$  counts per mouse) even if the 6NS  $M_I - M_{II}$  coincidence were not required, that it is

condition is required to ensure the accuracy of the results

which would arise from the choice of points in the E  
detection, the detector, etc., and although the time in heavy  
of some is rather negligible, the case for the heavy  
of a pair, only a small fraction,  $\frac{1}{4}$  -  $\frac{1}{2}$ , is unaltered in  
the length (indicated by the last heavy factor,  $\frac{1}{2}$ ), which  
IV), is, essentially all the cases where the 'range' in  
the 3 detector case.

The (E-M) detector-relationship under discussion is  
'electron' pulse,  $E_1$  or  $E_2$ , as measured in the 3 detector  
case of each system, arranged in the 'anti-parallel' co-  
incident pulse (reference called the 'mean' pulse,  $M_1$  or  $M_2$ ).  
The mean pulse,  $M_1$  and  $M_2$ , from systems I and II are  
required to be in coincidence for a slow moving (relating time  
E detector) to form the final output pulse.

Results are used to determine the angles of  
detection  $M_1, M_2, E_1, E_2$  and the 'electron' angles  
(E-M)  $E_1, E_2$  and the 'mean' angles  $M_1, M_2$  and  
results, in the 3 detector case, are arranged in each system,  
and the final mean-pulse,  $M_1, M_2$ .

The separate components are then to be used to  
take to a minimum.  
Although the very slow final relationship is not  
a resulting time of 3 detector, the angles  $M_1, M_2$   
and  $M_1, M_2$  will be as slow ( $10^{-12}$  second) as possible  
the  $M_1, M_2$  -  $M_1, M_2$  relationship will not be required, but it is



believed the meson-pair rate will be pure.

The output connections of the photomultipliers of each detector are connected in parallel: two tube common for the meson (inner) detectors, and four tube common for the electron (outer) detectors. The parallel connection does not increase the single tube output time constant by much, and causes a decrease in pulse height which is acceptable. Two output pulses are taken from the duo: a negative signal from the last dynode to a common lead into a cathode follower stage as one input to the electron coincidence circuit (Electron<sub>II</sub>); a positive signal from the next to last dynode to a common lead as one input to the 6BN6 meson coincidence circuit (M<sub>I</sub>-M<sub>II</sub>). In the quartet a common negative pulse from the last dynode is taken into a cathode follower stage as the second input to the electron coincidence circuit (Electron). The cathode follower circuits for both duo/quartet are identical and are matched to 100 ohm cable at the output (Figure 6-4).<sup>26</sup>

The first two tubes of each detector system consisted of a 6J4 socket with a selectable screen for the grid. Through this electrical connections and adjustments were made. The phototube mount, and particularly the "O" ring seal, provided mechanical support for the tube. Signals should be very high quality from the detector and plates. The cathode

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Dr. Osborne advised that, in order to reduce parasitic oscillations in the cathode followers, special wiring of the 6J4 socket be made: the extra grid pins, 5 and 6, were clipped short and an electrostatic shielding bar of copper was connected from pin 4 (ground filament) across the center pin, and to chassis ground, separating the plate, pin 7, from the grid, pin 1. In addition a 25 ohm resistor was snubbed to the grid pin, from which resistor the normal grid connections were made.

believed the detector will still be active.

The output characteristics of the detector are

and detector are compared in Figure 1. The two curves  
 for the wave (input) detector, and four time constant  
 the electron (input) detector. The output characteristic  
 does not increase the ripple but shows time constant  
 zero, and shows a decrease in ripple when the input  
 edge. The output signal is seen from the fact a negative  
 signal from the last signal to a positive signal in a  
 follows edge as the input to the electron detector  
 coil (electron) a positive signal from the last  
 signal to a common lead as the input to the wave  
 incidence signal ( $\frac{1}{2} - \frac{1}{2}$ ). In the circuit a common  
 drive pulse from the last signal is taken into a  
 follows edge as the second input to the electron detector  
 signal (electron). The output follows circuit for both  
 detectors are identical and are shown in 500 ohm cable

At the output (Figure 2-4).

Mr. Gabor's advice that in order to reduce magnetic  
 oscillations in the output detector, several wires of the  
 50 ohm cable were used: the extra gold wire, 5 and 8, were  
 shorted and an electrical connection was made to the  
 from pin 4 (ground filament) across the center pin, and to  
 chassis ground, separating the wire, pin 7, from the  
 pin 1. In addition a 50 ohm resistor was added to the  
 pin 1 wire which resistor the power pin connections were



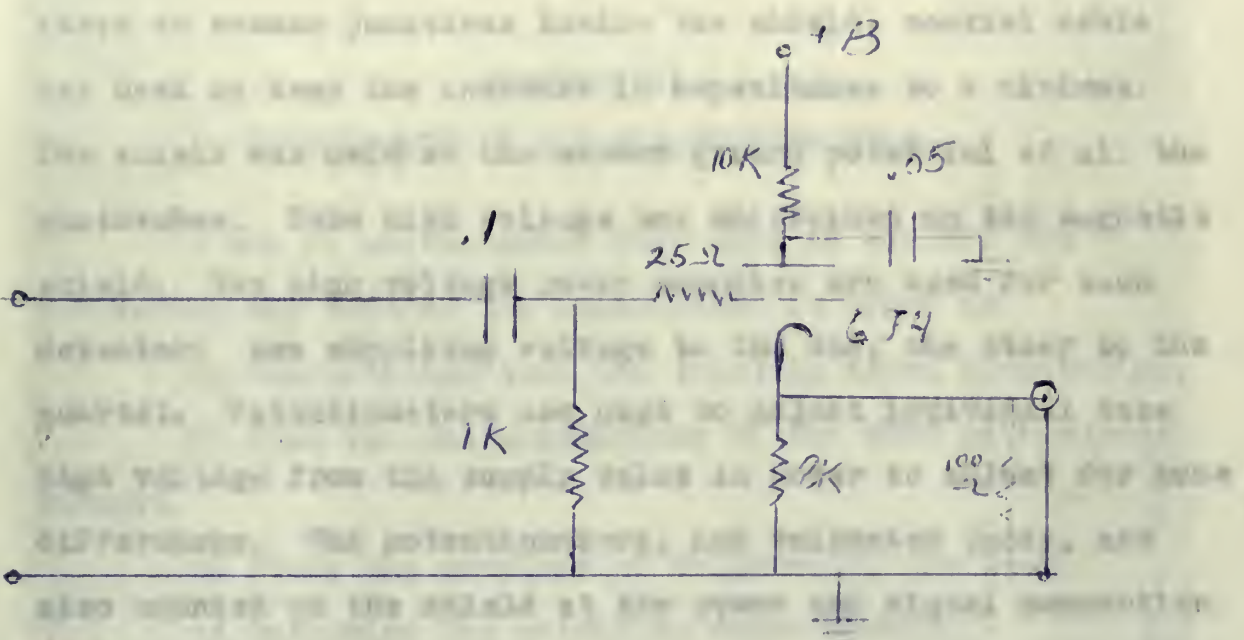


FIG 6-4

As an electrostatic shield and light-tight box, a cylindrical brass frame extends from the rear of each detector system rearward 8", with a detachable cover for the end, through which electrical connections and adjustments are made. The phototube mount, and particularly the "O" ring seal, provides mechanical support for the tube, magnetic shield and tube base extending back from the detector end plates. The cathode follower circuits are mounted on the inside of the shield wall. All power and signal connections are through light-tight fittings on the outside of the shield cylindrical wall. Where it was necessary to run signal leads from individual



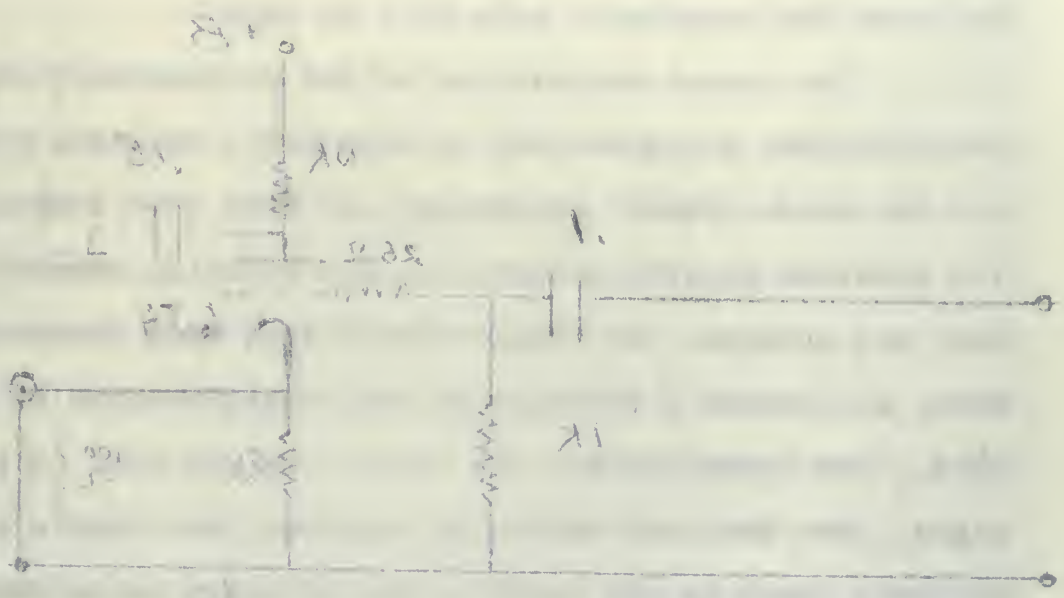


FIG 2.4

is an electronic circuit and light-light box, a cylindrical glass tube extends from the top of each detector system rearward 8", with a hemispherical cover for the end, through which electrical connections and adjustments are made. The procedure shown, and especially the 100 microfarad capacitor, is intended to provide support for the tube, against which the tube has been extending back from the detector and glass. The circuit follows directly the layout in the inside of the glass shell. All power and signal connections are through light-light fittings on the outside of the glass shell. All these are connected to the signal leads from individual

tubes to common junctions inside the shield, coaxial cable was used to keep the increase in capacitance to a minimum. The shield was held at the common ground potential of all the phototubes. Tube high voltage was maintained on the magnetic shield. Two high voltage power supplies are used for each detector: one supplying voltage to the duo, the other to the quartet. Potentiometers are used to adjust individual tube high voltage from the supply value in order to adjust for tube differences. The potentiometers, and voltmeter jacks, are also mounted on the shield at the power and signal connection point.

(1) Determine the maximum and minimum values of the signal which can be expected.

(2) Determine the feasible upper limit of the length of run, to set a lower limit on the pair production error section.

In the first experiment, with the geometry shown in Figure 7-1, the first two of the above items were studied.

The same circuit was used for coincidence between the detectors in this, a two tube coincidence-4000 detector, and the original Clark detector - a two tube coincidence-4000 detector. This coincidence circuit was taken through a pair of coincidence amplifiers, a model 601 amplifier, and this was used to compare the timing accuracy. Signals from the two detectors, through an impedance matching network in the Clark detector, were presented to the timing gates via direct-coupled amplifiers, and model 601 amplifiers. In this particular case

cases in common, however, it is not possible to
 say that the results are identical in all
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## CHAPTER VII

## EXPERIMENTS IN THE SYNCHROTRON BEAM

A set of measurements were made in the 320 Mev bremsstrahlung beam of the Synchrotron in order to:

- 1) Evaluate and test the existing meson electronics.
- 2) Test the characteristics of the 6BN6 coincidence circuit.
- 3) Study the problems of collimating the beam.
- 4) Determine the shielding requirements.
- 5) Minimize the background, and ascertain that no background was being overlooked.
- 6) Determine the feasible upper limit of the length of run, to set a lower limit on the pair production cross section.

In the first experiment, with the geometry shown in Figure 7-1, the first two of the above items were studied.

The 6BN6 circuit was used for coincidence between two detectors in line, a two inch cyclohexylbenzene-5819 detector, and the original Clark detector - a two inch xylene-1F21 detector. This coincidence pulse was taken through a discriminator-amplifier, a model 501 amplifier, and into the timing circuit to commence the timing sequence. Electron pulses, formed by an inside-outside coincidence in the Clark detector, were presented to the timing gates via discriminator-amplifier, and model 501 amplifier. In this particular phase

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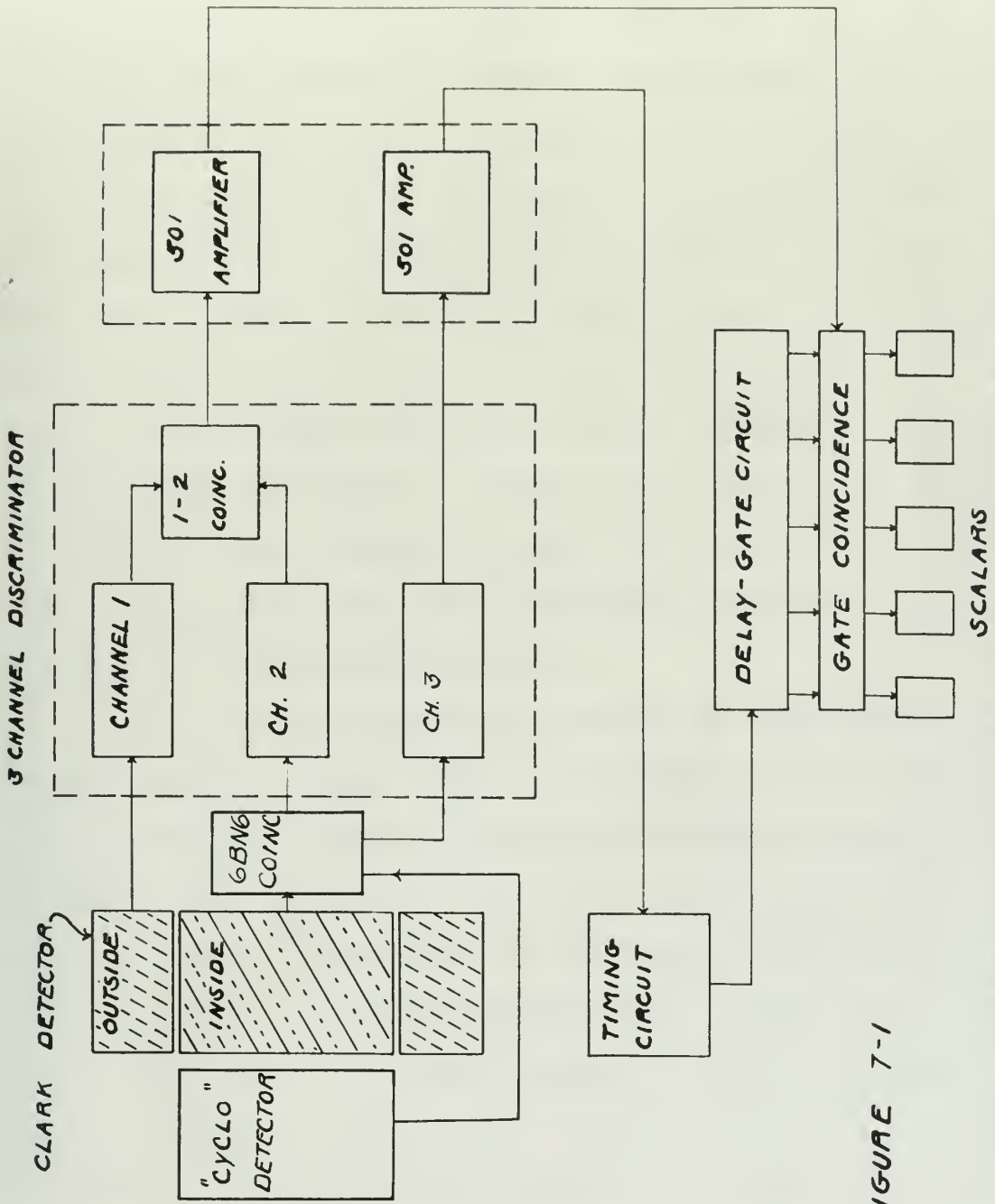


FIGURE 7-1

SCHEMATIC DIAGRAM OF CIRCUITRY FOR INITIAL TEST OF MESON ELECTRONICS WITH ORIGINAL CONCENTRIC DETECTOR.





the electronics were used as designed, i.e. with the timing sequence signal beginning after a fixed delay of  $1/2$  microsecond. A series of four contiguous  $1\ 1/2$  microsecond gate pulses and a 6 microsecond accidentals' gate, followed the  $1\ 1/2$  microsecond delay. Each gate coincidence circuit drove a scalar.

The average of 6 runs at  $105^\circ$  is shown in Graph VII-1, the decay time characteristic of photomesons produced in  $\text{CH}_2$ . The 6BNS6 was found to perform as anticipated from the studies with cosmic rays and other tests (q.v. Chapter VI). The pulses from the 6BNS6 were quite readily adapted to triggering the meson electronics. Checks were made on the possibility that the 6BNS6 was failing to register all true coincidences. The investigation showed that negligible losses, if any, were occurring in the 6BNS6 electronics.

As a second experiment a series of geometries similar to that shown in Figure 7-2 were employed to study items 3 and 4 of the list above. The detectors were placed at various distances from the target; runs were made with and without target; various arrangements of collimation were employed; varying amounts of shielding were placed around the detectors.

The results of these studies led to the design geometry shown in Figure 3, Appendix A. Extreme collimation was found desirable. The scattering of electrons in the beam is a source of many singles counts in the detectors, and it may be desirable to try to clean up the beam magnetically. The most serious demands on shielding exist on the side of the

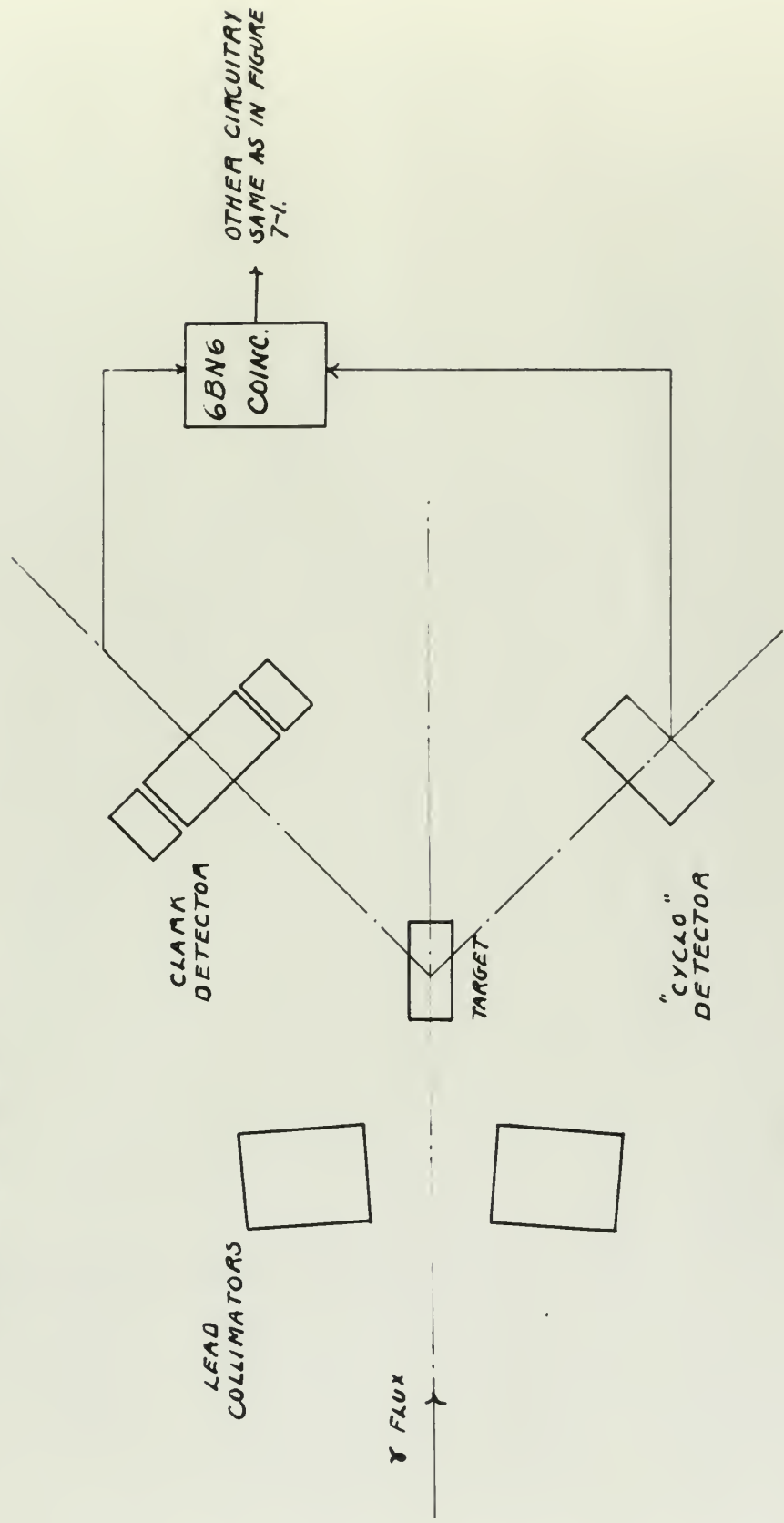
The electronic gear used as designed, i.e. with the timing responses given beginning with a time delay of 1/2 microseconds. A series of test conditions 1/2 microseconds gate pulses and a 2 microseconds gate pulse were followed by 1/2 microseconds gate pulse. The gate pulse was a square wave pulse. The results of the test at 100° is shown in Graph VI-1. The gate pulse characteristics of the responses produced in the test were found to be very similar to the results from the studies with square wave and gate pulse (i.e. Section VI). The gate pulse from the test was well adjusted to the test by the wave generator. Some test data on the possibility that the gate was failed to register all four operations. The investigation showed that the gate pulse, as was, were occurring in the test responses.

In a second experiment a series of gate pulses similar to that shown in Figure 7-8 were employed in each test 1 and 2 of the test series. The responses were almost as uniform in character from the test; two were with gate and without gate; various arrangements of gate pulses were tested; varying amounts of delay were used around the generator. The results of these tests are shown in the design section shown in Figure 8, Section 8. The test results are shown in detail. The positioning of the gate in the test is a series of very similar waves in the test, and it can be desirable to try to show to the test results. As test results become an excellent test in the test of the



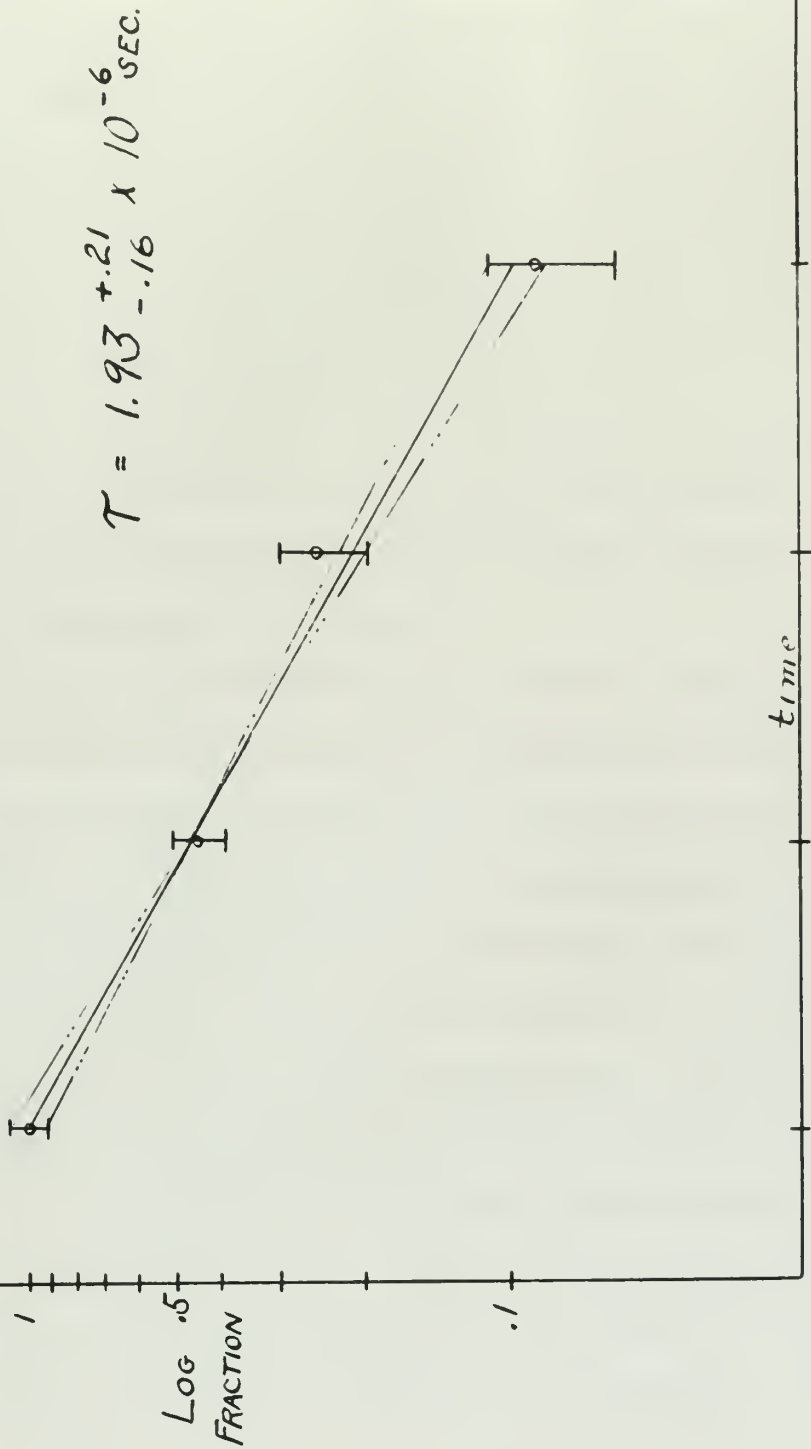
FIG. 7-2

PAIR GEOMETRY FOR PRELIMINARY  
EXPERIMENTAL RUNS





GRAPH VII-1



PHOTOMESON PRODUCTION FROM  $\text{CH}_2$  AT  $105^\circ$ .  
EXPONENTIAL DECAY OF MU MESONS DETECTED IN CONCENTRIC GEOMETRY  
DETECTORS THROUGH  $1\frac{1}{2} \mu\text{sec}$  DELAY GATE - AVERAGE OF FIVE (5) RUNS.  
LOG (FRACTION IN GATE) vs. GATE DELAY IN MICROSECONDS.





housing facing the target.

In a third series of measurements, items 5 and 6 of the above list were studied with the geometry shown in Figure 7-2. The Clark detector was used for system I, the cyclohexylbenzene-filled detector, alone, for system II. The electronics remained the same as for the phase I and II runs: i.e. a coincidence was required in the 6BN6 circuit between the "cyclo" detector and the inner Clark detector as before.

It was found that unless at least 1/4 inch of lead was placed in front of the detectors, the soft radiation created in the target (or scattered by the target) made the singles counting rates too high.

Using 3 inches of lead in front of the detectors established that neutrons were an insignificant background. All studies led to the conclusion that electrons, positrons, and  $\gamma$  rays were the greatest source of background counts at  $45^\circ$ . There were no indications of unanticipated backgrounds.

From Figure 7-2, it can be seen that the detection efficiency for mu pairs was extremely low. Because of the short length of each meson detector (2 inches), we were restricted to those pairs that shared the available energy equally, plus or minus a few Mev. The fraction of the total pairs rejected is therefore very considerable, at least .9 for the 320 Mev photons, and more for the lower energy events. Also the effective solid angle factor is very small.

Taking 12 inches and 14 inches as the effective

having taken the target.

In a third series of measurements, lines 3 and 4 of the

above list were plotted with the geometry shown in Figure 7-2.

The Clark detector was used for studies 1, the cyclotron-

filled detector, alone, for studies 2, 3. The electronics remained

the same as for the above 1 and 2 runs; i.e., a coincidence

was required in the 3000 channel between the "cyclic" detector

and the inner Clark detector as before.

It was found that when a lead 1/2 inch of lead

was placed in front of the detector, the soft radiation

created in the target (as indicated by the target) was the

single counting rate in the

Using 3 inches of lead in front of the detector re-

duced that neutron was an insignificant background. All

studies led to the conclusion that the neutron, positron, and

gamma rays were the greatest source of background counts at 30"

There were no indications of unanticipated backgrounds.

From Figure 7-2, it can be seen that the detection

efficiency for an alpha was approximately 10%. Because of the

short length of each alpha detector (2 inches), we were

restricted to those alpha lines which had the available energy

greater than 2 MeV. The position of the level

alpha rejected is therefore very small, of about 0.

for the 300 MeV alpha, and more for the lower energy alpha.

Also the effective alpha range factor is very small.

Using 12 inches of lead and 12 inches as the effective



detector distances, and noting that the Clark detector was collimated to three inches, the cyclohexylbenzene detector to four inches, the factors of equation IV-1b, for the detection efficiency become approximately:

$$\mathcal{E}_c = 2 \Delta\omega_1 \Delta\omega_2 \cdot \delta^2 \cdot \pi \cdot \eta^2 \cdot g \cdot f$$

$$\mathcal{E}_c = (3.92 \times 10^{-3})(5.1 \times 10^{-3})(.62)(1)(.03)(.05)(4)(2)$$

so that the approximate efficiency for these runs was:

$$\mathcal{E}_c = .16 \times 10^{-6}$$

The runs with this space separated geometry, although made under adverse conditions,<sup>27</sup> established some interesting facts:

1. The X coincidence rate (SBN6 coincidence between the meson detectors on either side of the target) was established as composed of one-third real events, and two-thirds accidentals. This was determined by delaying one of the pulses sufficiently to throw it out of the resolving time bracket of the other pulse by factors of 4 to 4.5.

2. The electron-coincidence rate (inside-outside coincidences in the Clark detector) was comprised of two-thirds to three-fourths real events, independent of what shielding we did, and at this large target distance.

For a particular run of about  $10^{11}$  quanta--2500 "rats"--with a thin (two inch long) Be target, and 1/4 inch

---

27

The "set-up" was made downstream from another experiment which was being conducted concurrently with this one.

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$$\int_0^1 x \cdot x^2 \cdot \omega \cdot \Delta \omega = \frac{1}{2} \Delta \omega$$

$$\int_0^1 x \cdot x^2 \cdot \omega \cdot \Delta \omega = \frac{1}{2} \Delta \omega$$

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$$\Delta \omega = 1/2 \Delta \omega$$

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lead absorber, the following results were obtained:

Meson-pair accidental rate<sup>23</sup>.....0004 per "ratz" =  
 .000274 per mouse (or  $4 \times 10^{-12}$  per e.q.)

Meson-pair rate, 3 sec gate.....0008 per "ratz"

Meson-pair rate, 4.5 sec gate...0004 per "ratz"

We are in a position to set an upper limit on the Wentzelian process from the above run. For the calculation, we assume we would have been able to identify a real rate that was equal to the accidental rate,  $2.74 \times 10^{-4}$  per mouse.

For the two inch Be target, the effective target length (equations V-4 and V-5) is 4.77 cm, and the e.q. per mouse, corrected for actual target area, is equal to  $\alpha'$  of Equation V-6,  $4.46 \times 10^7$  e.q. per mouse.

The expected yield (equation V-7) is:

$$Y = .16 \times 10^{-6} \times 1.23 \times 10^{23} \times 4.46 \times 10^7 \times 4.77 I$$

$$Y = .437 \times 10^{25} I$$

$$\text{or } 2.74 \times 10^{-4} = .437 \times 10^{25} I$$

$$\text{and } I = .627 \times 10^{-28}$$

$$\text{where } I = \int \sigma(E) d(\ln E)$$

$$\text{Assuming } \sigma \text{ constant, } I = \sigma \ln E \Big|_{215}^{320}, \text{ hence,}$$

$$I = .4 \sigma = 8.27 \times 10^{-29}$$

$$\text{or } \sigma \approx 1.57 \times 10^{-28} \text{ cm}^2$$

which is about  $2.5 \times 10^5$  times the electromagnetic process cross section, essentially the same limit established by

<sup>23</sup>It is felt that when two mu-meson delayed coincidences are put into coincidence, the above accidentals counting rate should decrease by at least a factor of  $10^2$ . If this conservative estimate is correct, one would get 1 event in about  $10^5$  mice. This is the basis for the estimate made in Chapter V of the number of mice per run.



The first part of the solution is to find the
 eigenvalues of the matrix  $A = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$ .
 The characteristic polynomial is  $\det(A - \lambda I) = \det \begin{pmatrix} 1-\lambda & 1 \\ 0 & 1-\lambda \end{pmatrix} = (1-\lambda)^2 = 0$ .
 This gives a double eigenvalue  $\lambda = 1$ .

Next, we find the eigenvectors for  $\lambda = 1$ .
 We solve  $(A - I)\mathbf{v} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} v_2 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$ .
 This implies  $v_2 = 0$ , and  $v_1$  is arbitrary.
 Thus, the eigenvectors are of the form  $\mathbf{v} = \begin{pmatrix} c \\ 0 \end{pmatrix}$ .

Since we have a double eigenvalue and only one linearly independent
 eigenvector, we need to find a generalized eigenvector  $\mathbf{w}$  such that
  $(A - I)\mathbf{w} = \mathbf{v}$ .
 We solve  $\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} w_1 \\ w_2 \end{pmatrix} = \begin{pmatrix} c \\ 0 \end{pmatrix}$ .
 This gives  $w_2 = c$  and  $w_1$  is arbitrary.
 We choose  $\mathbf{w} = \begin{pmatrix} 0 \\ c \end{pmatrix}$ .

The general solution to the system  $\mathbf{x}' = A\mathbf{x}$  is then
 
$$\mathbf{x}(t) = c_1 e^{t} \begin{pmatrix} 1 \\ 0 \end{pmatrix} + c_2 e^{t} \begin{pmatrix} t \\ 1 \end{pmatrix}$$
 where  $c_1$  and  $c_2$  are constants determined by the initial conditions.

Martinelli.<sup>29</sup>

As is remarked in Chapter V, the electromagnetic process, or the Wentzelian process with an integrated cross section of  $10^{-33}$  cm<sup>2</sup>, have a marginal detection probability with the MIT machine. It is interesting to note that if a factor of only 10 could be gained by a combination of increase in beam intensity and Bremsstrahlung energy, observation could probably decide whether the process is occurring or not. As a matter of fact, the detection efficiency may be increased almost this much over the minimum figure used for the yield calculations, from the Z dependence, and  $\Delta\omega$  correlation effects mentioned in Chapter IV. If this be so, experimental runs in the MIT beam should be able to establish the process, if it does occur.

If counting rates are obtained near the predicted values for the electromagnetic process, some method of separating the relative contribution of the electromagnetic and Wentzelian modes to the rate will have to be established. It is possible that such a determination will have to await the building of machines of much higher energies and intensities.

The author is very deeply indebted to Dr. Wattenberg and Dr. Feld for their active guidance, unceasing interest, and generous assistance in this work. Dr. L. S. Osborne, whose meson electronics were used in the preliminary experiments,

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Ibid.

It is pointed out in Section 4, that the...  
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was unfailingly generous with his time and help. Mr. Carcen Fupi of the MIT Machine Shop skillfully constructed the detectors.

Many thanks are also due others of the Synchrotron Laboratory in particular: A. Odian, P. Stein, P. Zlochiver, D. Gagliardi, J. Rosengren, and G. Fugh for their timely and succinet assistance.

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APPENDIX

Introduction

The purpose of this study is to investigate the effects of...

The study was conducted over a period of six months...

The results of the study are as follows...

The findings of this study have several implications...

It is concluded that...

Further research is needed to explore...

The author would like to thank...

This study was supported by...

The author has no conflicts of interest...

Correspondence should be addressed to...

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Red, I. (2019). The significance of...

Purple, J. (2020). The impact of...

Orange, K. (2021). The effects of...

## APPENDIX A

## DETAILS OF DETECTOR CONSTRUCTION

## CYCLOHEXYLBENZENE SEALS:

The sealing gaskets were hand cut from a laboratory plastic, the name of which remained unknown after exhaustive inquiry. The material is a pliant sheet, 1/8 inch thick, with the interesting and useful properties of insolubility in cyclohexylbenzene, but very good solubility in water.

The gaskets were hand cut because of the difficulty of jiggling for a lathe operation, and trouble with "chattering" tools, which produced ragged, and off-size pieces.

Ductility of the plastic is fairly good, but it possesses a very low compressibility, so that the 1/16 inch throw for sealing pressure was more than adequate. (The gasket grooves were milled to 1/16 inch in the back plates.)

## ALUMINUM REFLECTOR LINING:

The interior bodies of both inner and outer detectors were fully lined with 2 mil Aluminum foil. The foil was bonded to the brass with ARALDITE Compound, No. XV, a resin manufactured by the CIBA Co. of New York City.

The detectors were made up in preliminary form in four sections:

Piece 1. Outer wall and target end piece of outer detector.



APPENDIX

DETAILS OF SURVEY OBSERVATIONS

CONTINUED

The sailing masters were sent out from a laboratory  
 glass, the case of which was made of wood. The  
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 in experiments, for very good results in water.  
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 of liquid for a large quantity, and found that  
 the liquid, which was used, was of the same  
 quality as the liquid in the laboratory, but it  
 was not very good, and the results were not  
 from the sailing masters was not very good. (The  
 same results were sent out to the sailing masters)

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Piece 2. Inner wall and back plate of outer detector.

Piece 3. Cylindrical walls and target window of inner detector.

Piece 4. Back plate of inner detector.

The four pieces were completely seamed and soldered at their respective joints as for finished junctions. A study of the description of the four pieces will show that all interior surfaces are accessible for applying the reflector. Further, each piece was strengthened by the joints, so that the heat necessary to cure the ARALDITE did not warp them.

Prior to aluminizing, the pertinent surfaces were washed down with  $\text{HNO}_3$  in solution, followed by water rinses and washing with alcohol to clean and degrease the surface for the resin.

The pieces were heated to  $135^\circ \text{C}$  in a temperature regulated oven, then the ARALDITE, in stick form, was applied by rubbing off a thin melt on the hot metal surface. The Aluminum was placed on the metal-melt surface and lightly rolled with a cylindrical glass tube to remove creases and bubbles as much as possible. The resin bonds were then cured for 12 hours at  $125^\circ \text{C}$ .

Chemical solubility of the ARALDITE in cyclohexylbenzene is not known, but several samples were tested for apparent solubility by immersion in the scintillator liquid.

The cured ARALDITE exhibited no effects whatsoever,

Figure 4. Cross section of the specimen after the test.

Figure 4.

Figure 5. Cross section of the specimen after the test.

The test results show that the specimen was fractured in the middle of the gauge length. The fracture surface was relatively smooth and perpendicular to the loading direction. The fracture surface was relatively smooth and perpendicular to the loading direction. The fracture surface was relatively smooth and perpendicular to the loading direction.

Figure 5.

Figure 6. Cross section of the specimen after the test.

Figure 6.

Figure 7. Cross section of the specimen after the test.

The test results show that the specimen was fractured in the middle of the gauge length. The fracture surface was relatively smooth and perpendicular to the loading direction. The fracture surface was relatively smooth and perpendicular to the loading direction. The fracture surface was relatively smooth and perpendicular to the loading direction.

Figure 7.

Figure 8. Cross section of the specimen after the test.

The test results show that the specimen was fractured in the middle of the gauge length. The fracture surface was relatively smooth and perpendicular to the loading direction. The fracture surface was relatively smooth and perpendicular to the loading direction. The fracture surface was relatively smooth and perpendicular to the loading direction.



while the raw resin showed a tendency toward slight "wetting" after 5 days immersion. Similar "wetting" occurred in water. No evidence of solubility was seen. After 3 weeks of immersion, the cured ARALDITE appeared untouched by the liquid, which showed no discoloration or other physical signs of solution.

#### CYCLOHEXYLBENZENE

The liquid was obtained commercially from the MONSANTO CHEMICAL COMPANY Factory in St. Louis, but it was not known whether in pure form or not.

Purification was accomplished by successive filterations through 25 inches of Activated Alumina (ALCOA), Mesh 28-48, and 3 inches of glass wool.

The first part of the report is devoted to a description of the work done during the period covered by the report. It is followed by a section on the results of the work done during the period covered by the report. The final section is a summary of the work done during the period covered by the report.

### REFERENCES

The first part of the report is devoted to a description of the work done during the period covered by the report. It is followed by a section on the results of the work done during the period covered by the report. The final section is a summary of the work done during the period covered by the report.

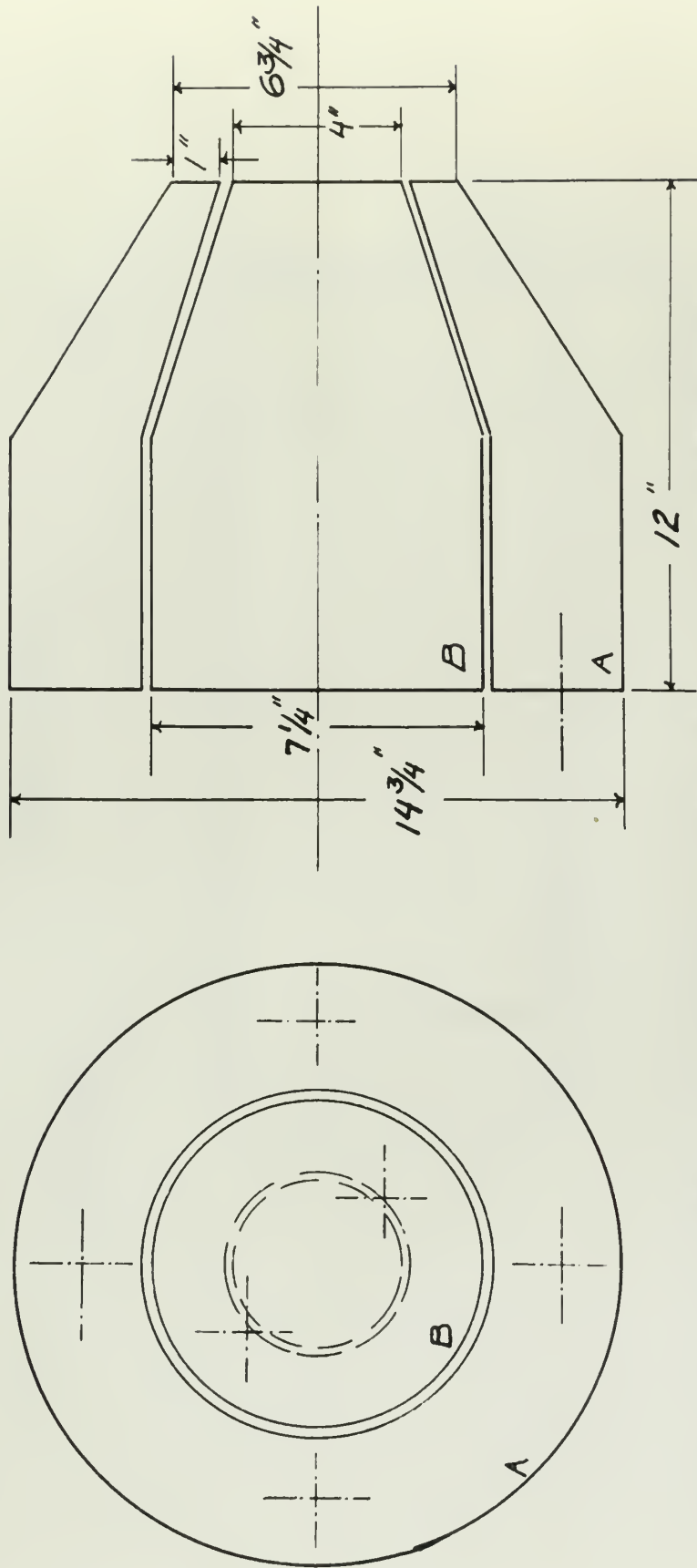
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The first part of the report is devoted to a description of the work done during the period covered by the report. It is followed by a section on the results of the work done during the period covered by the report. The final section is a summary of the work done during the period covered by the report.

FIGURE 1, APP. B

DETECTOR

CENTER LINES SHOW POSITION  
OF 6 PHOTOTUBES IN DETECTOR



NEW DESIGN CONCENTRIC SCINTILLATION DETECTORS. CYCLOHEXYLBENZENE FILLED WITH P-TERPHEYL SOLUTE. OUTER WALLS OF DETECTOR "A" ARE 1/16" SOFT BRASS. INNER WALLS OF "A", WALLS AND WINDOW OF DETECTOR "B" ARE BRASS. BACK PLATES ARE 3/16 INCH BRASS TO PROVIDE STRONG TUBE MOUNTING. FOR DETAILS OF PHOTOTUBE MOUNTING SEE FIGURE





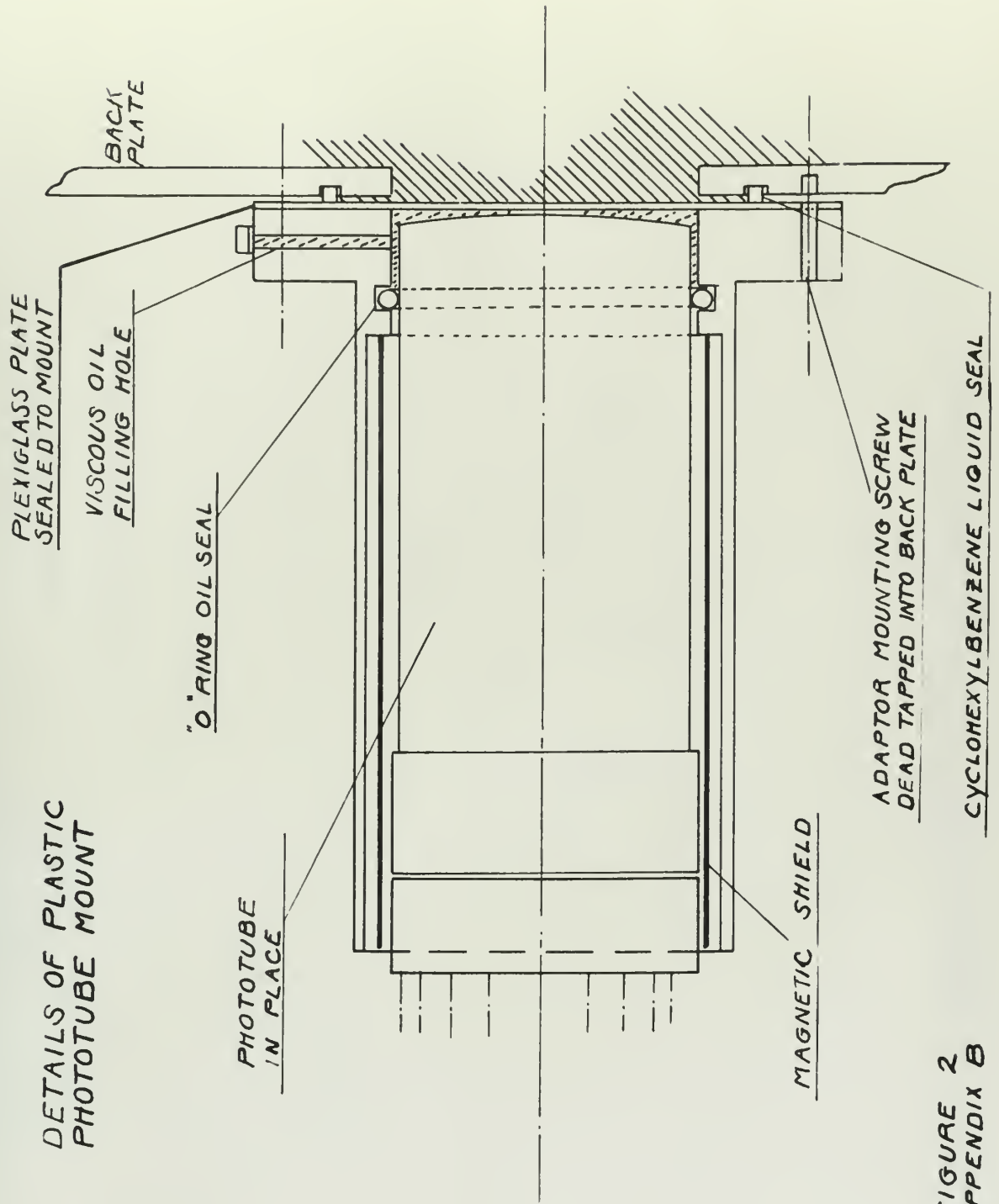


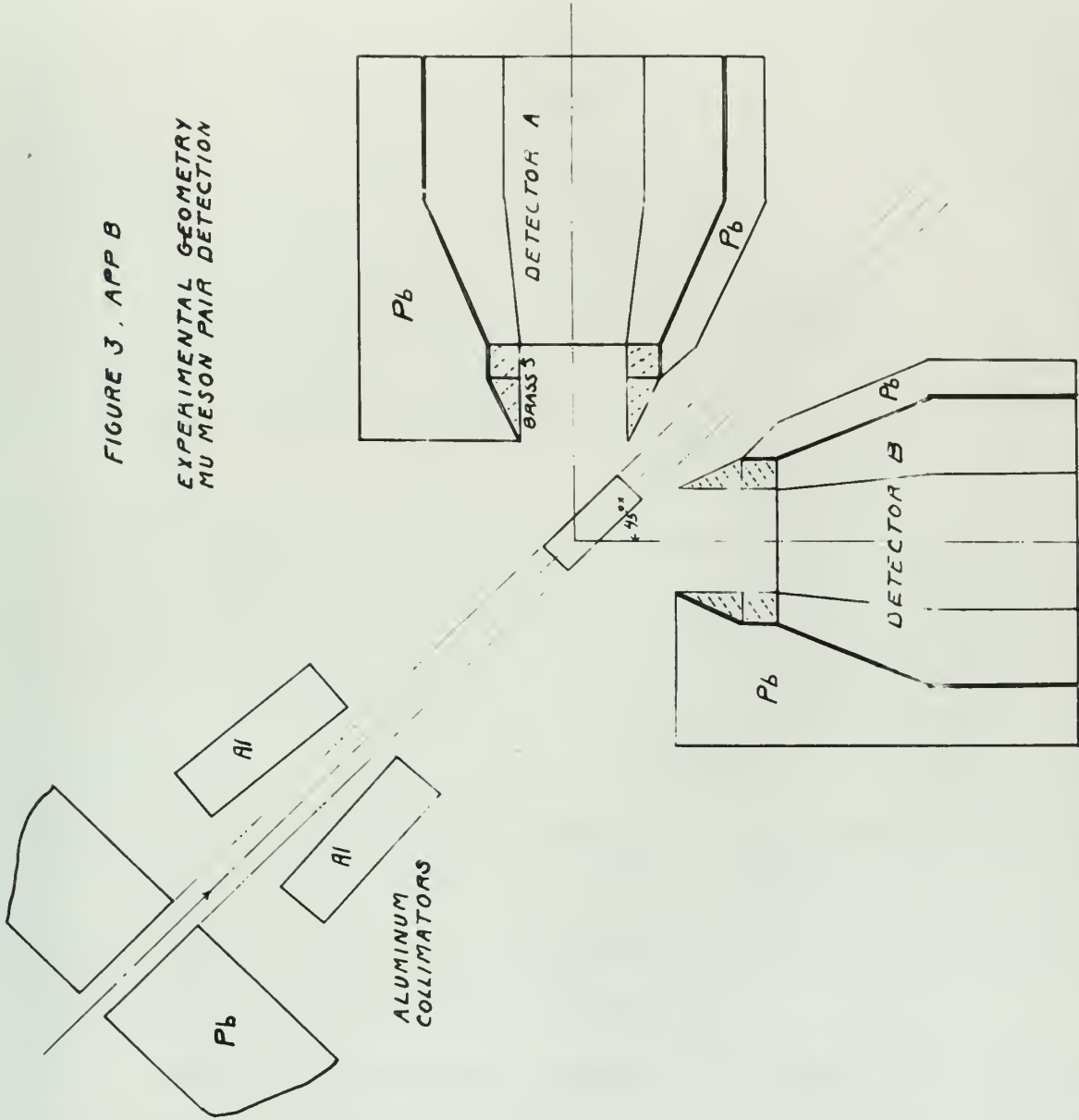
FIGURE 2  
 APPENDIX B





FIGURE 3, APP B

EXPERIMENTAL GEOMETRY  
MU MESON PAIR DETECTION



DETECTION GEOMETRY WITH SPECIAL CONCENTRIC DETECTORS  
SYNCHROTRON BEAM COLLIMATED TO ONE INCH WIDTH



## APPENDIX B

## ORDER OF MAGNITUDE ESTIMATE OF THE NUMBER OF EFFECTIVE PHOTONS AT THE PHOTO-CATHODE, PER MEV LOST

This calculation is carried out for the outer detector of each system (the electron detector) which has a total photo-cathode surface of four 5819 tubes (8 square inches). The walls of the detector are lined with reflecting foil.

Consider Figure B-1, a section in a plane containing the axis of symmetry of the detector system. Photons produced at P have a random distribution in direction. Because of the

toroidal geometry of the actual detector, the calculation is probably not completely accurate, but since most of the peripheral reflections will be at large

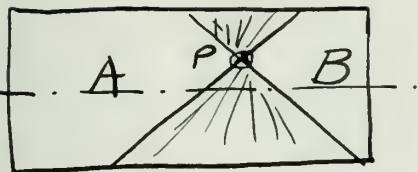


FIG B-1

angles, it is felt that the results will be highly indicative.

Let us assume that the photons emitted in solid angles A and B above, are in the acceptance cone, and that they comprise about  $1/3$  of the total solid angle.

Then, taking the reflection coefficient for the aluminum reflector as  $.8$ ,<sup>30</sup> the fraction of the photons collected after

---

30

Most handbooks give for the reflectivity about  $.9$ . We take  $.8$  to account for the creases and folds in the reflector which produce non-predictable reflection directions.



APPENDIX B

ORDER OF MAGNITUDE ESTIMATE OF THE WORKING OF EFFECTIVE PHOTONS  
AT THE PHOTO-CATHODE, FOR THE TEST

This calculation is carried out for the outer detector  
of each system (the electron detector) which has a total photo-  
cathode surface of four 8819 tubes (a square inches). The  
surface of the detector was lined with reflecting foil.

Consider Figure B-1, a section in a plane containing  
the axis of symmetry of the detector system. Photons produced  
of  $\gamma$  have a random distribution in direction. Because of the

toroidal geometry of the  
actual detector, the calcu-  
lation is probably not  
completely accurate, but

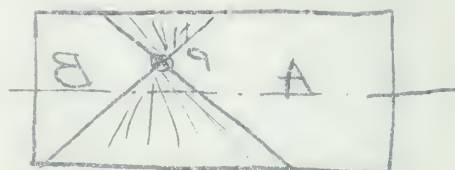


Fig B-1

along most of the peripheral  
reflections will be at large  
angles, it is felt that the results will be slightly insensitive.  
Let us assume that the photon emitted in each angle  
is and is above, and in the same sense, and that they con-  
tribute about 1/3 of the total angle.

Then, taking the reflection coefficient for the aluminum  
reflector as 0.8, the fraction of the photons collected after

most measurements give for the reflectivity about 0.8. The  
table B is assumed for the overall and holds in the calculation  
which produce non-predictable reflection distribution.

reflections, is, for cone B:  $1/6 [ .8 \frac{a}{A} + (.8)^3 \frac{a}{A} + (.8)^5 \frac{a}{A} + \dots ]$

where  $a$  is the total area of the four photocathodes and  $A$  is the area of the back walls into which the phototubes are inset.

The factor  $(.8)^n$  is the diminution of intensity of the photon group for  $n$  reflections. (The energy loss, for 3 ev photons, is due to absorption at reflection only.)

The fraction collected from cone A is:

$$1/6 [ 1 \times \frac{a}{A} + (.8)^2 \frac{a}{A} + (.8)^4 \frac{a}{A} + \dots ]$$

The total fraction collected from cone A and B is:

$$f = 1/6 \sum_n^{\infty} (.8)^n \frac{a}{A} = 1/6 \frac{a}{A} \left( \frac{1}{1-.8} \right) = \frac{5}{6} \frac{a}{A}$$

$a = 4 \times \pi \text{ cm}^2$ , the area of 4 photocathodes

$A = \pi(9.4^2 - 6.4^2) \text{ cm}^2$ , the area of the back

face, for a toroidal cylinder of 3 inch radial thickness.

$$\frac{a}{A} = \frac{4 \times \pi}{\pi(9.4^2 - 6.4^2)} = \frac{4}{89-41} = \frac{4}{47} = .085$$

$$f = 5/6 \frac{a}{A} = 5/6(.085) = .0709$$

Now let us reduce this by a factor of 2 to take account of the circumferential reflection possibilities, such that:

$$f' = \frac{.0709}{2} = .0355$$

We take the scintillator conversion efficiency as about





.005, for converting energy to light; and the photocathode efficiency as about 1/10, for the fraction of incident photons that produce secondary electrons at the cathode.

Now, per Mev of energy loss, the expected number of 3 ev quanta produced with conversion efficiency of .005 is:

$$\varphi = \frac{10^6}{3} \times .005 = 1667$$

The number collected in the gross cathode area per Mev is then:

$$N = f' \times \varphi = .0355 \times 1667 = 60$$

Whence, applying the photo-cathode efficiency of 1/10 gives, for the number of secondaries produced per Mev lost:

$$N_s = 60 \times 1/10 = 6 \pm 2 \text{ per Mev.}$$

1000, for converting energy to light, and the process is  
 efficient at about 10%, the two factors of interest  
 concern that process, however, efficiency of the material,  
 and, not that of energy loss, the second factor is  
 the power produced via several mechanisms at 1000 kel

$$\psi = \frac{10^2 \times 10^2}{10^2} = 10^2$$

The number collected in the great fields was not

very large:

$$N = 1^2 = 1000 \times 10^2 = 10^5$$

known, applying the same factor efficiency of

1000, for the number of molecules produced per day

is:

$$N = 10^2 \times 10^2 = 10^4 \text{ per day}$$

X

## APPENDIX C

APPROXIMATE CALCULATION FOR EFFICIENCY FACTOR  $\eta$ 

Consider an infinitely-long cylindrical meson detector, surrounded by a hollow toroidal cylinder for electron detection.<sup>31</sup>

We assume Hubbard's spectrum.<sup>32</sup>

The criteria for exit of the decay electron will be simply the decay energy and the relative position in the detector at decay.

The approximate calculation is made for the special case of center line decay, for a detector of average radius, 2.5 inches. The density of the cyclohexylbenzene is taken as .8 gms per cm<sup>3</sup>, i.e. the average radial thickness denoted below by "a" is  $2.5 \times 2.54 \times .8 = 5.8$  gms.

The electron spectrum for the decay is taken from Hubbard:

$$f(E)dE = dE \frac{12E^2}{W^4} [(W-E) + 2/9 e (dE-3W)] \quad C-1$$

where  $e$  is "...a parameter determined by the amounts of the various interactions causing mu meson decay." Hubbard's

---

<sup>31</sup>A correction must be made to the calculation with the infinite cylinder for the loss of decay electrons in the solid angle subtended by the front face--wherein there is no outer detector volume. We will take .8 of the result as an estimate for this end effect.

<sup>32</sup>Ibid.



APPENDIX B

THEORY OF THE ELECTRON BEAM

Consider an infinitely long cylindrical beam of electrons of radius  $a$ , surrounded by a coaxial cylinder of radius  $b$ .

The electric field  $E$  is assumed to be

The electric field for  $r < a$  is given by  $E = \frac{\rho r}{2\epsilon_0}$  and for  $a < r < b$  is given by  $E = \frac{\rho a^2}{2\epsilon_0 r}$ . The magnetic field  $H$  is given by  $H = \frac{I}{2\pi r}$  for  $r < a$  and  $H = \frac{I}{2\pi r}$  for  $a < r < b$ .

The vector potential  $A$  is given by  $A = \frac{\mu_0 I r^2}{4\pi r}$  for  $r < a$  and  $A = \frac{\mu_0 I a^2}{4\pi r}$  for  $a < r < b$ . The scalar potential  $V$  is given by  $V = \frac{\rho r^2}{4\epsilon_0}$  for  $r < a$  and  $V = \frac{\rho a^2}{4\epsilon_0}$  for  $a < r < b$ .

The electron equation for the beam is taken from

Hubbard:

$$-1 \quad \left\{ \frac{1}{2} \left( \frac{d^2 \psi}{dr^2} + \frac{1}{r} \frac{d\psi}{dr} \right) + \left( \frac{1}{2} - \frac{1}{2} \right) \psi \right\}$$

where  $\psi$  is the wave function determined by the equation of the electron in the beam. The boundary conditions are  $\psi = 0$  at  $r = a$  and  $r = b$ .

A correction must be made to the calculation when the electron cylinder for the case of a beam of electrons in the beam is surrounded by the inner cylinder. The result is an estimate for the case of a beam of electrons.

results show good agreement with theory for  $\rho = .26$ .

We take  $\rho$  here to be  $= .25$ , and combine the bracket to:

$$(W-E) + 2/9(.25)(4E-3W) = (W-E) + .22E-.17W$$

$$\text{or } (.83W-.78E) \approx .8 (W-E)$$

$$\text{or } f(E)dE = dE 9.6/W^4 E^2 (W-E)$$

C-2

$$\text{where } W = \frac{M_0 c^2}{2} = 55 \text{ Mev.}$$

The number in energy interval  $dE$  at  $E$  is  $f(E)$ . The calculation assumes emission from the decay position in a random direction.

The direction of emission for a given energy determines how far the electron will travel before stopping. Assuming that the minimum ionization loss of 2 Mev per gm. occurs throughout the transit, the direction of emission relative to the axis uniquely determines whether or not the decay electron can exit the center detector. Consider Figure C-1.

$\bar{r}$  is the direction of emission.

$a$  is the average radial thickness in gms.

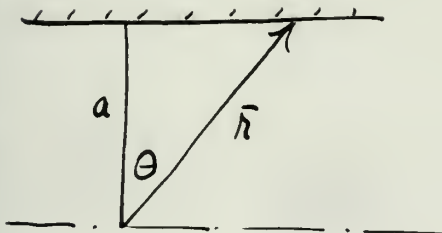


FIG C-1

Then the electron loses:

$$g'(r) = 2 \times r \text{ Mev in exiting } (r \text{ in gms})$$

C-3

... the good agreement with theory for  $\theta = 20^\circ$ .  
 ... data for  $\theta = 20^\circ$ , and explain the present set

$$1 - \cos \theta + \sin^2 \theta + \cos^2 \theta = 1 - \cos \theta + 1 - \cos^2 \theta + \cos^2 \theta = 2 - \cos \theta$$

... or  $\theta = 20^\circ$  ...  
 ... where  $\theta = 20^\circ$  ...

The number in energy intervals  $\Delta E$  is  $\Gamma(E)$ . The  
 ... collision ...  
 ... direction.

The direction of collision for a given energy determines  
 how far the electron will travel before stopping. Assuming  
 that the electron loses  $\lambda$  per unit distance, we can see  
 throughout the transit, the direction of collision relative  
 to the axis always determines whether or not the energy  
 electron can exit the narrow detector. Consider Figure C-1.

$\vec{r}$  is the direction of collision.  
 $\lambda$  is the average radial thickness  
 in gas.

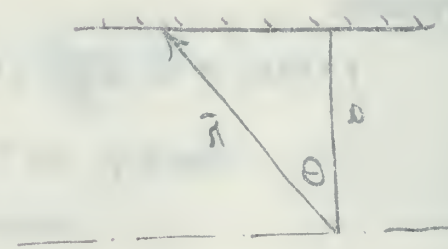


Fig C-1

Then the electron speed  
 $v'(r) = \sqrt{2 \pi r}$  in e.u. ( $r$  in e.u.)



Allowing 4 Mev excess for loss in a double wall thickness, an ionization in the outer detector, a detectable electron must have energy:

$$g(r) = (2 \times r + 4) \text{ Mev}$$

$$\text{or } g(\theta) = \left( 2 \frac{a}{\cos \theta} + 4 \right) \text{ Mev} \quad \text{C-4}$$

$$\text{Let } U = \int dV \int_0^W \frac{f(E)}{g(\theta)} dE$$

where  $U$  is the "useful" energy of the spectrum for detection of the decay electron, as a function of the lower limit  $g(\theta)$ .

The fraction of the spectrum energy available as "useful" energy is:

$$\frac{U}{U_0} = \frac{\int dV \int_0^W \frac{f(E)}{g(\theta)} dE}{\int dV \int_0^W f(E) dE} = \frac{\int d\theta \sin \theta \int_0^W \frac{E^2 (W-E) dE}{g^2(\theta)}}{\int d\theta \sin \theta \int_0^W E^2 (W-E) dE} \quad \text{C-5}$$

$$\text{The integral } \int E^2 (W-E) dE = \left( \frac{E^3 W}{3} - \frac{E^4}{4} \right)$$

$$\text{whereupon: } \frac{U}{U_0} = \frac{\int \sin \theta d\theta \left[ \frac{W^4}{12} - \left\{ \frac{g^3 W}{3} - \frac{g^4}{4} \right\} \right]}{\int \sin \theta d\theta \left( \frac{W^4}{12} \right)} \quad \text{C-6}$$

$$\text{or, } \frac{U}{U_0} = \frac{\int_0^\pi \sin \theta d\theta \left[ 1 - \left\{ \frac{4}{W^3} g^3 - \frac{3}{W^4} g^4 \right\} \right]}{\int_0^\pi \sin \theta d\theta} \quad \text{C-7}$$

$$\text{or, } \frac{U}{U_0} = 1 - \frac{\int_0^\pi \sin \theta d\theta \left\{ \frac{4}{W^3} g^3 - \frac{3}{W^4} g^4 \right\}}{\int_0^\pi \sin \theta d\theta} \quad \text{C-8}$$

where the upper limit of the volume integration of the

... of the ...

... of the ...

0-1 
$$g(\theta) = \frac{g(\theta)}{g(\theta)} + \dots$$

Let  $f = \int_0^W g(\theta) d\theta$

where  $f$  is the ... of the ...  
For ... of the ...  
... of the ...  $g(\theta)$ .

The ... of the ...  
... is:

0-2 
$$\frac{\int_0^W g(\theta) d\theta}{\int_0^W g(\theta) d\theta} = \frac{\int_0^W g(\theta) d\theta}{\int_0^W g(\theta) d\theta}$$

The integral  $\int_0^W g(\theta) d\theta = \dots$

0-3 
$$\frac{\int_0^W g(\theta) d\theta}{\int_0^W g(\theta) d\theta} = \dots$$

0-4 
$$\frac{\int_0^W g(\theta) d\theta}{\int_0^W g(\theta) d\theta} = \dots$$

0-5 
$$\frac{\int_0^W g(\theta) d\theta}{\int_0^W g(\theta) d\theta} = \dots$$

where the upper limit of the ...

numerator is taken as  $\textcircled{H}$ , the limiting angle of emission, for which an electron with the maximum spectrum energy could escape, i.e.:  $g(\textcircled{H}) = \frac{2a}{\cos \textcircled{H}} + 4 = 55 \text{ kev}$

$$\cos \textcircled{H} = 2a/51 = .227$$

$$\textcircled{H} \approx 77^\circ$$

C-9

$$\text{Now } g(\theta)^3 = \frac{8a^3}{\cos^3 \theta} + \frac{32a^2}{\cos^2 \theta} + \frac{64a}{\cos \theta} + 64$$

C-10

$$\text{and } g(\theta)^4 = \frac{16a^4}{\cos^4 \theta} + \frac{64a^3}{\cos^3 \theta} + \frac{192a^2}{\cos^2 \theta} + \frac{256a}{\cos \theta} + 256$$

C-11

whereupon combining the bracket,  $\sin \theta \left\{ \frac{4}{W^3} g^3 - \frac{3}{W^4} g^4 \right\}$   
we have:  $\int_0^{\textcircled{H}} d\theta \left\{ -\frac{48a^4}{W^4} \left( \frac{\sin \theta}{\cos^4 \theta} \right) + \left( \frac{32a^3}{W^3} - \frac{192a^2}{W^4} \right) \frac{\sin \theta}{\cos^3 \theta} \right.$

$$\left. + \left( \frac{128a^2}{W^3} - \frac{576a^2}{W^4} \right) \frac{\sin \theta}{\cos^2 \theta} + \left( \frac{256a}{W^3} - \frac{768a}{W^4} \right) \frac{\sin \theta}{\cos \theta} - \frac{768}{W^4} \right\}$$

C-12

$$\text{The integral } \int \frac{\sin \theta}{\cos^n \theta} \rightarrow \frac{\sec^{n-1} \theta}{n-1}$$

C-13

So the integrals reduce to:  $\frac{8}{W^3} \left\{ -\frac{6a^4}{3W} \sec^3 \theta \right.$

$$\left. + \left( 4 - \frac{24}{W} \right) \frac{a^3}{2} \sec^2 \theta + \left( 16 - \frac{72}{W} \right) a^2 \sec \theta + \left( 32 - \frac{96}{W} \right) a \ln \sec \theta - \frac{96}{W} \right\} \Big|_0^{\textcircled{H}}$$

C-14

$$\sec \textcircled{H} = 4.4 \quad \sec^2 \textcircled{H} = 19.3 \quad \sec^3 \textcircled{H} = 85$$

$$\sec 0 = 1 \quad \sec^2 0 = 1 \quad \sec^3 0 = 1$$

which leads to the following value for equation C-14:

$$\frac{8 \times (5656)}{W^3} = .272$$

$$\text{So that, } \frac{U}{U_0} = 1 - .136 = .864$$

C-15

An estimate must now be made of the way in which this



... the ...  
 ... the ...  
 ... the ...

$$\text{...} = \text{...} \quad (1)$$

0-2  
 0-10

$$\text{...} = \text{...} + \text{...} + \text{...} + \text{...}$$

0-11

$$\text{...} = \text{...} + \text{...} + \text{...} + \text{...}$$

... the ...  
 ... the ...

0-12

$$\text{...} = \text{...} + \text{...} + \text{...} + \text{...}$$

0-13

$$\text{...} = \frac{\text{...}}{\text{...}}$$

... the ...

0-14

$$\text{...} = \text{...} + \text{...} + \text{...} + \text{...}$$

$$\text{...} = \text{...} \quad \text{...} = \text{...} \quad \text{...} = \text{...}$$

$$\text{...} = \text{...} \quad \text{...} = \text{...}$$

... the ...

$$\text{...} = \text{...}$$

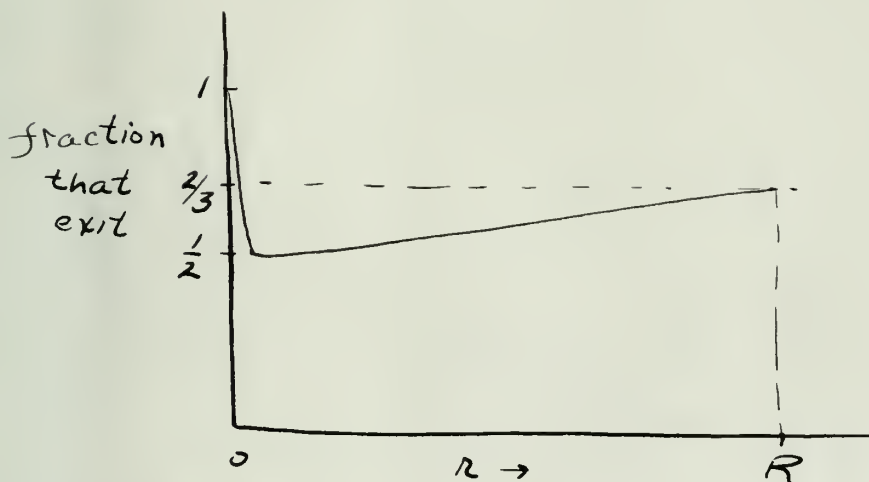
0-15

$$\text{...} = \text{...}$$

... the ...

figure is decreased by reason of non-centerline decay. Suppose that the decay electron were mono-energetic, having just enough energy to produce a pulse in the outer detector, if it has decayed on the centerline and been emitted normal to the detector axis. A curve like Figure C-2 would represent the fraction of these normal-incidence, mono-energetic electrons that produce a pulse, as a function of the radial distance from the center line at decay.<sup>33</sup> Of course the decay electrons do not all come off normally, nor from center line. For a cyclohexylbenzene-filled cylinder of 3 inches radius, a relativistic electron will lose on the order of 12 Mev existing normally from the centerline. Integration of equation C-2 shows that less than 1% of the total number of decay electrons have less kinetic energy than 12 Mev.

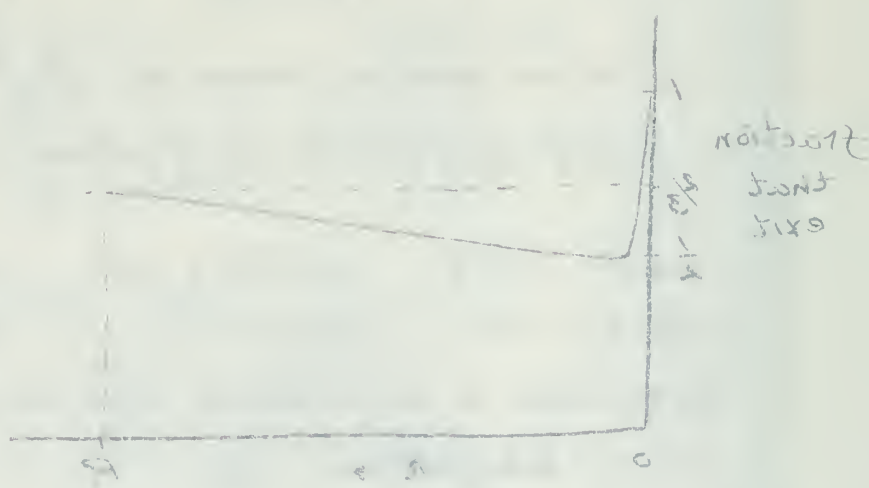
Figure C-2



<sup>33</sup>The qualitative shape of this curve may be seen by considering the problem of two disks of equal area whose centers move, from conjunction, to a distance equal to the radius. The area common to the two disks expressed as a fraction of the area of one, corresponds to our fraction that produce a pulse.

Figure 1 shows the variation of the concentration of the active species in the reaction mixture as a function of time. The concentration of the active species increases rapidly at first and then reaches a steady state. The concentration of the active species is higher in the presence of the inhibitor than in its absence. The concentration of the active species is also higher in the presence of the inhibitor than in its absence. The concentration of the active species is also higher in the presence of the inhibitor than in its absence.

Figure 1



The concentration of the active species in the reaction mixture as a function of time. The concentration of the active species increases rapidly at first and then reaches a steady state. The concentration of the active species is higher in the presence of the inhibitor than in its absence. The concentration of the active species is also higher in the presence of the inhibitor than in its absence. The concentration of the active species is also higher in the presence of the inhibitor than in its absence.



For normal incidence decay, an electron with greater than about 24 Mev will be able to exit the inner detector from any point in it. In other words, if all electrons having greater than 24 Mev kinetic energy are normally incident, they will leave the detector; adding 4 Mev for penetration of the double wall, and energy loss in the outer detector, "normal" electrons having greater than 28 Mev will all be counted. The fraction of the decay electrons having greater than 28 Mev is .673.

The fraction of electrons having less than 16 Mev is about .09 (16 Mev is the energy necessary to just exit normally from the center line with 4 Mev excess).

The energy spectrum then contains three regions of interest for these normal incidence decays:

1. Kinetic energy less than 16 Mev.
2. Kinetic energy between 16 Mev and 28 Mev.
3. Kinetic energy greater than 28 Mev.

In group 1, many decay electrons will not be energetic enough to be counted. Let us take that 1/4 of all the normal decays in group 1 are energetically countable.

The fraction of decay electrons in group 2 that will be counted is certainly greater than .5 (see Figure C-2), and is weighted toward a higher fraction, because of the greater likelihood for higher energies than low, in this range. Let us take that about .8 is the fraction collected from this group.

For general purposes, an electron volt is defined as the amount of energy which will be given to an electron by a potential difference of one volt. In other words, it is the amount of energy given to an electron by a potential difference of one volt. The electron volt is a unit of energy, and is usually denoted by the symbol e.v. It is equal to 1.6 x 10<sup>-19</sup> joules. The electron volt is a unit of energy, and is usually denoted by the symbol e.v. It is equal to 1.6 x 10<sup>-19</sup> joules.

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3. The electron volt is a unit of energy, and is usually denoted by the symbol e.v. It is equal to 1.6 x 10<sup>-19</sup> joules.

In group 1, the electron volt is a unit of energy, and is usually denoted by the symbol e.v. It is equal to 1.6 x 10<sup>-19</sup> joules. The electron volt is a unit of energy, and is usually denoted by the symbol e.v. It is equal to 1.6 x 10<sup>-19</sup> joules.

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In group 3, collection of the total group is indicated, at least for normal incidence decay.

The combined collection fraction for normal incidence decay is then about .89 for the total spectrum.

Let us apply this factor to extend the evaluation of  $U/U_0$  to a fair approximation for the whole volume.

The factor  $\eta$  then becomes:

$$\eta = .864 \times .88 \times .8 = .609$$

$$\text{and } \eta^2 = .37$$

C-16



The first part of the report is devoted to a general  
 description of the project and its objectives. It  
 is followed by a detailed account of the work  
 done during the period covered by the report.  
 The results of the work are then discussed and  
 compared with those of other workers in the  
 field. Finally, some conclusions are drawn and  
 suggestions are made for further work.

THE UNIVERSITY OF CHICAGO  
 DEPARTMENT OF CHEMISTRY  
 CHICAGO, ILL. U.S.A.

1955

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## APPENDIX D

TABLE V-1

The integral  $I^a$  (Equation V-13)  $I^a = \frac{I^1}{C} = \frac{1}{3} (\kappa-2)^3 \left(\frac{2}{\kappa}\right)^3 \frac{dk}{\kappa}$

$E_{\max}$	$E_{\min}$	$\kappa_{\max}$	$\kappa_{\min}$	$I^a$	$1.12 I^a$
350	280	3.27	2.62	.0574	.0633
340	280	3.18	2.62	.0457	.0523
330	280	3.09	2.62	.0371	.0416
350	260	3.27	2.45	.0622	.0696
340	260	3.18	2.45	.0514	.0575
330	260	3.09	2.45	.0418	.0469
360	240	3.27	2.24	.065	.0728
340	240	3.18	2.24	.0542	.0607
330	240	3.09	2.24	.0447	.0501

The last column  $1.12 \times I^a$  reflects the 12% plus correction to  $I^a$  for the Hough cross section at  $\kappa=3$ , and is taken as an average correction for the range of  $\kappa$  in the integrations.

APPENDIX 2

TABLE 1

The integral  $\int_0^1 (1-x)^n x^m dx = \frac{1}{(n+1)} \left( \frac{1}{m+1} - \frac{1}{m+2} + \frac{1}{m+3} - \dots \right)$

$n$	$m$	$\int_0^1 (1-x)^n x^m dx$	$\frac{1}{(n+1)}$	$\frac{1}{(m+1)}$	$\frac{1}{(m+2)}$	$\frac{1}{(m+3)}$
0.000	0.000	0.500	1.000	1.000	0.500	0.333
0.000	0.007	0.493	1.000	0.993	0.500	0.333
0.000	0.014	0.486	1.000	0.986	0.500	0.333
0.000	0.021	0.479	1.000	0.979	0.500	0.333
0.000	0.028	0.472	1.000	0.972	0.500	0.333
0.000	0.035	0.465	1.000	0.965	0.500	0.333
0.000	0.042	0.458	1.000	0.958	0.500	0.333
0.000	0.049	0.451	1.000	0.951	0.500	0.333
0.000	0.056	0.444	1.000	0.944	0.500	0.333
0.000	0.063	0.437	1.000	0.937	0.500	0.333
0.000	0.070	0.430	1.000	0.930	0.500	0.333
0.000	0.077	0.423	1.000	0.923	0.500	0.333
0.000	0.084	0.416	1.000	0.916	0.500	0.333
0.000	0.091	0.409	1.000	0.909	0.500	0.333

The last column is the integral  $\int_0^1 (1-x)^n x^m dx$  plus correction for  $n$  for the range of  $x$  in the table as an average correction for the range of  $x$  in the table.



TABLE V-2

Cross section for the electromagnetic production of mu meson pairs from Hough's formulae, mass extrapolated to this process from electronic mass.  $Z$  dependence taken to be linear as a lower limit, i.e., complete incoherence assumed. (Cross section times  $10^{33}$  cm<sup>2</sup>.)

Energy of the quantum	350 Mev	340 Mev	330 Mev	280 Mev	260 Mev
Be	7.24	5.33/5.2	4.97	1.63	.887
C	10.88	9.49/9.3	8.17	2.44	1.03
Al	23.5	20.55/21	17.7	5.27	2.23
Cu	52.5	45.8/44.9	39.5	10.9	4.97

The values under the slant sign for 340 Mev are the cross sections as per Bethe-Heitler mass extrapolated, with linear  $Z$  dependence.

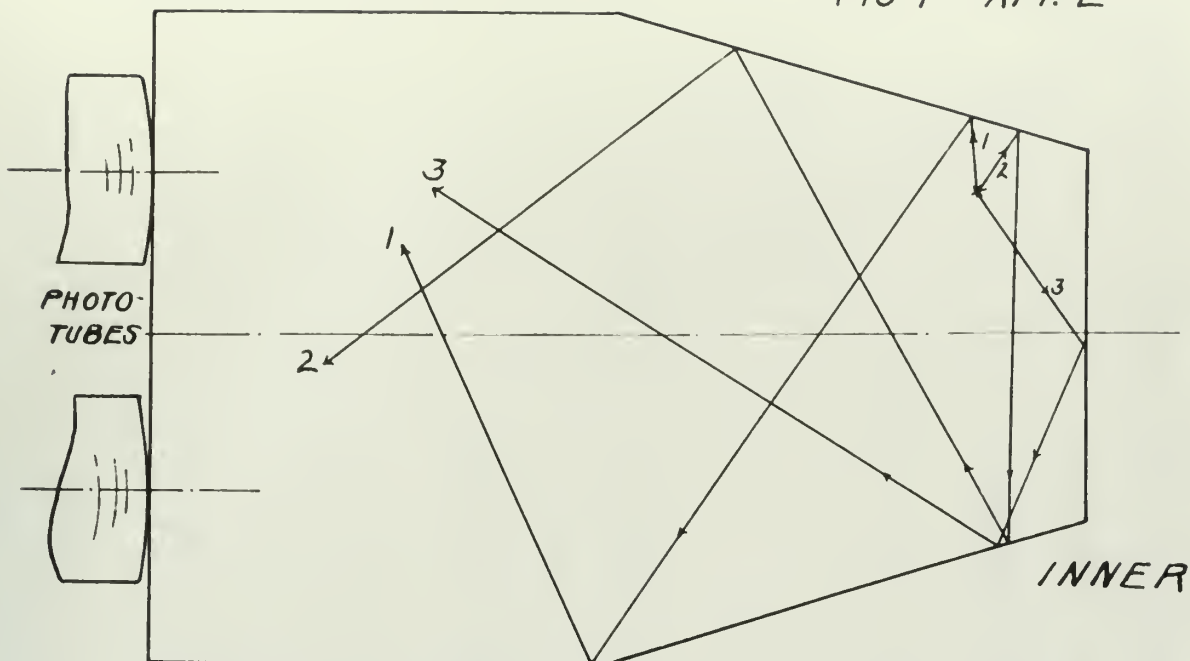
## TABLE 7

These results for the experimental production of an enzyme which is not normally present in the cells of the organism are shown in Table 7. The results are given in terms of the amount of enzyme activity per unit of protein. The results are given in terms of the amount of enzyme activity per unit of protein. The results are given in terms of the amount of enzyme activity per unit of protein.

Enzyme activity		Protein		Enzyme activity		Protein	
mg	g	mg	g	mg	g	mg	g
1.00	0.01	1.00	0.01	1.00	0.01	1.00	0.01
1.00	0.01	1.00	0.01	1.00	0.01	1.00	0.01
1.00	0.01	1.00	0.01	1.00	0.01	1.00	0.01
1.00	0.01	1.00	0.01	1.00	0.01	1.00	0.01

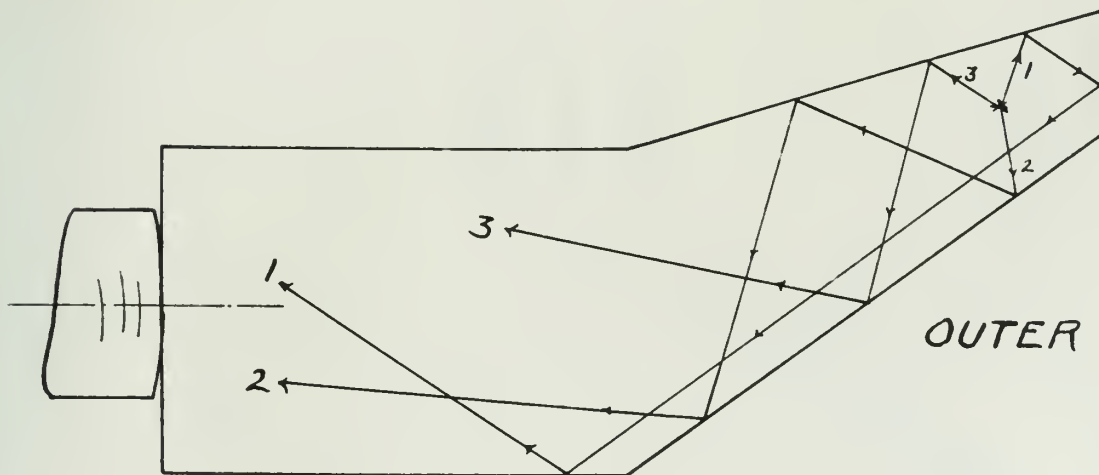
The results show that the amount of enzyme activity per unit of protein is not significantly different from that of the control. The results are given in terms of the amount of enzyme activity per unit of protein. The results are given in terms of the amount of enzyme activity per unit of protein.

FIG 1 - APP. E



FUNNELING EFFECT UPON SUCCESSIVE REFLECTIONS IN INNER DETECTOR. THE ILLUSTRATION IS FOR COPLANAR REFLECTION - NOT NECESSARILY TRUE FOR THE DESIGN DETECTORS. THE ROTATION OF REFLECTIONS IN THE CYLINDRICAL GEOMETRY ALTERS THE EFFECT QUANTITATIVELY.

FIG 2 - APP. E



FUNNELING EFFECT UPON SUCCESSIVE REFLECTIONS IN OUTER DETECTOR. SEE REMARKS OF FIG 1 APPROPRIOS NON COPLANAR REFLECTION.





# GRAPH IV-1

## ENERGY DISTRIBUTION OF PAIRS

$$\phi_0 = \frac{1}{3} \left( \frac{2}{k} \right)^3 (k-2)^3 \times 1.12$$

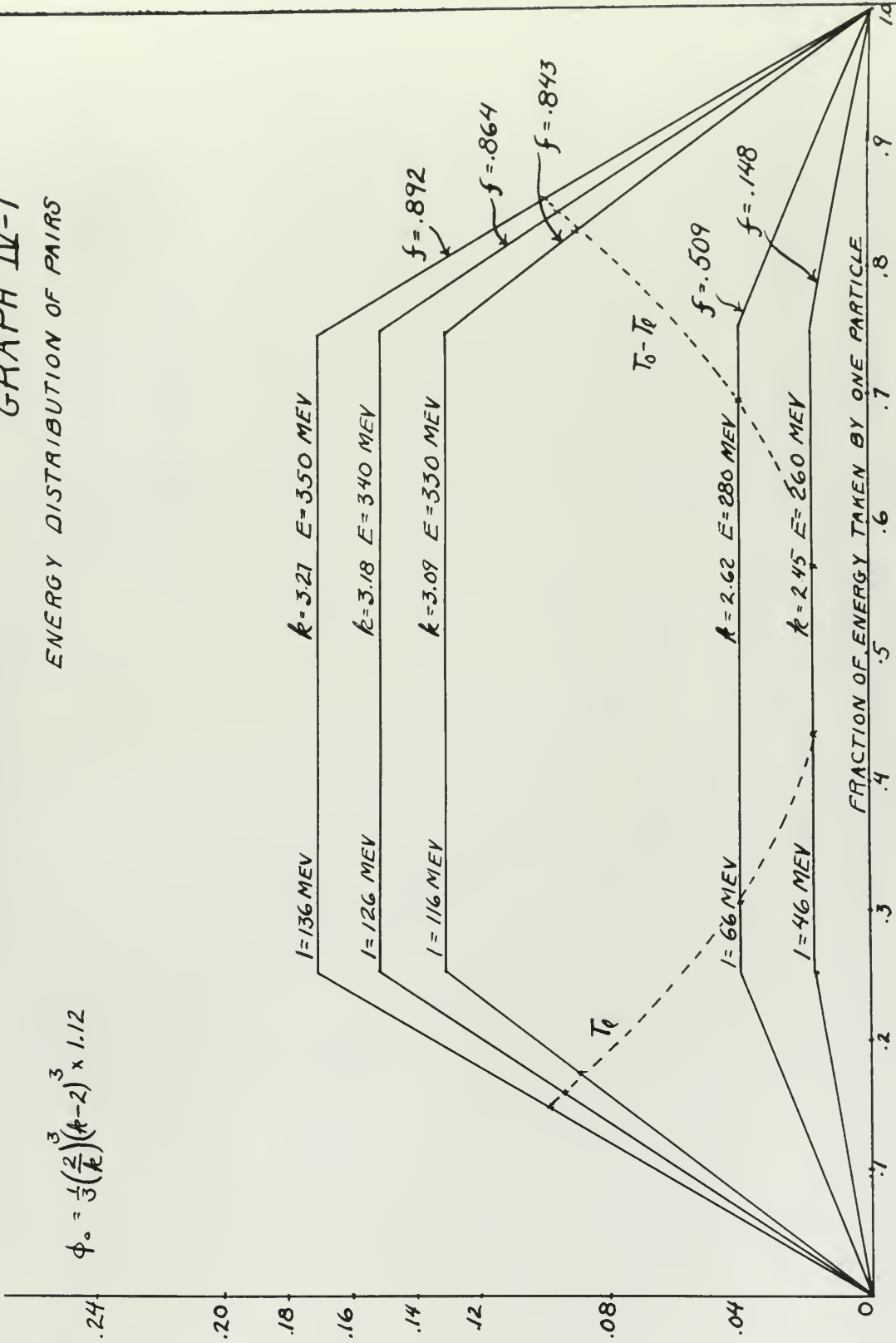
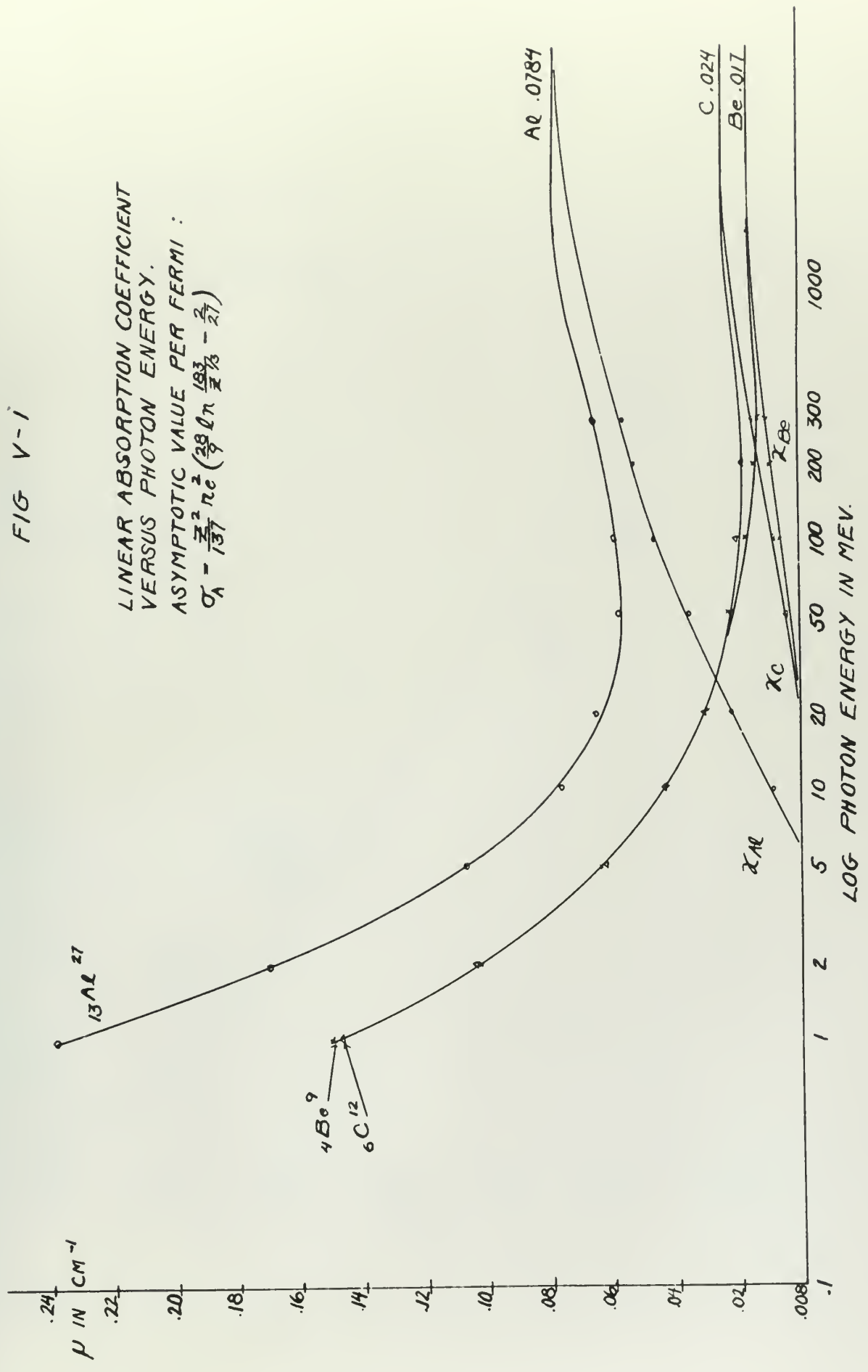




FIG V-1

LINEAR ABSORPTION COEFFICIENT  
 VERSUS PHOTON ENERGY.  
 ASYMPTOTIC VALUE PER FERMI :  
 $\sigma_A = \frac{Z^2}{137} \pi e^2 \left( \frac{28}{9} \ln \frac{183}{Z^{1/3}} - \frac{2}{27} \right)$





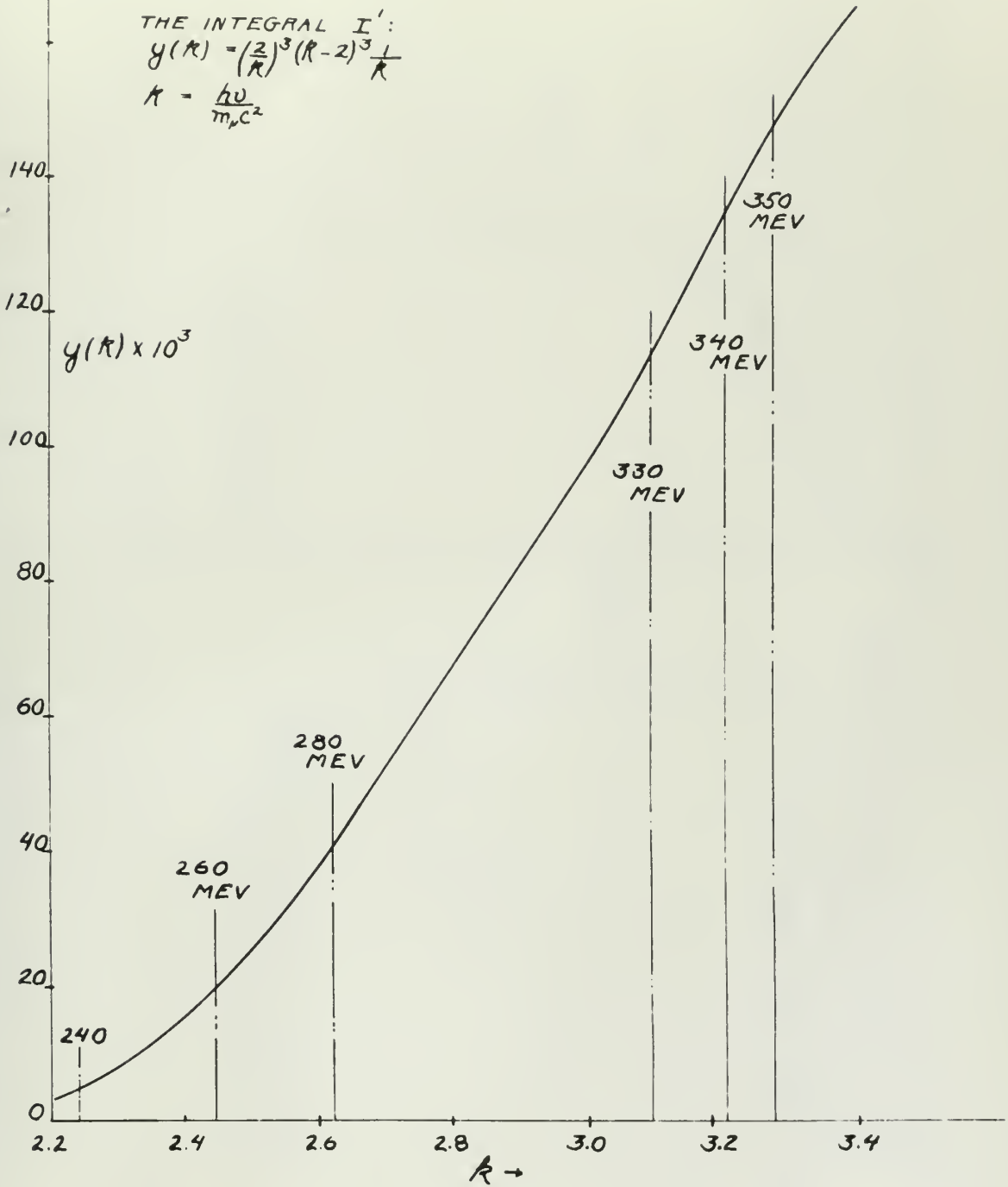


GRAPH V-2

THE INTEGRAL I':

$$y(\kappa) = \left(\frac{2}{\kappa}\right)^3 (\kappa - 2)^3 \frac{1}{\kappa}$$

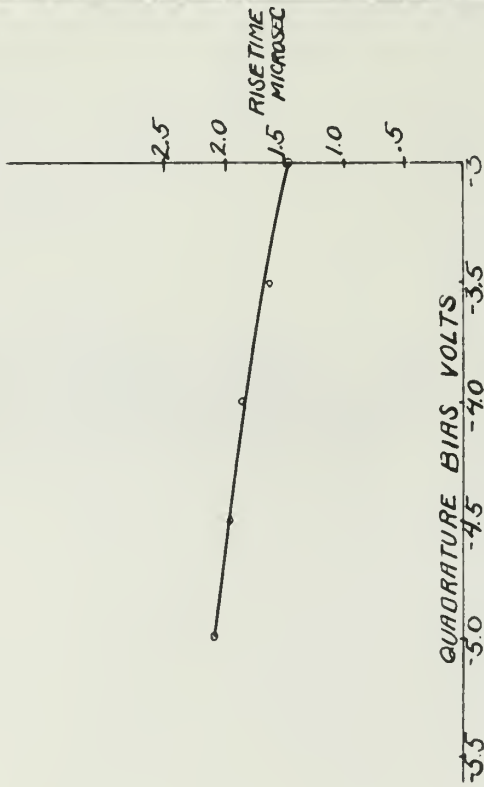
$$\kappa = \frac{h\nu}{m_0 c^2}$$





VI-2

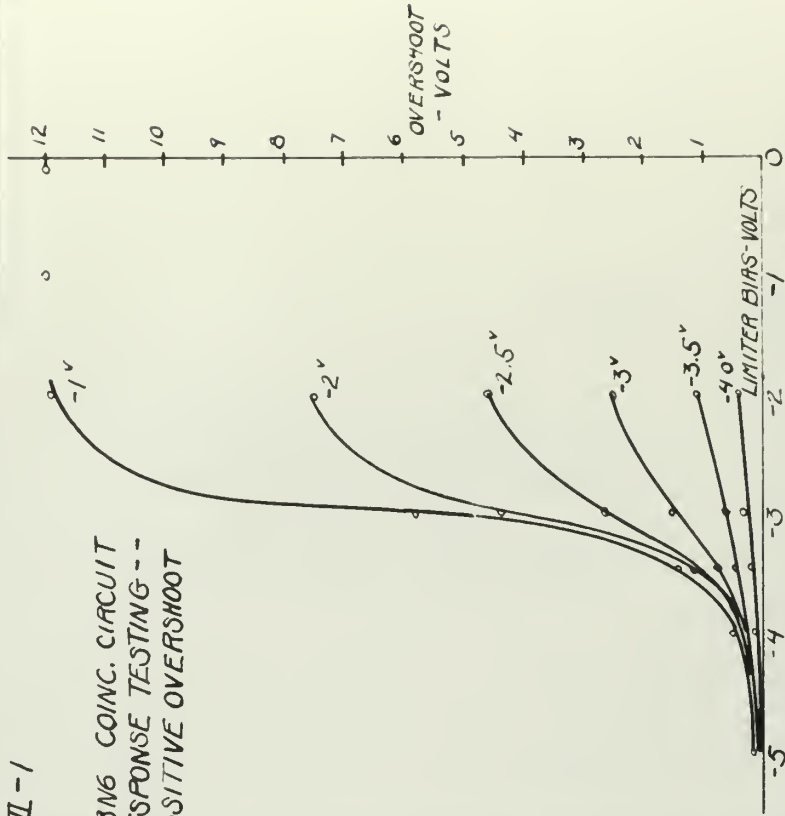
6BM6 RESPONSE TESTING ---  
RISE TIME OF COINCIDENCE PULSE



COINCIDENCE PULSE RISE TIME AS A  
FUNCTION OF QUADRATURE BIAS FOR  
IDENTICAL PULSE INPUTS ( $\tau_r = 24500$ ) TO BOTH  
GRIDS - AN AVERAGE FOR LIMITER BIASES  
FROM -3 TO -5 VOLTS.

VI-1

6BM6 COINC. CIRCUIT  
RESPONSE TESTING ---  
POSITIVE OVERSHOOT



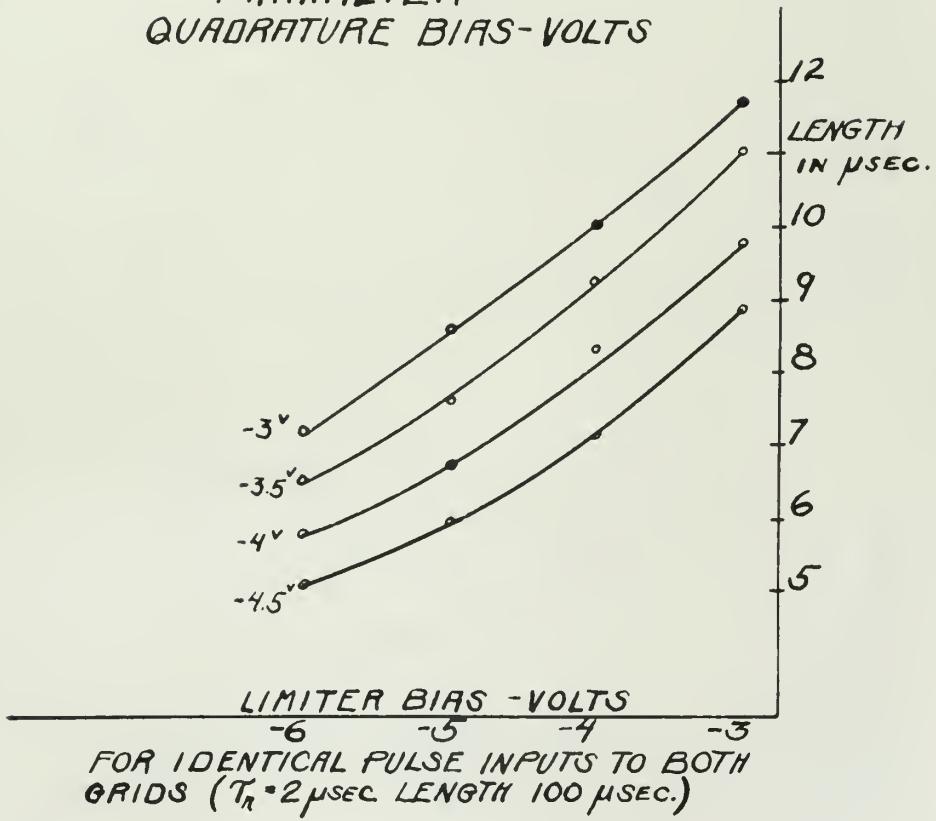
COINCIDENCE PULSE POSITIVE OVERSHOOT AS A FUNCTION  
OF LIMITER GRID BIAS. IDENTICAL PULSES ( $\tau_r = 24500$ ) TO  
BOTH GRIDS  
PARAMETER QUADRATURE BIAS - VOLTS





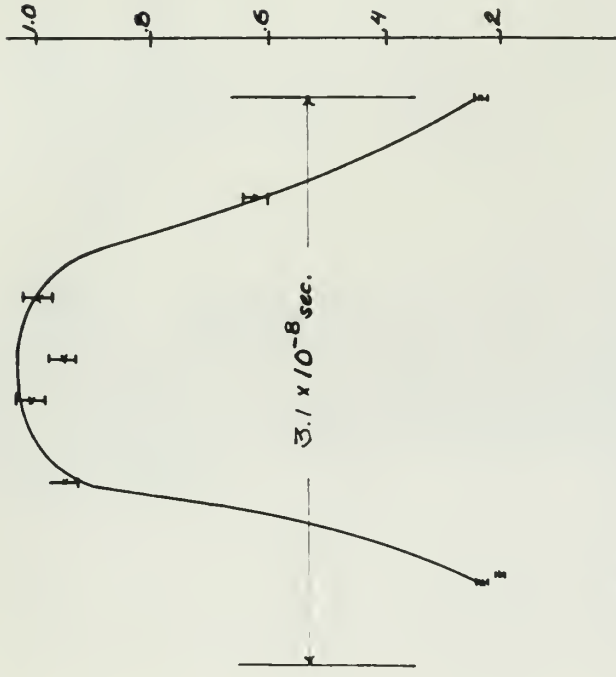
GRAPH VI-3

6BN6 RESPONSE TESTING  
COINCIDENCE PULSE LENGTH  
PARAMETER :  
QUADRATURE BIAS-VOLTS



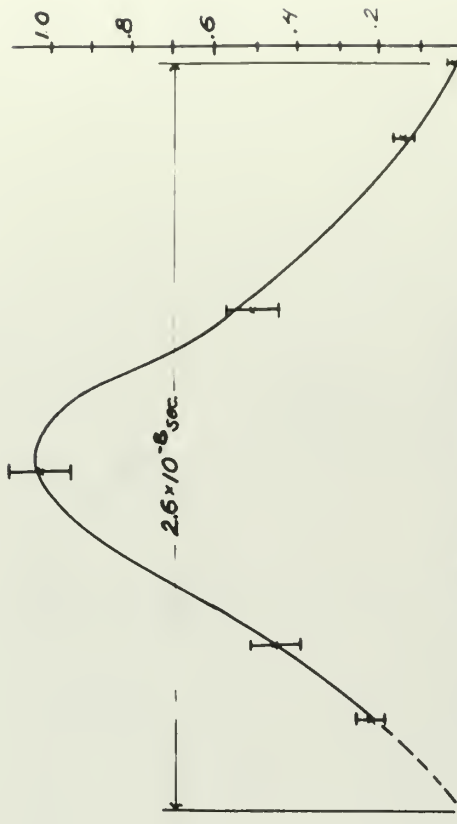


GRAPH VI-5



6BN6 RESOLVING TIME  
AS A FUNCTION OF SIGNAL DELAY.  
Ra-γ IN TERPHENYL-CYCLOHEXYLBENZENE.  
SPLIT PULSE INPUT.

GRAPH VI-6



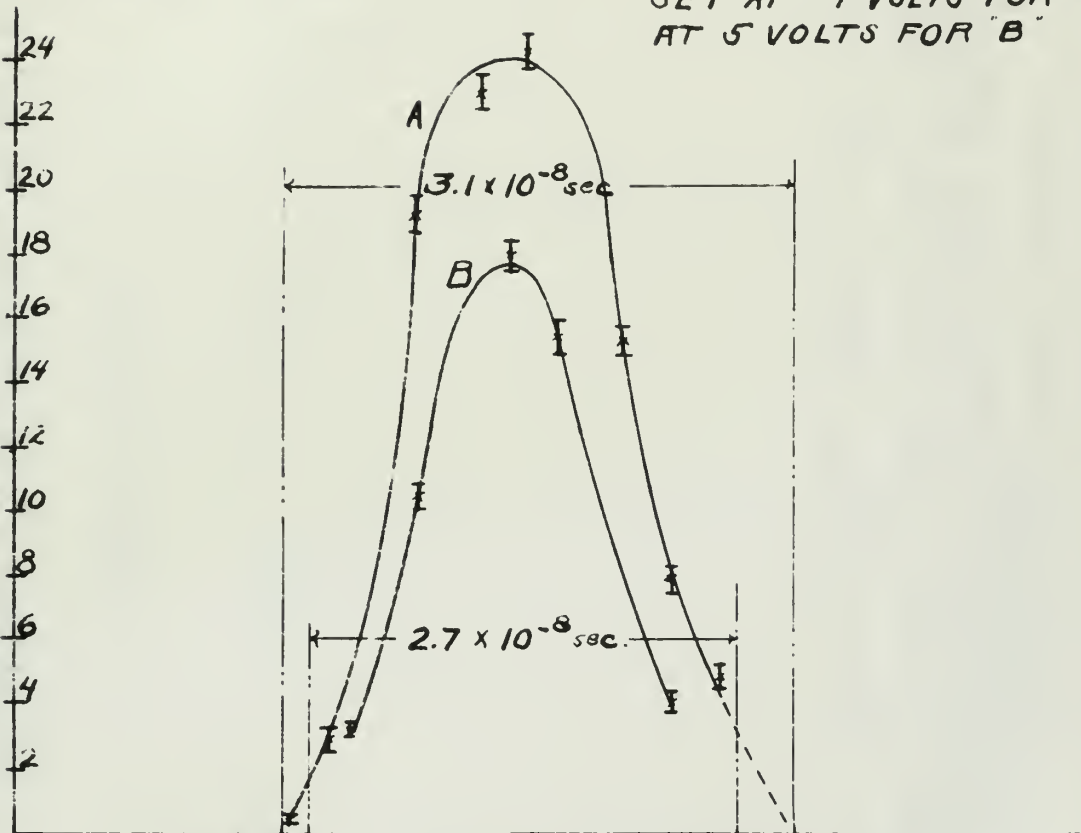
6BN6 RESOLVING TIME  
COINCIDENCE COUNTING RATE (FRACTION) AS A  
FUNCTION OF SIGNAL DELAY.  
COSMIC RAY EVENTS IN TERPHENYL-CYCLO-  
HEXYLBENZENE.





GRAPH VI-B

6BN6 BIASES (EQUAL)  
SET AT 4 VOLTS FOR "A";  
AT 5 VOLTS FOR "B"

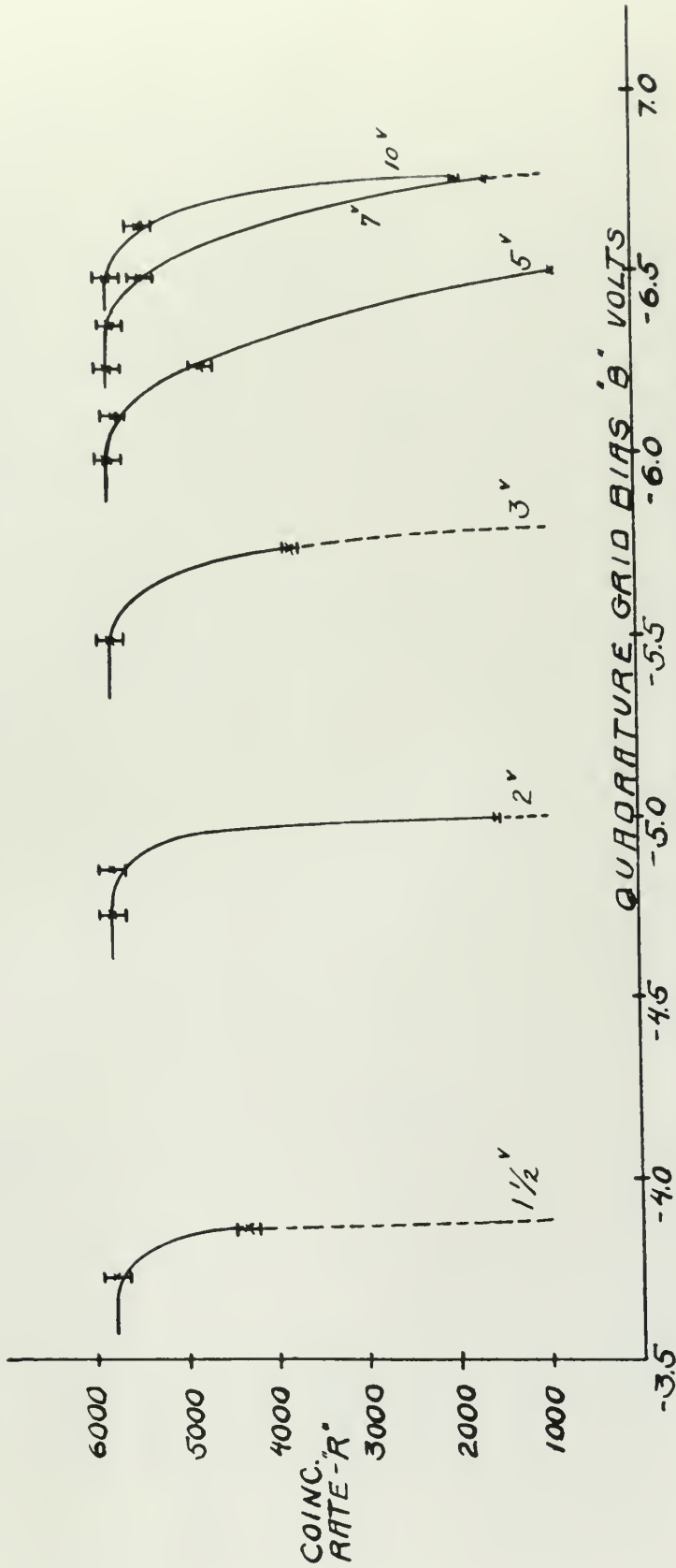


**6BN6 RESOLVING TIME**

COINCIDENCE RATE "R" (PROPORTIONAL TO RATE PER EQUIVALENT QUANTA) VS SIGNAL DELAY USING COINCIDENCE GEOMETRY DETECTORS COUNTING REAL COINCIDENCES FROM A CARBON TARGET IN THE SYNCHROTRON BEAM.



GRAPH VI-9a

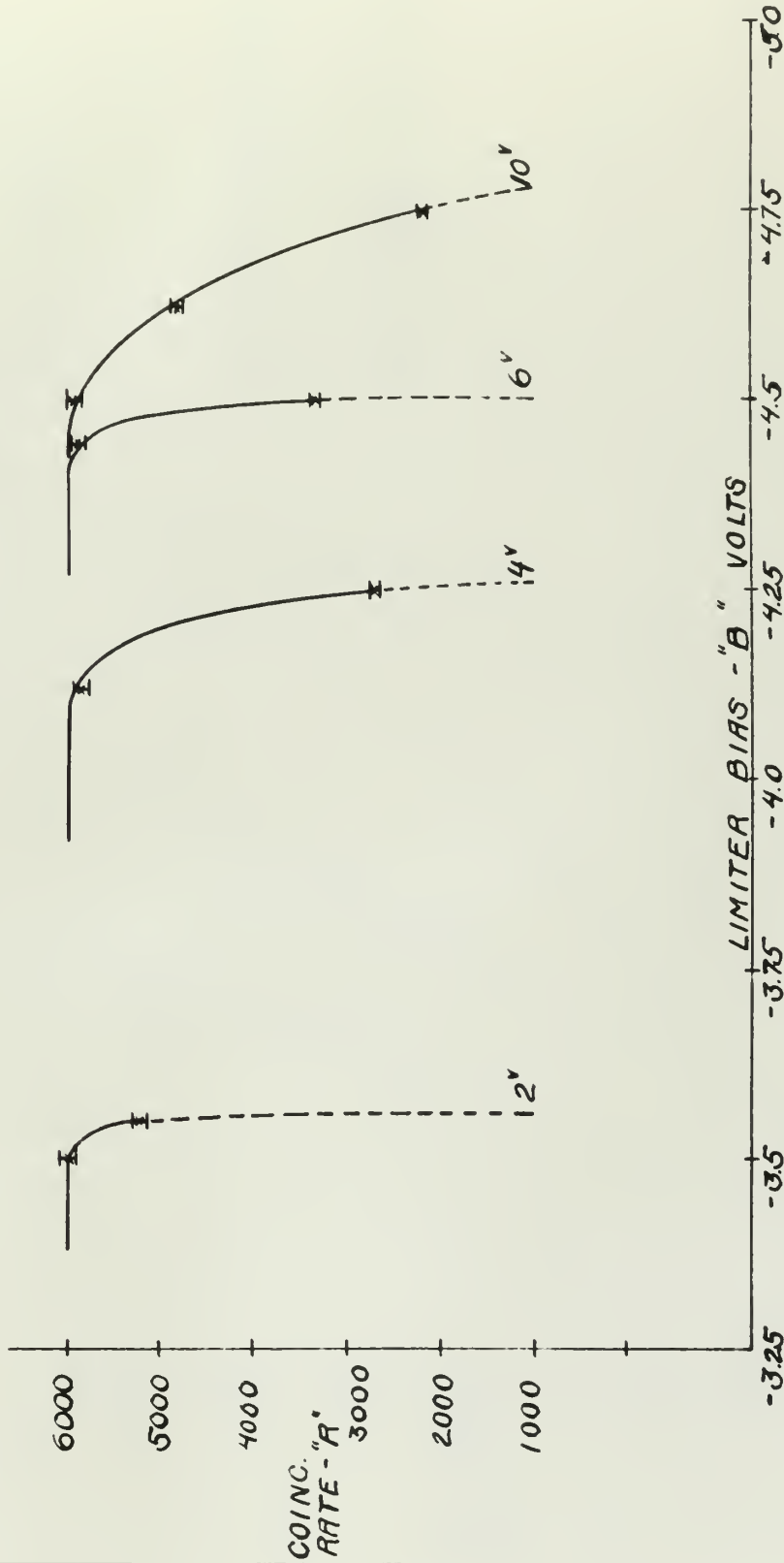


DISCRIMINATOR TESTING - 6BN6 COINCIDENCE CIRCUIT.  
 COINCIDENCE COUNTING RATE - "R" AS A FUNCTION OF QUADRATURE GRID BIAS - "B".  
 PARAMETER - INPUT PULSE HEIGHT IN VOLTS - EQUAL PULSE HEIGHTS ON BOTH  
 LIMITER AND QUADRATURE GRIDS.  
 LIMITER GRID BIAS - 3 VOLTS





GRAPH VI-96



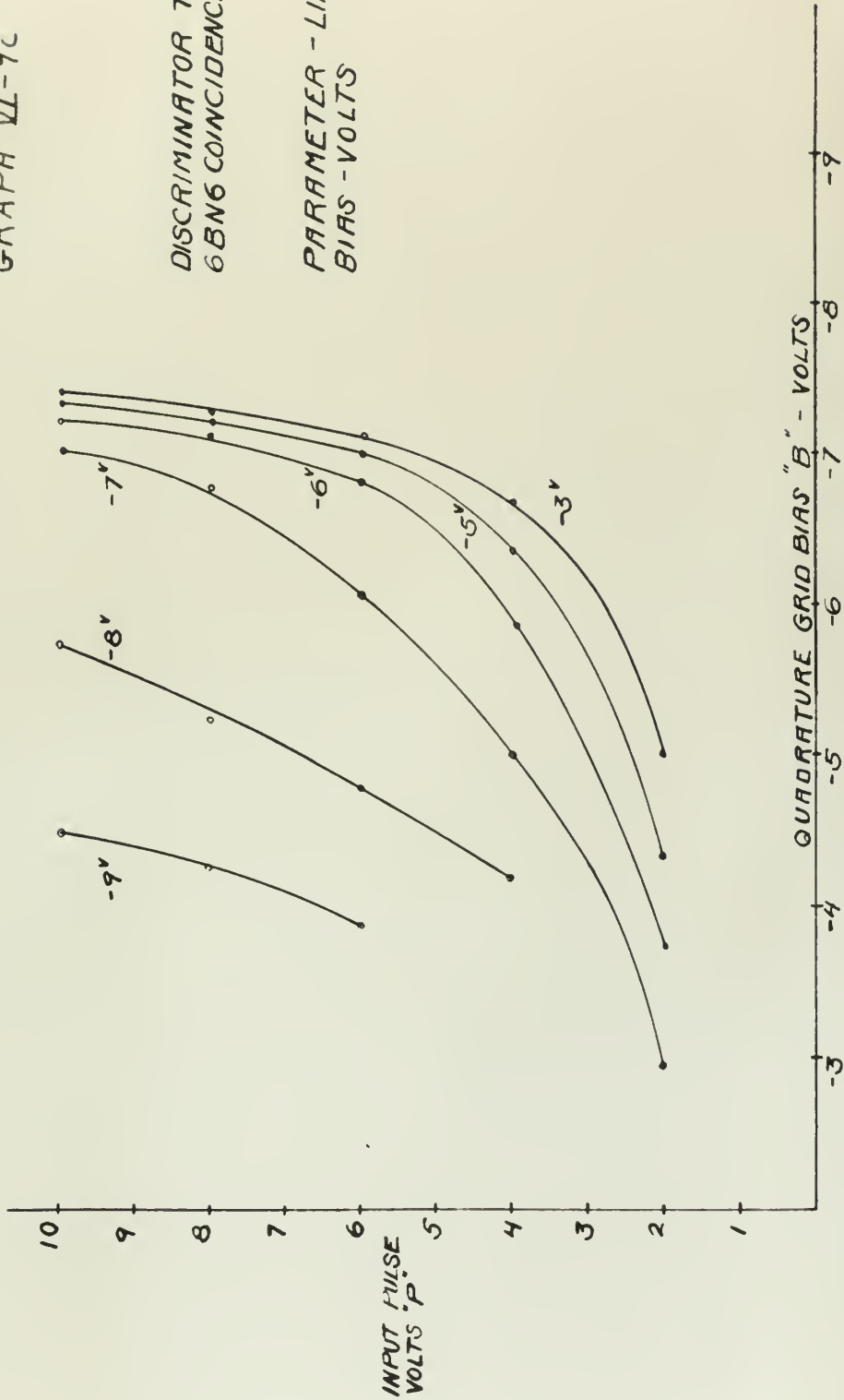
DISCRIMINATOR TESTING - 6BNG COINCIDENCE CIRCUIT.  
 COINCIDENCE COUNTING RATE "A" AS A FUNCTION OF LIMITER GRID BIAS - "B"  
 PARAMETER - INPUT PULSE HEIGHT IN VOLTS [EQUAL PULSE HEIGHTS  
 ON BOTH LIMITER AND QUADRATURE GRIDS]  
 QUADRATURE BIAS ~ 3 VOLTS



GRAPH VI-9c

DISCRIMINATOR TESTING  
6BN6 COINCIDENCE CIRCUIT

PARAMETER - LIMITER GRID  
BIAS - VOLTS



QUADRATURE GRID BIAS "B" VS. INPUT PULSE HEIGHT (SAME TO BOTH GRIDS) FOR  
BREAK IN PLATEAU-COINCIDENCE COUNTING RATE.  
FOR 90% CUTOFF - ADD ONE (1) VOLT TO GRAPH VALUE.















JUL 2

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