5-26-1953

An Investigation of the Collision Lengths of Penetrating-Shower-Producing Radiation in Various Materials

James Francis Kenney

KENNEY — COLLISION LENGTHS

AN INVESTIGATION OF THE COLLISION LENGTHS OF
PENETRATING-SHOWER-PRODUCING RADIATION
IN VARIOUS MATERIALS

A Thesis
Presented to
the Faculty of the Physics Department
The University of New Mexico

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Physics

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by
James Francis Kenney
June 1953

This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

E F Castetter
DEAN

5/26/53
DATE

Thesis committee

David Froman
CHAIRMAN

John H. Green

Roy Thomas

Victor H. Regener

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CHAPTER I

INTRODUCTION

For the past few years there has been a considerable amount of work done in the investigation of nuclear interactions of high energy cosmic radiation with various materials. The general purpose of work in this field is to obtain a better understanding of nucleon-nucleon-nucleon and nucleon-nucleus interactions at high energy.

The existence of elementary particles with a mass intermediate between the electron and the proton masses has now been definitely established. These particles are unstable, and the mechanism of their production is of prime importance in the theory of nuclear forces. One of these elementary particles is called the pi meson, and can be produced with high kinetic energy in a penetrating shower. If a highly energetic cosmic ray strikes a nucleus, it can create a shower of several highly energetic elementary particles such as protons, neutrons, V particles, and mesons. This event is known as the production of a penetrating shower.

The purpose of this paper is to compile and tabulate some of the experimental data that have been obtained on penetrating showers, and to compare these data with the results that should be expected from the various theories

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The [illegible] zone of [illegible] penetration [illegible] results that [illegible] that have been advanced.

One type of pertinent experiment is an investigation of penetrating showers produced locally in some material. An investigation of this nature will give the collision length in a material of that component of the cosmic radiation which is capable of producing penetrating showers. By suitable coincidence-anticoincidence arrangements of geiger tubes, one can select either ionizing or neutral particles as the primaries that initiate the shower.

Chapter II of this paper will constitute a rather detailed analysis of one of these experiments so that the overall method and theory of this type of experiment will be clear. This will be followed in Chapter III by briefer descriptions of some of the other experiments in which collision lengths of the penetrating-shower-producing radiation have been measured in various materials.

The remainder of this paper will be devoted to a presentation of some of the theories of nuclear collisions, and to a comparison of these theories with the experimental data.

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CHAPTER II

METHOD AND THEORY OF THE EXPERIMENT

Cosmic-ray particles which are capable of producing nuclear interactions are called "N-rays". The N-rays may be subdivided into charged and neutral particles. At appreciable depths in the atmosphere, the charged N-rays are composed almost entirely of protons and pi mesons. The flux of neutral pi mesons is certainly small because of their short mean life, estimated by Carlson, Hooper, and King[1] to be about 3×10^{-14} seconds. This is also true for the V_o particle whose mean life has been estimated as being of the order of 10^{-10} seconds.[2] Therefore, the neutral N-rays are believed to consist almost exclusively of high energy neutrons.

The average distance that an incoming particle travels in a material before the first nuclear event or collision involving the particle is called the collision length L_c. The average distance that an incoming particle travels in a particular substance before it is absorbed is called the absorption length λ. The collision length, L_c, for a radiation which produces penetrating showers, is given by:

1) $$L_c = m/\sigma \quad g/cm^2,$$

---

[1] Carlson, A. G., Hooper, J. E., and King, D. T., Phil. Mag. 41, 701 (1950)

[2] Fretter, W. B., May, M.M., and Nakada, M.P., Phys. Rev. 89, 148 (1953)

where, for a molecular substance, m is the mass of a molecule of the substance, and σ is the sum of the effective collision cross sections for the production of penetrating showers in the nuclei composing the molecule.

In the measurement of collision lengths of charged N-rays, it is difficult to arrive at unambiguous results. However, in 1940, Rossi and Regener[3] devised a coincidence-anticoincidence system which can be used for unambiguous measurements of the collision lengths of neutral N-rays. The first experiment which will be analyzed in this paper is based on the Rossi-Regener method.

THE FROMAN, KENNEY, REGENER EXPERIMENT[4]

I APPARATUS

Two elevations of the geiger counter and absorber arrangement are shown in Figures 1 and 2. All of the equipment below Σ_1 was mounted on a car which could be moved under either of two stainless steel tanks Σ_1, which were filled with water and heavy water respectively. The counts that were recorded were those that were caused by the discharge of a given counter in Tray A, a given counter in Tray B, two counters of a selected portion of Tray C, one

---

[3] Rossi, B., and Regener, V. H., Phys. Rev. 58, 837 (1940)

[4] Froman, D. K., Kenney, J. F., and Regener, V. H., (paper not yet published)

where, for a molecular substance, [illegible] of the substance, and [illegible]
nion cross sections [illegible]
in the manner [illegible]

In the [illegible] of [illegible]
X-rays, it is difficult [illegible]
However, in 19[illegible] [illegible]
anticoincidence system [illegible]
measurements of [illegible] of [illegible]
The first experiment which will [illegible]
is based on the Rossi-[illegible] method.[3]

THE [illegible][4]

[illegible]

Two elevations of the [illegible]
arrangement are shown in Figures [illegible]
ment below C_1 was [illegible]
under either of the [illegible]
filled with water and [illegible]
that were recorded [illegible]
charge of a given counter in Tray [illegible]
Tray B, two counters [illegible]

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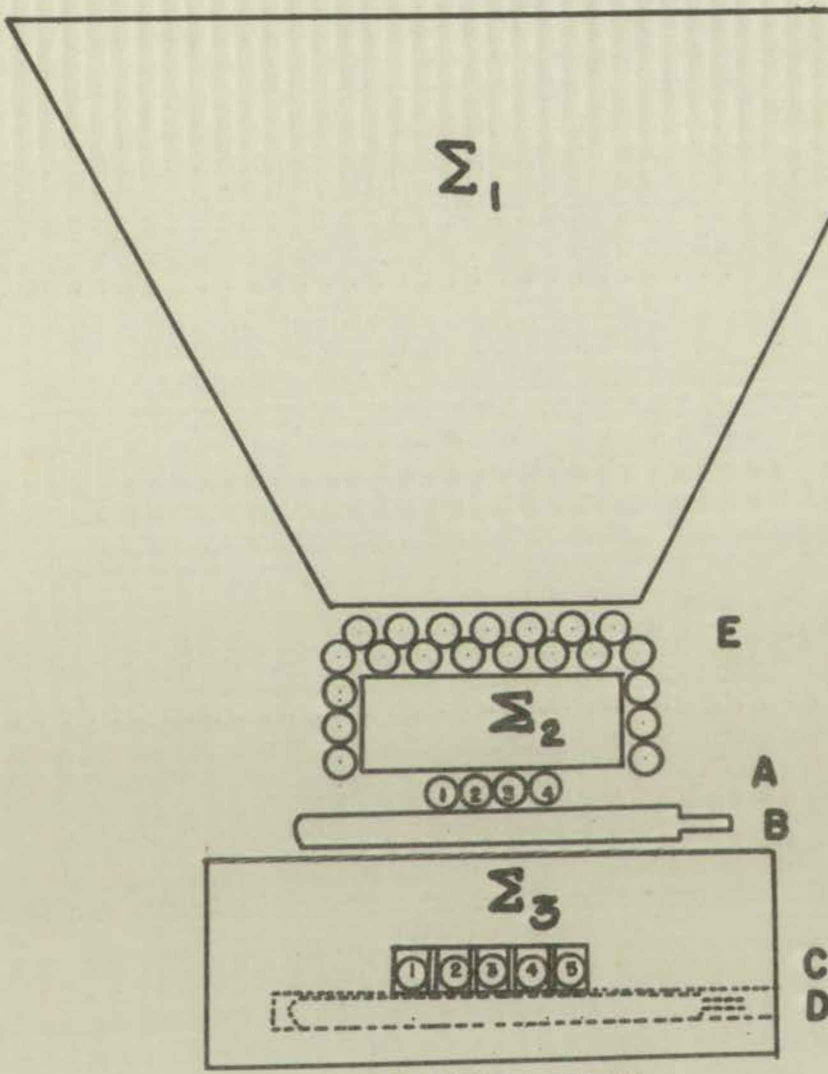
[3] Rossi, B., and [illegible]

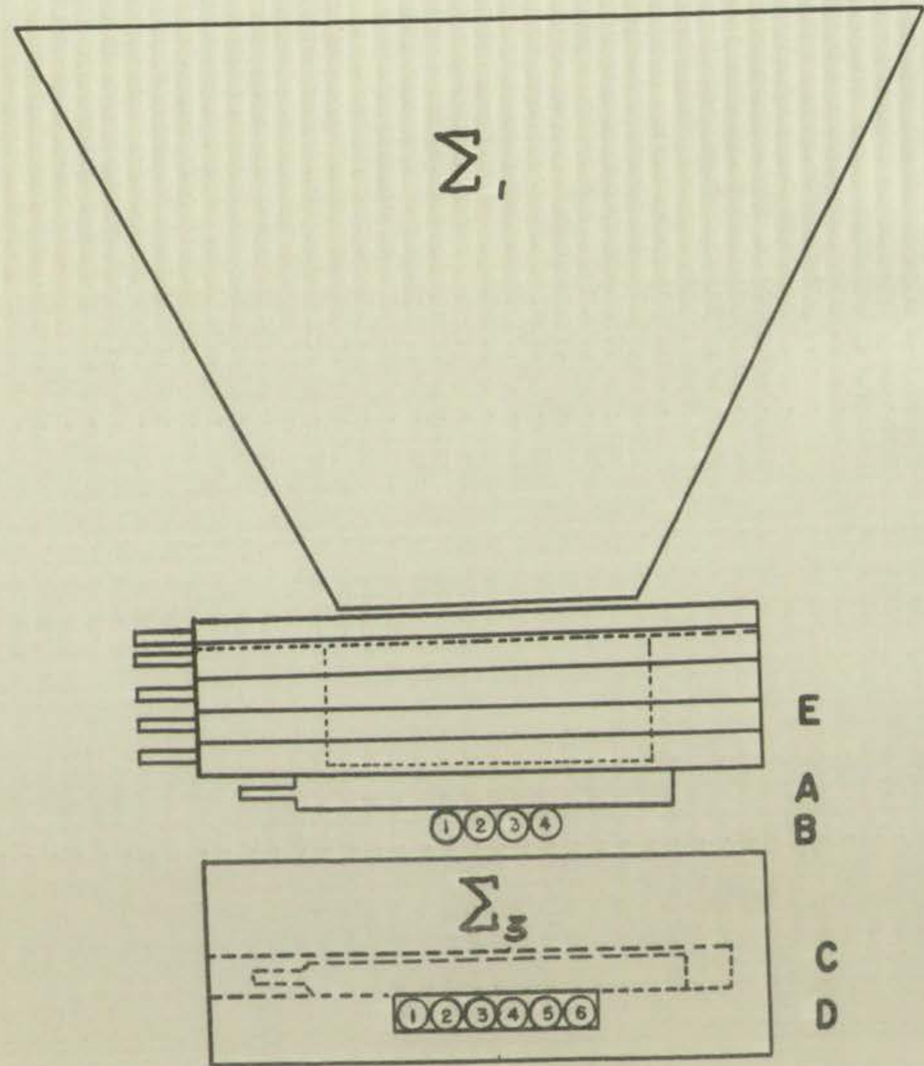
[4] [illegible]
(paper not yet published)



FRONT VIEW

EXPERIMENTAL ARRANGEMENT

FIGURE 1



SIDE VIEW

EXPERIMENTAL ARRANGEMENT

FIGURE 2

counter from a selected portion of Tray D, and no counter from Tray E. This is called an NPS event, i.e., a penetrating shower initiated by a neutral particle. In the remainder of this paper, PS and IPS shall be taken to stand for a penetrating shower, and a penetrating shower initiated by an ionizing particle respectively. Other terminology that will be useful will be PSPR, NPSPR, and IPSPR, which shall be taken to stand for penetrating-shower-producing radiation, neutral penetrating-shower-producing radiation, and ionizing penetrating-shower-producing radiation respectively.

The selection of the various possible combinations of tubes in Trays A, B, C, and D was made in such a way that any straight line drawn through discharging counters would lie inside Σ_1. This should insure that any particle that initiated a shower had to traverse Σ_1. This will have the effect of eliminating primaries that are inclined far from the vertical.

In this experiment, it was desired to record the number of penetrating showers produced in a block of lead Σ_2, by non-ionizing primaries which had traversed Σ_1 without a nuclear interaction. The requirement that no tube in Tray E was discharged ensured that the shower was initiated in Σ_2 by a neutral particle that had traversed Σ_1 without a nuclear interaction. If it had had a nuclear interaction in Σ_1 it would have been accompanied by charged particles as it crossed counter from a selected portion of tray C, and no counter from tray E. This is called a PS event, i.e., a penetrating shower initiated by a neutral particle. In the remainder of this paper, PS and IPS shall be taken to mean penetrating shower, and a penetrating shower initiated by an ionizing particle respectively. Other terminology that will be useful will be PSPR, NPSPR, and IPSPR, which are to be taken to stand for penetrating-shower-producing radiation, neutral penetrating-shower-producing radiation, and ionizing penetrating-shower-producing radiation respectively.

The selection of the various particle counting tubes in trays A, B, C, and F was made in such a way that any straight line drawn through discharged counters would lie inside Σ_1. This should insure that any particle that initiated a shower had to traverse Σ_1. This will have the effect of eliminating primaries that are inclined far from the vertical.

In this experiment, it was desired to measure the number of penetrating showers produced in a target in Σ_2 by non-ionizing primaries which had traversed Σ_1 without a nuclear interaction. The requirement that no counter in tray E was discharged ensured that the shower was initiated by a neutral particle that had traversed Σ_1 without a nuclear interaction. If it had had a nuclear interaction in Σ_1, it would have been accompanied by [illegible]

Tray E, and the count would not have been recorded. The requirement that two tubes in Tray C were discharged ensured that the shower was composed of at least two ionizing particles, and the 6 inches of lead between Trays B and C ensured that recorded showers originating in Σ_2 were made up of penetrating particles. Half-inch lead plates were inserted between adjacent tubes in Tray C to prevent local soft showers and knock-on electrons from registering as penetrating showers.

A block diagram of the circuitry is given in Figure 3. As one can see from the block diagram, Trays B and D were put into 2-fold coincidence, and Trays A and C were put into 3-fold coincidence. These were then put into 5-fold coincidence in the mixer circuit, and this 5-fold event was recorded as a PS. The 5-fold event was also put into anticoincidence with Tray E. This event was recorded as an NPS count. Both the PS and the NPS events were channeled into recorders in which the total number of each type of event that had occurred was recorded hourly.

Figure 4 is a schematic diagram of the 3-fold coincidence circuit. By inspecting the circuit, one can see that the allowable coincidences were the following:

One given tube in Tray A can register in coincidence with two given tubes in Tray C:

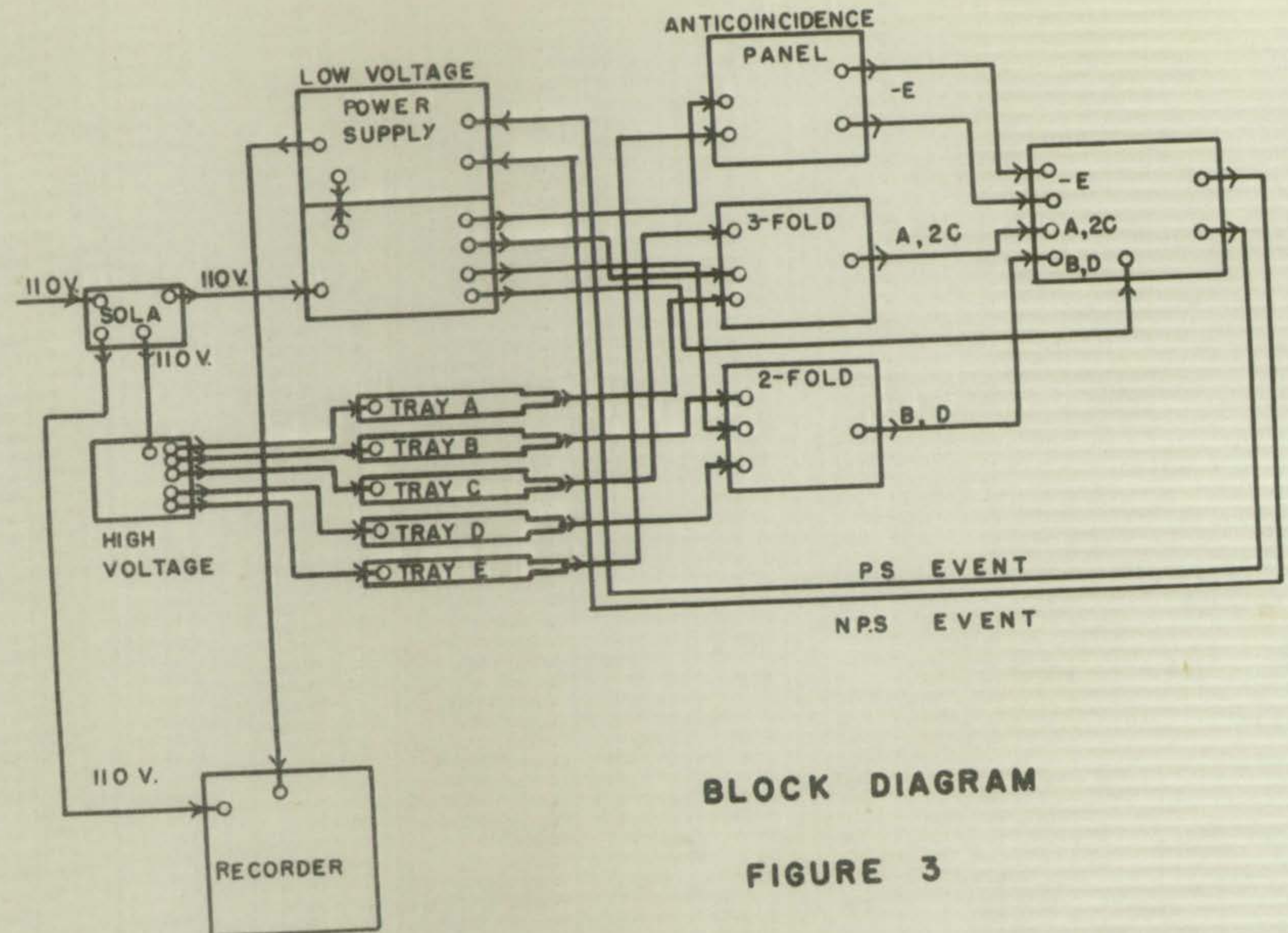
tube 1 with tubes 1 and 2 or 2 and 3

Tray B, and the event would not be a [illegible]. [illegible]
quirement that two tubes in Tray C [illegible]
that the shower was created [illegible]
cles, and the 6 inches of lead between Tray B and [illegible]
that protons which are originating in Σ, [illegible]
trating particles. [illegible]
tween adjacent tubes in Tray C [illegible]
and knock-on electrons from [illegible].

A block diagram of the circuitry [illegible]
As one can see from the block diagram, [illegible]
into 2-fold coincidences, and Trays A and B [illegible]
3-fold coincidence. [illegible]
dence in the [illegible] circuit, and this [illegible]
as a PE. The [illegible]
with Tray E. This event was recorded [illegible]
the PE and the [illegible] events were [illegible]
which the total number of each type of event [illegible]
red was recorded [illegible].

Figure 4 is a [illegible] diagram of [illegible]
dence circuit. By [illegible] the [illegible]
the allowable coincidences [illegible]

One given tube in Tray A [illegible]
with two given tubes in [illegible]
tube 1 with tubes [illegible]



BLOCK DIAGRAM

FIGURE 3

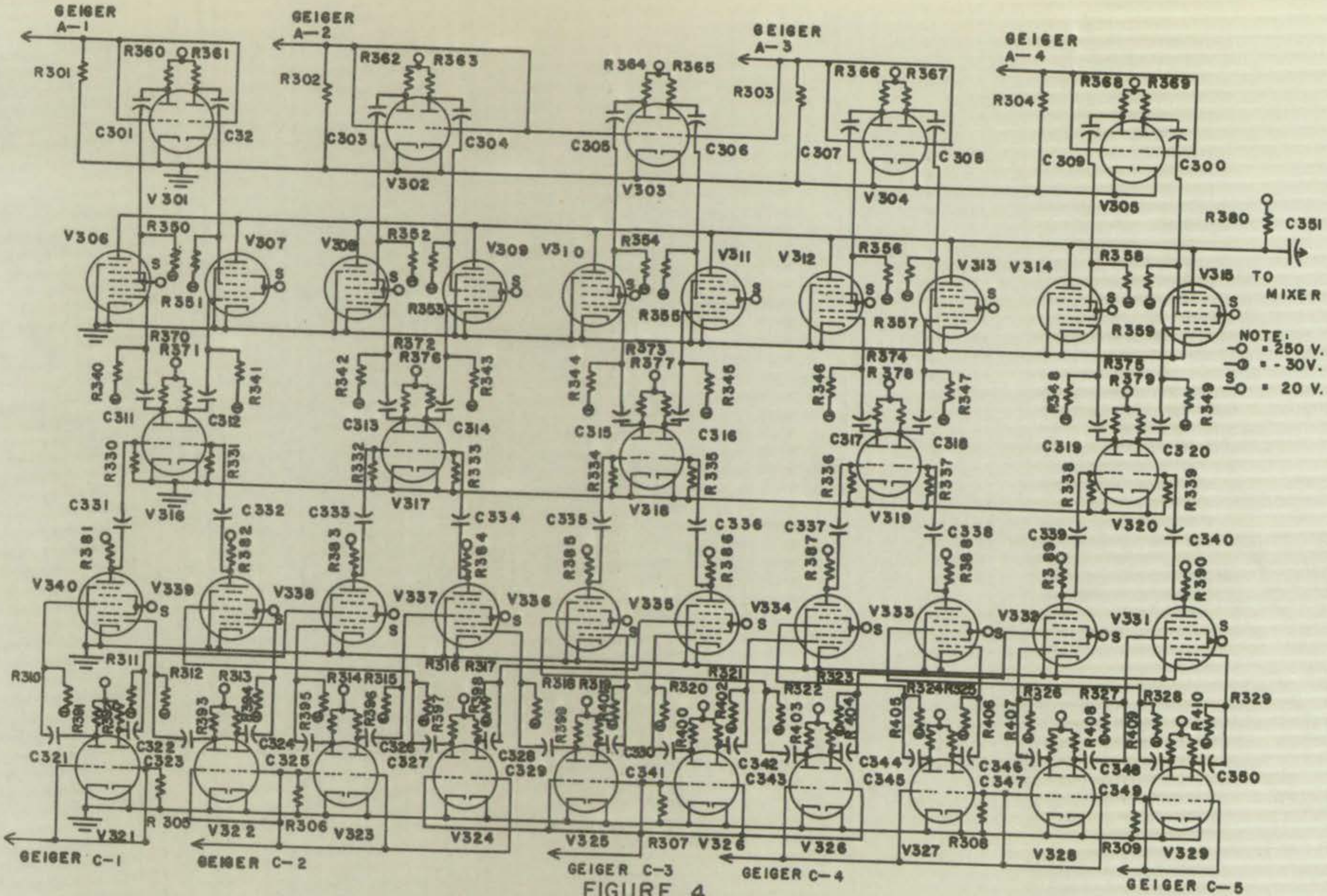
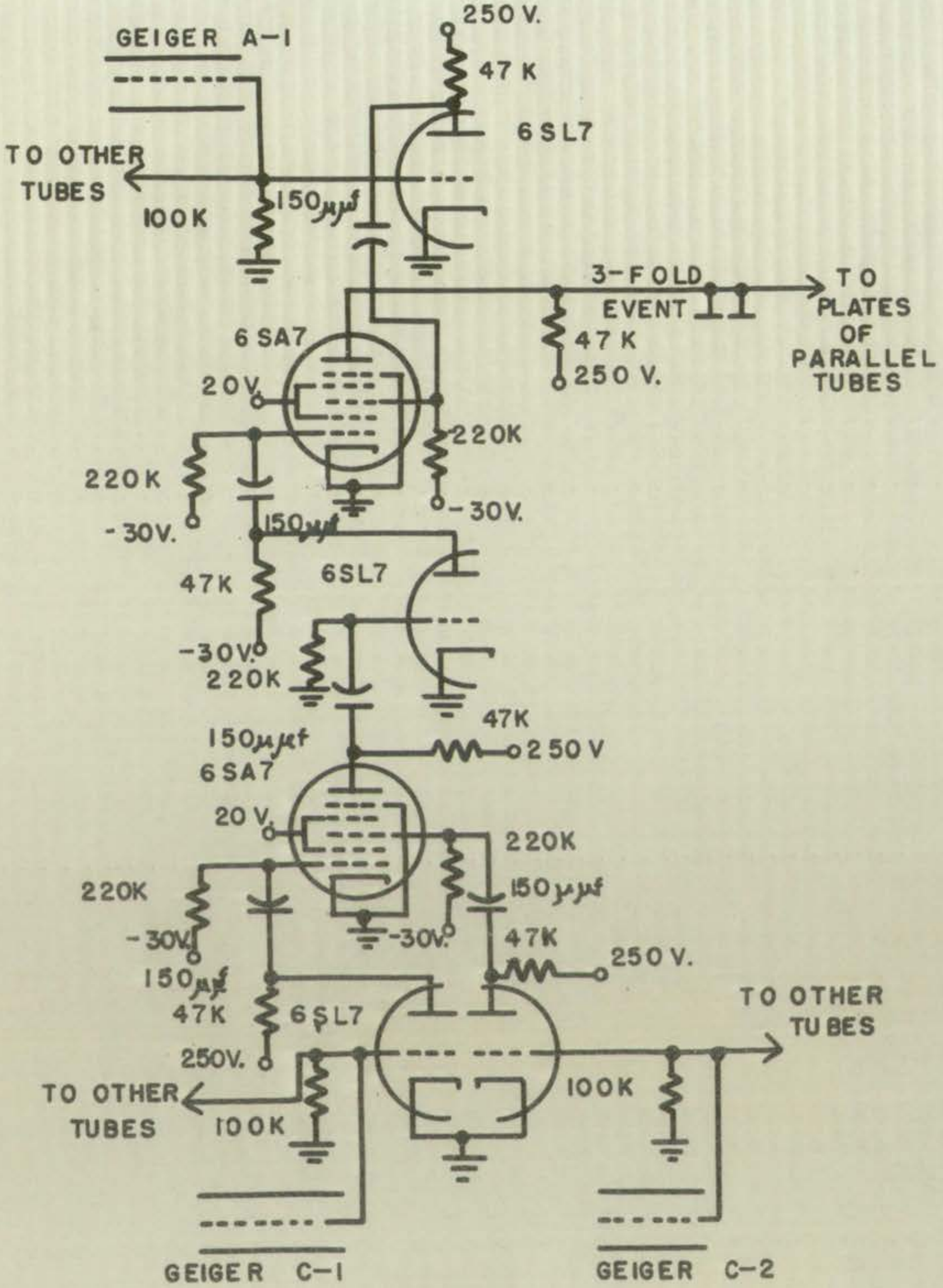


FIGURE 4

3-FOLD COINCIDENCE CIRCUIT



DETAIL
OF THE

3-FOLD COINCIDENCE CIRCUIT

FIGURE 5

tube 2 with tubes 1 and 2 or 2 and 3 or 3 and 4
tube 3 with tubes 2 and 3 or 3 and 4 or 4 and 5, and
tube 4 with tubes 3 and 4 or 4 and 5.

The three-fold coincidence circuit was therefore composed of ten similar channels, one of which is presented in Figure 5. A tabulation of the values of all the component parts of the equipment is presented in Appendix I.

Figure 6 is the schematic diagram of the 2-fold coincidence circuit. By inspecting the circuit, one can see that the allowable coincidences were the following:

One given tube in Tray B can register in coincidence with one given tube in Tray D:

tube 1	with tubes 1 or 2 or 3 or 4
tube 2	with tubes 1 or 2 or 3 or 4 or 5
tube 3	with tubes 1 or 2 or 3 or 4 or 5, and
tube 4	with tubes 2 or 3 or 4 or 5.

The 2-fold coincidence circuit was therefore composed of eighteen identical channels, one of which is presented in Figure 7. The circuits employed in the 2-fold coincidence are basically the same as those used in the 3-fold chassis.

Figure 8 is the schematic diagram of the anticoincidence pre-amplifier panel. The circuit was arranged so that the outputs of five or six tubes were put in parallel and amplified by a vacuum tube. Figure 9 is a detailed view of one tube 2 with tubes 1 and 2 or 2 and 3 or [illegible],

tube 3 with tubes 2 and 3 or 3 and 4, or [illegible], and

tube 4 with tubes 3 and 4 or 4 and 1.

The three-fold [illegible] diversity [illegible] composed of ten similar [illegible], one of which is [illegible] in Figure 5. A tabulation of the values of [illegible] parts of the equipment is [illegible].

Figure 6 is the schematic diagram of the two-fold [illegible] dence circuit. By inspecting the circuit, one [illegible] the allowable coincidences [illegible] the following:

One given tube in Tray A [illegible] coincidence with one given tube in Tray B.

tube 1 with tubes 1 or 2 or 3 or 4

tube 2 with tubes 1 or 2 or [illegible]

tube 3 with tubes 2 or 3 or [illegible] or 4

tube 4 with tubes 3 or 4 [illegible]

The 2-fold coincidence circuit [illegible] composed of eighteen identical channels, one of which is [illegible] in Figure 7. The circuits employed in the [illegible] dence are basically the same as those used in the [illegible] channels.

Figure 8 is the [illegible] diagram of the [illegible] pre-amplifier panel. The [illegible] outputs of five or [illegible] fied by a vacuum tube. [illegible]

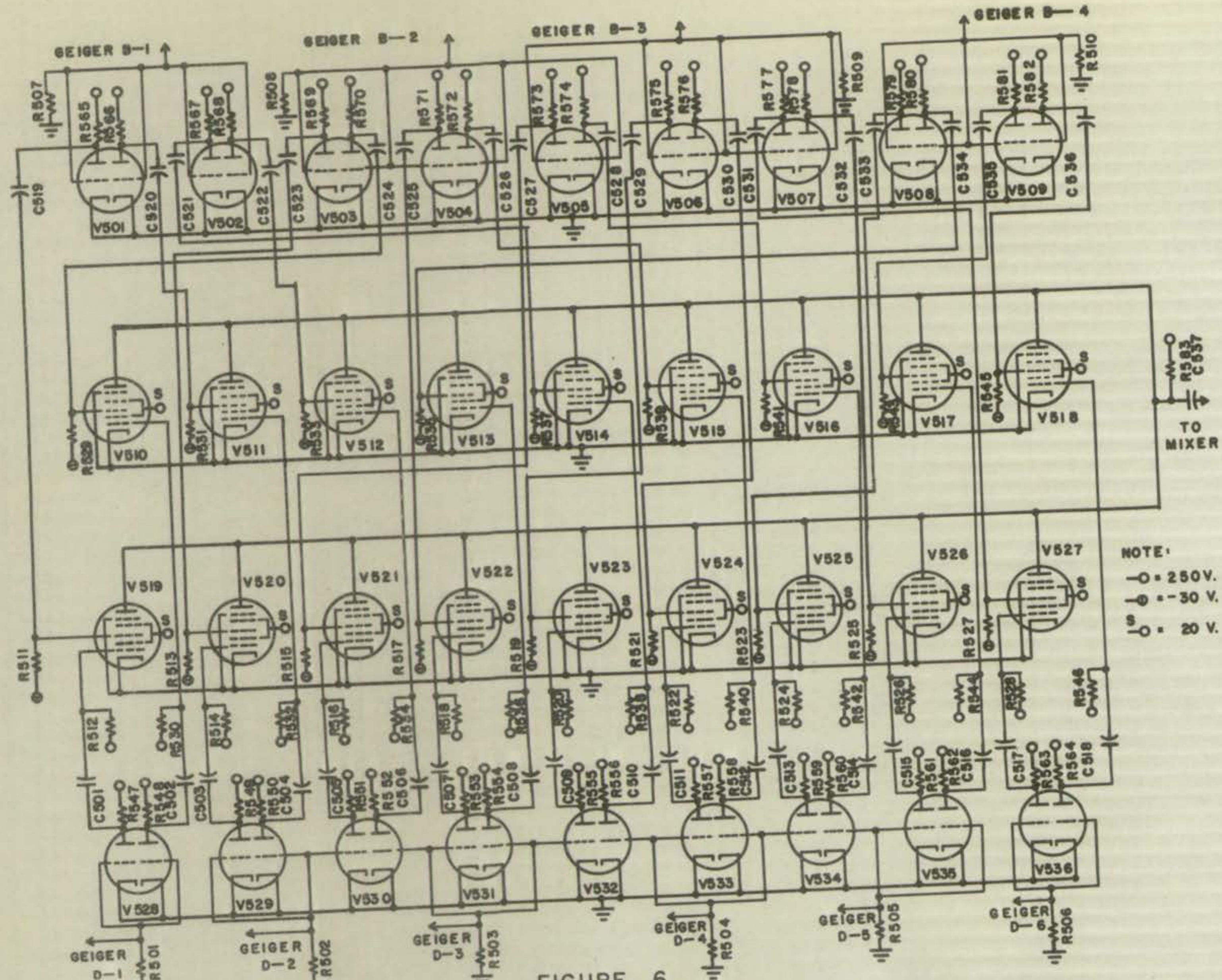
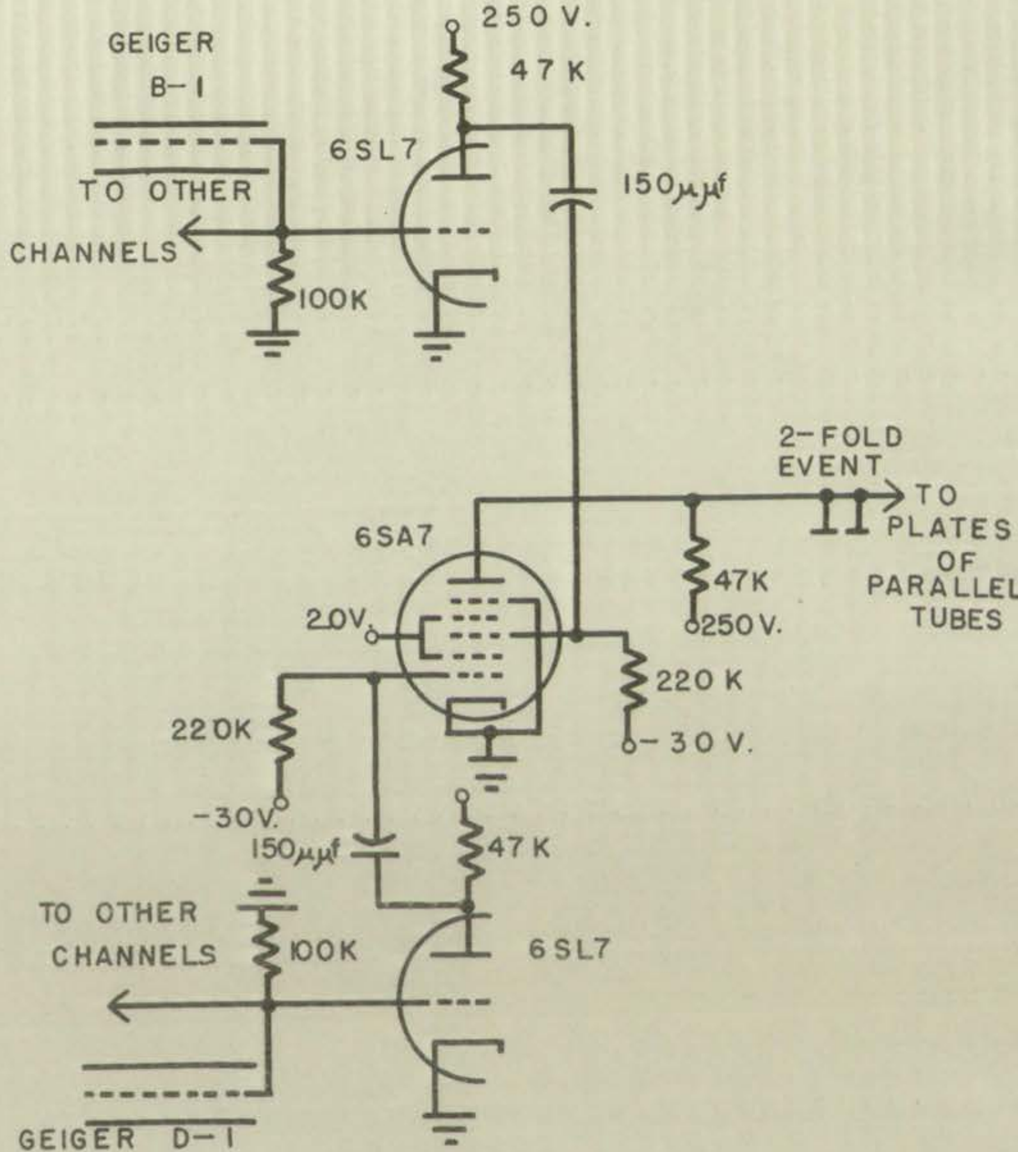
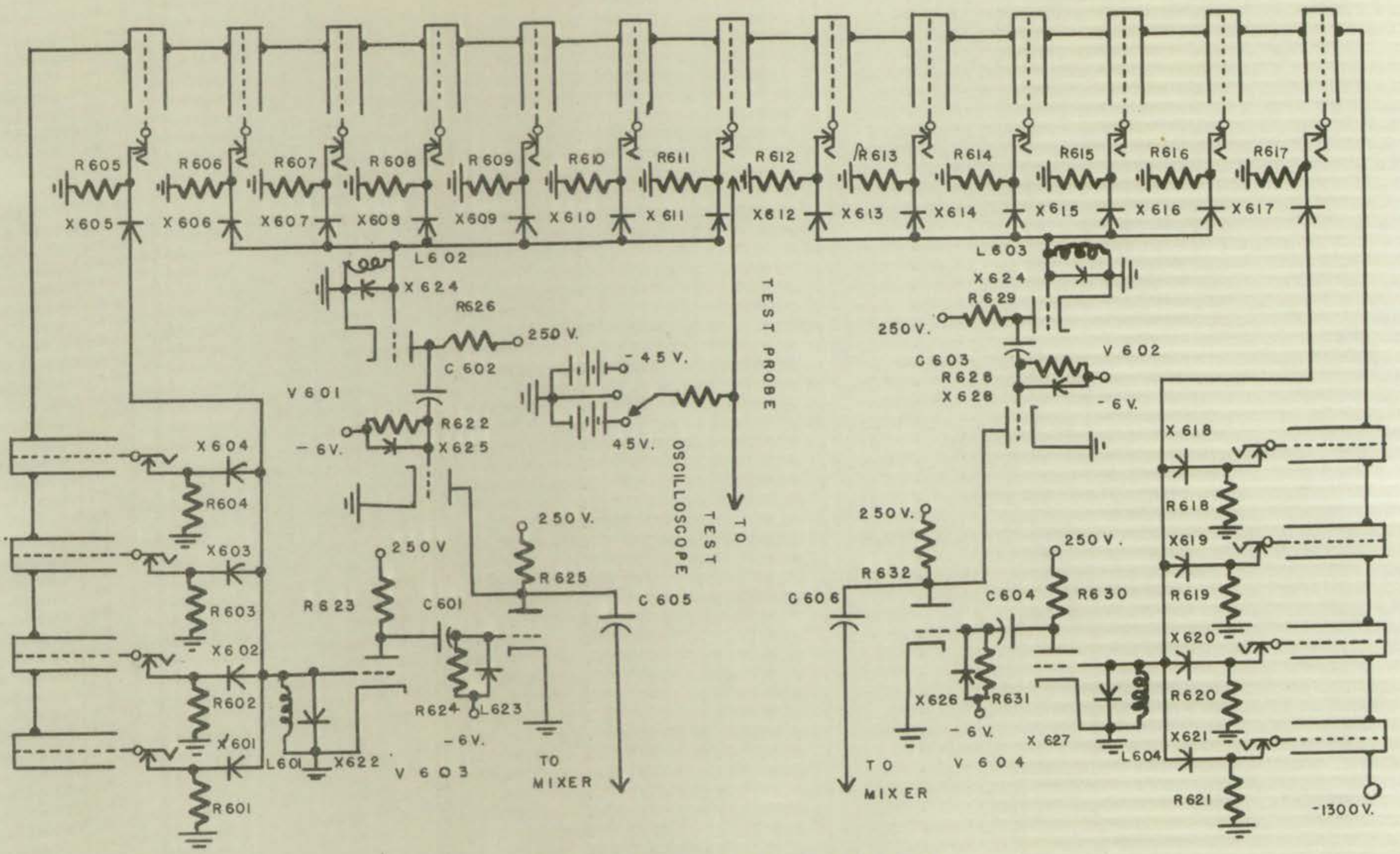


FIGURE 6
2-FOLD COINCIDENCE CIRCUIT



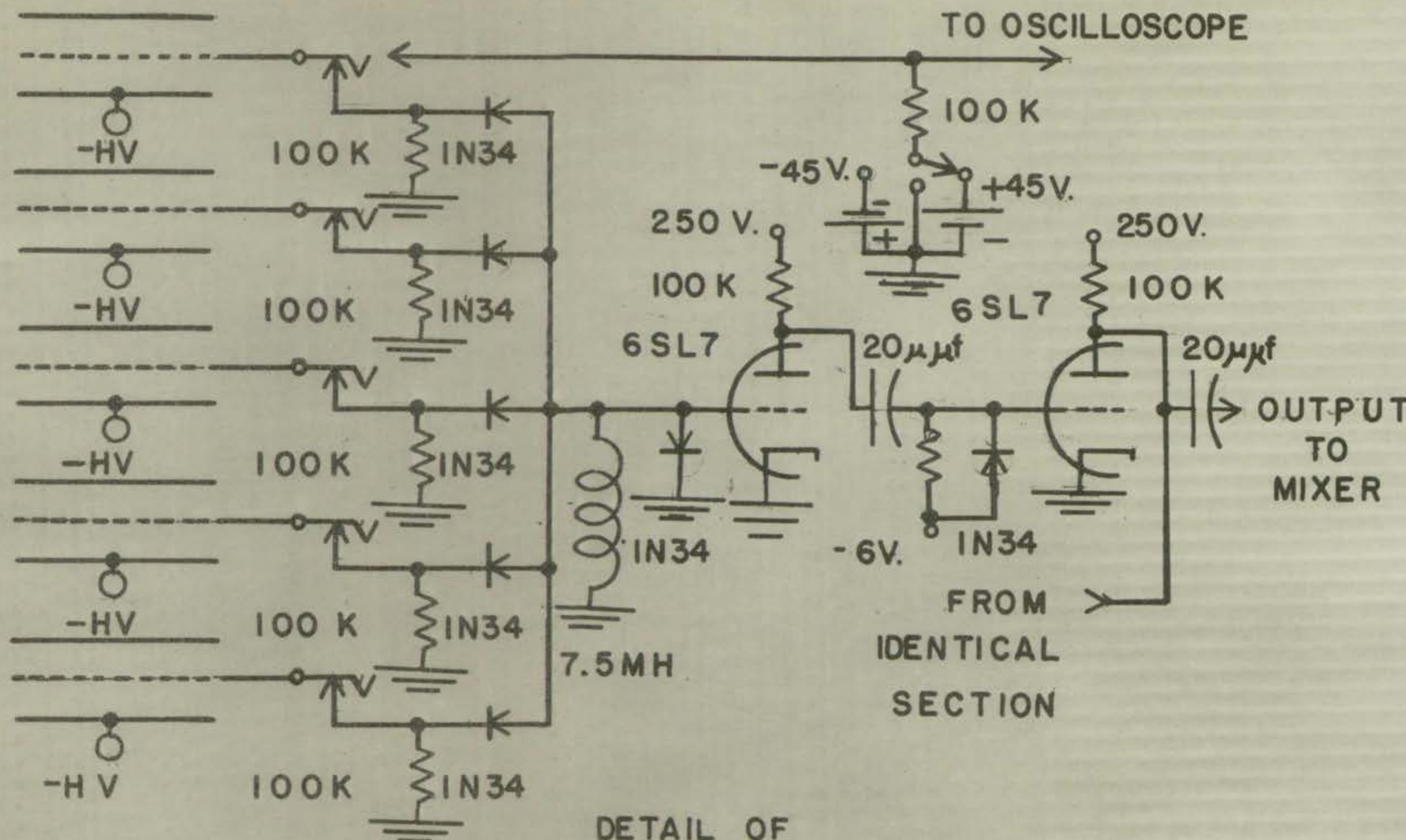
DETAIL
OF THE
2-FOLD COINCIDENCE CIRCUIT

FIGURE 7



ANTICOINCIDENCE PANEL

FIGURE 8



DETAIL OF
ANTICOINCIDENCE
TEST PANEL

FIGURE 9

subgroup of tubes. The 1N34 crystal diodes were put in series with the geiger tubes to prevent the capacities of the tubes from adding and thus causing a long dead time. Test points were included in this panel so that each geiger tube could be checked individually for proper operation.

The outputs of the anticoincidence panel and the 2 and 3-fold coincidence chasses were fed into the mixer circuit, shown in Figure 10. V 101 and V 102 composed a multivibrator whose function was to lengthen and clip the output from the 2-fold chassis. V 104 and V 105 performed the same function for the 3-fold chassis, V 103 and V 106 composed a coincidence circuit for the outputs of the 2 and 3-fold coincidences. Thus, in order to get a coincidence at this point there had to be a 5-fold coincidence (A, B, 2C, and D) of the proper geiger tubes. This 5-fold coincidence was amplified in V 107, and fed into V 108, V 115, and V 118.

The outputs of the anticoincidence pre-amplifier panel were amplified and put into coincidence in tubes V 109 and V 110. This was then amplified successively in tubes V 111, V 112, and V 113. The output pulses of V 108 and V 113 were put into parallel coincidence and amplified in V 114. The purpose of this last coincidence is to form a blocking pulse which will prevent the multivibrator V 117 and V 118

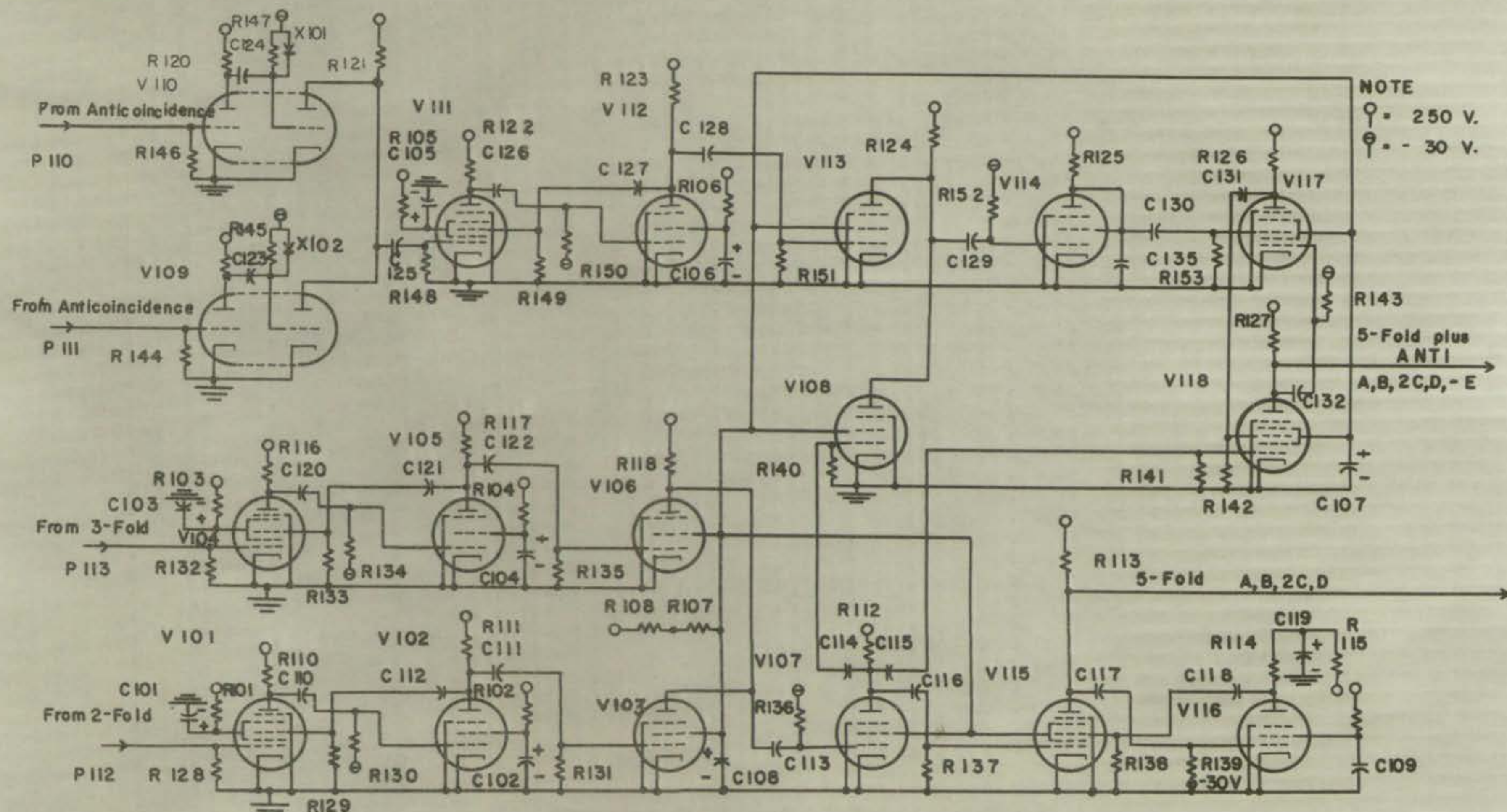


FIGURE 10 — MIXER CIRCUIT

from firing when a pulse from Tray E occurs at the same time as a 5-fold coincidence. This is necessary since the blocking pulse is lengthened to about nine microseconds by the capacitor combination C 130 and C 135. Therefore, the multivibrator V 117 and V 118 gave an output pulse every time an NPS event occurred. The multivibrator V 115 and V 116 gave an output pulse each time there was a PS event.

The output pulses of these multivibrators were sent into a pair of 6V6's located in the low voltage power supply, Figure 12. They were then fed into the printing mechanism, Figure 11, which was a modified Streeter-Amet traffic recorder. The total number of PS events, and the total number of NPS events were recorded hourly.

The counter tubes were of the type described by Regener[5]. All were two inches in diameter and twenty-four inches long, except those in Tray E which were thirty-six inches long. The high voltage power supply is shown in Figure 13.

The circuits were rather straightforward, and it is believed that no further explanation of them is necessary. The equipment was installed inside a building at Los Alamos,

---

[5] Regener, V. H., Rev. Sci. Instr. 18, 267 (1947)

from firing such a pulse, [illegible] take as a 5-[illegible] the blocking [illegible] seconds [illegible] Therefore, [illegible] pulse [illegible] V 11 and V [illegible] by event.

The output [illegible] into a [illegible] Figure 12. [illegible] Figure 13; [illegible] recorder. The [illegible] number of N-E events [illegible]

The [illegible] Regener[5]. All were [illegible] inches long, except those in [illegible] inches long. The [illegible] Figure 13.

The circuits were [illegible] believed that no further [illegible] The equipment [illegible]

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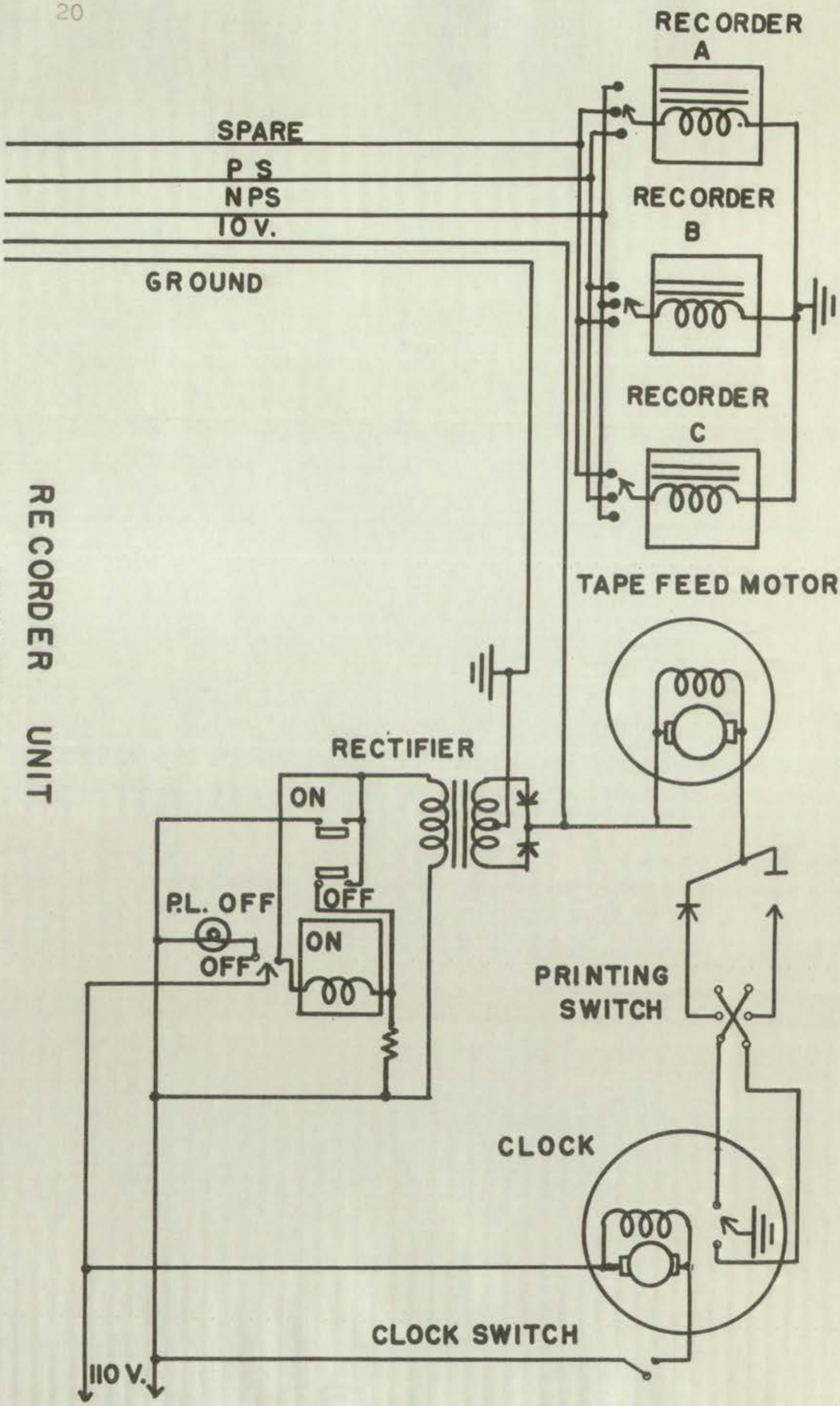
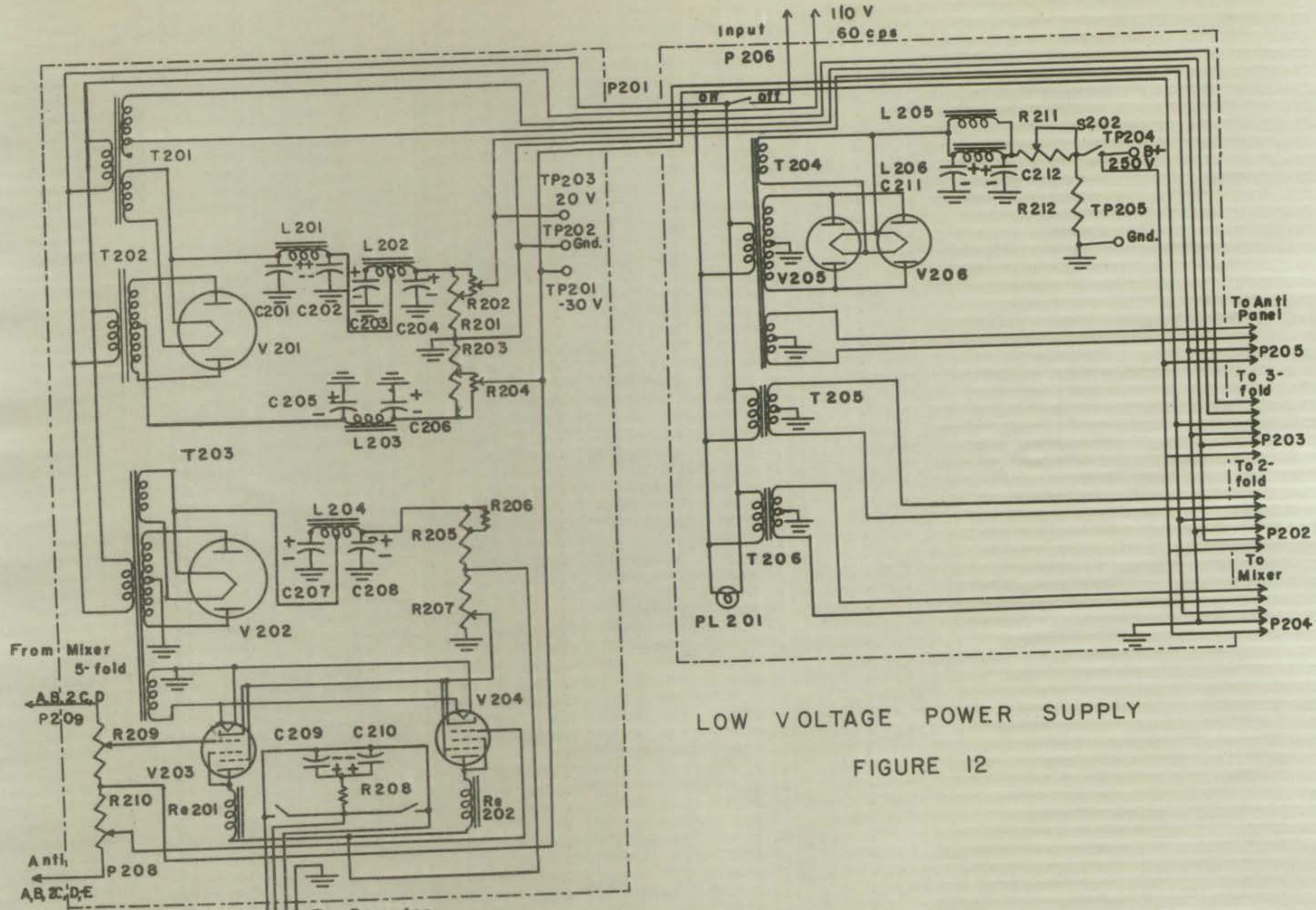
[5] Regener, V. H., [illegible]



RECORDER UNIT
FIGURE 11



LOW VOLTAGE POWER SUPPLY

FIGURE 12

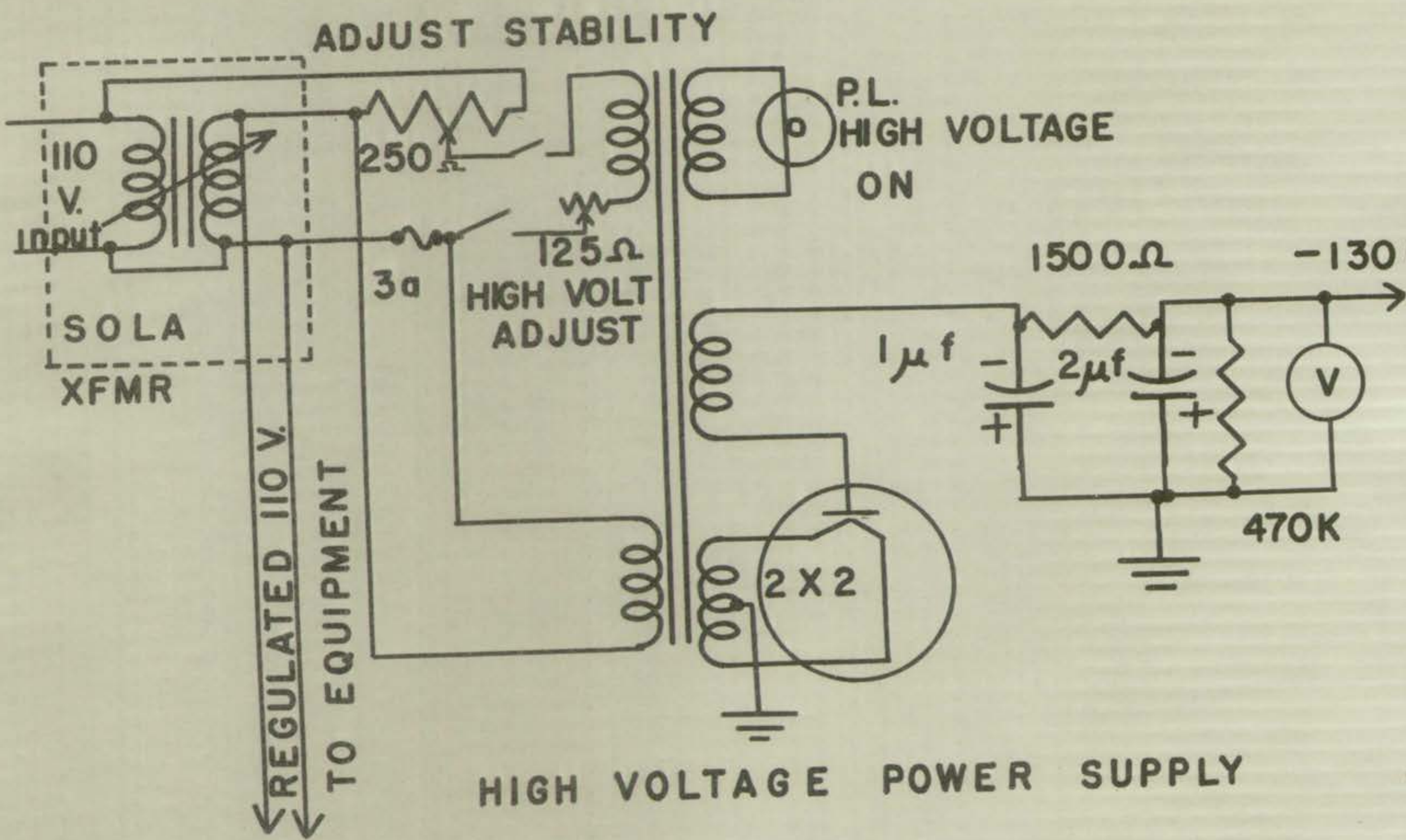

ADJUST STABILITY
P.L.
HIGH VOLTAGE
ON
110
V.
input
250Ω
3a
125Ω
HIGH VOLT
ADJUST
SOLA
XFMR
1500Ω
-1300V.
1μf
2μf
470K
2X2
REGULATED 110 V.
TO EQUIPMENT
HIGH VOLTAGE POWER SUPPLY

FIGURE 13

New Mexico, altitude 2,280 m, under as nearly identical roof sections as possible. The positions of the tanks were interchanged twice so that the effect of the slight variation in roof thickness could be eliminated.

As the thickness of Σ_1 is increased, an exponential decrease in the number of showers produced in Σ_2 by non-ionizing primaries is expected. Such an exponential decrease provides a measure of the collision length of the shower-producing radiation in Σ_1.

It should be observed that a nuclear collision of an incident neutron in Σ_1 might conceivably lead to the transfer of only a small fraction of its energy to ionizing secondaries. These low-energy secondaries might be absorbed in Σ_1 before reaching the anticoincidence Tray E, and the primary neutron might still be able to produce a penetrating shower in Σ_2 and thus an NPS count. If this process does happen the magnitude of the effect would certainly be dependent upon the thickness of absorber in Σ_1 and, consequently, one could not obtain an unambiguous experimental result for the collision length. However, the data from previous experiments,[6,7,8]

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[6] Rollosson, G. R., Phys. Rev., 87, 71 (1952)

[7] Boehmer, H. W., and Bridge, H. S., Phys. Rev., 85, 863 (1952)

[8] Sitte, K., Phys. Rev., 78, 714 (1950)

New Mexico, [illegible]
roof sections [illegible]
interchanged [illegible]
in roof thickness [illegible]

As the [illegible]
decrease in the number of [illegible]
izing [illegible]
provides a measure of [illegible]
producing [illegible] in S_1.

It should be [illegible]
incident neutron [illegible] S_2 [illegible]
of only a small [illegible]
aries. These [illegible]
before reaching [illegible]
neutron might still be [illegible]
in S_2 and thus [illegible]
the magnitude of the [illegible]
the thickness [illegible] in S_2 [illegible]
not obtain an [illegible]
length. However, [illegible]

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[6] [illegible], [illegible], Phys. Rev. [illegible]

[7] [illegible], [illegible] Phys. Rev. [illegible]
803 (1952)

[8] [illegible]

performed under similar conditions seem to show an exponential decrease of the NPS rate with thickness in Σ_1. This indicates that the primary neutron does not penetrate beyond the distance which is penetrated in Σ_1 by its ionizing secondaries. This supports the view that an experiment of this type does measure the collision length for nuclear interactions of high energy non-ionizing N-rays.

Runs, usually of duration about 24 hours each, were made alternately under the tanks containing the H_2O and D_2O. The number of penetrating showers, both PS and NPS, and the time were recorded for each run. Similar runs were made with the tanks empty, and some data were taken with fillings of intermediate depth.

Some of the runs were made with lead in position Σ_2, some without. A few NPS events were always observed with no lead in Σ_2. At least some of these arose from showers formed in the counter walls and the supports for Tray E, and some may have come from wide-angle showers produced in the main lead shield Σ_3 by rays incident at a large zenith angle.

II TREATMENT OF DATA

The anticoincidence Tray E was not 100% efficient. Its inefficiency was measured frequently by moving the equipment away from both tanks, placing Tray B above Tray E, and connecting two counters in Tray C together. Thus, single performed under [illegible] tial decrease of [illegible] indicates that [illegible] yond the distance [illegible] secondaries. This [illegible] this type does [illegible] interactions [illegible].

Runs, [illegible] were made alternately [illegible] The number of [illegible] tion were [illegible] the tanks empty, and [illegible] intermediate [illegible].

Some of [illegible] some without. A few [illegible] no lead in Σ_2. [illegible] formed in the counter [illegible] some may have come [illegible] main lead shield Σ_3 [illegible].

IV. [illegible]

The anticoincidence [illegible]. Its inefficiency [illegible] sent away from both [illegible] connecting two [illegible] ionizing rays passing through the system could cause counts on the PS recorder but, since these rays would have to pass through Tray E, no counts should be observed on the NPS recorder. However, some NPS counts, arising in part possibly from side showers and accidental coincidences, were always found. The inefficiency, ε, defined as the ratio NPS/PS for this case, was assumed to have the same value during normal operations and this value was used to correct the observed rate of NPS counts. In general, daily checks were made upon the operation of the individual counters and the electronic circuits.

The barometric pressure was recorded and corrections were applied to the data for variations of the pressure from an arbitrary standard value near the mean.

The absorption of the roof was not quite the same for the two tank positions, designated N(north) and S(south), and the times spent with the equipment in each position for each arrangement of Σ_1 and Σ_2 were usually somewhat different. A weighted average of the ratio of the NPS counting rates in the two positions for the same absorber conditions showed that the counting rate in the N position exceeded that in the S position by 3.5%. That is, each differed from the average by 1.75%.

Let t_n and t_s be the times spent in the N and S positions ionizing rays [illegible] on the [illegible] recorder [illegible] through Tray 5, no counts [illegible] recorder. However, [illegible] from side showers and [illegible] found. The [illegible] this case, the [illegible] operations [illegible] rate of [illegible] counts. [illegible] the operation of the [illegible] counters and [illegible] circuits.

The barometric pressure [illegible] were applied to the [illegible] an arbitrary standard value [illegible].

The absorption of the [illegible] the two tank positions, [illegible] and the times [illegible] each arrangement of [illegible] A weighted average of the [illegible] the two positions [illegible] that the counting rate in the S position [illegible] S position by 1.6%. [illegible] by 1.75%.

Let t_n and t_s be the [illegible]

respectively, and let N_N and N_S be the corresponding numbers of NPS counts in the two positions. Then, in order to reduce the total number of counts to the basis of average position, the following corrections were applied:

$$0.0175\ N_S(t_S - t_N)/\ t_S, \quad \text{if } t_S > t_N$$

and $$-0.0175\ N_N(t_N - t_S)/\ t_N, \quad \text{if } t_N > t_S.$$

All data were reduced to average values for the N and S positions by applying the correction terms given above.

A correction for inefficiency, ε, of Tray E was made by subtracting the quantity ε x PS from the observed number of NPS counts for each configuration of the absorbers Σ_1 and Σ_2.

The absorption length of the NPSPR in air was taken to be 115 g/cm^2 = 3.33 inches Hg. Thus, the intensity of the incident radiation at pressure p (measured in inches Hg) is given by $I_p = I_{po} \exp[-(p-po)/3.33] \cong I_{po}\ (1-0.3\ \Delta p)$, where I_{po} is the intensity expected at an arbitrary pressure po, chosen near the mean pressure, and $\Delta p = p-p_0$. Thus, in order to bring the results to a common barometric pressure basis, a correction of $0.3\ \Delta p$ x NPS was added to the NPS count for each run after the correction for inefficiency of Tray E had been made.

The background NPS counts, obtained with the lead removed from Σ_2, were corrected in the same manner as the other NPS counts. As will be seen later, the background counting rate varies, within experimental error, at the same exponential

respectively, [illegible]
of NPS counts in [illegible]
the total number of [illegible]
the following correction [illegible]

and [illegible]

All data were reduced [illegible]
positions by applying [illegible]

A correction for [illegible]
subtracting the quantity [illegible]
NPS counts for each [illegible]

The absorption length [illegible]
to be 115 g/cm^2 = [illegible]
the incident radiation [illegible]
is given by [illegible]
where I_{po} is the [illegible]
po, chosen near the [illegible]
order to bring the [illegible]
basis, a correction of [illegible]
count for each [illegible]
Tray N had been made.

The background [illegible]
noved from Σ [illegible]
NPS counts. [illegible]
rate varies, [illegible]

rate with depth of water in Σ_1 as does the NPS counting rate when lead is present at Σ_2. Thus, for calculations of collision lengths, it does not seem to matter, except for accumulation of errors, whether or not the background rate is subtracted from the otherwise corrected value.

Let σ_p, σ_d, and σ_o be the collision cross sections of the hydrogen, deuterium, and oxygen nuclei respectively, for neutral N-rays, and let L_{c1} and L_{c2} be the collision lengths for these rays in light and heavy water, respectively. Let R_o, R_1, and R_2 be the corrected rates of production of penetrating showers in Σ_2 by neutral N-rays with $\Sigma_1 = 0$ (the empty steel tank), with $\Sigma_1 = x_1$ g/cm^2 H_2O and with $\Sigma_1 = x_2$ g/cm^2 D_2O, respectively. Let m_1 and m_2 be the molecular masses of light and heavy water respectively. If the number of penetrating showers produced in Σ_2 by neutral N-rays is a decreasing exponential function of the depth of water in Σ_1, then,

2) $$R_1 = R_o \exp(-x_1/L_{c1})$$

and $$R_2 = R_o \exp(-x_2/L_{c2}),$$

3) where $$L_{c1} = m_1/(2\sigma_p + \sigma_o) \quad ,$$

and $$L_{c2} = m_2/(2\sigma_d + \sigma_o) \quad .$$

From these above equations, one obtains

4) $$R_1/R_2 = \exp(x_2/L_{c2} - x_1/L_{c1})$$
$$= \exp\left\{2\left[x_2\,\sigma_d/m_2 - x_1\,\sigma_p/m_1\right] + \left[x_2/m_2 - x_1/m_1\right]\sigma_o\right\}.$$

rate with depth of [illegible]

when lead is [illegible]

lision leading [illegible]

cumulation of [illegible]

subtracted from the [illegible]

Let τ_p, τ_d, and τ_t [illegible]

the hydrogen, deuterium, [illegible]

nuclear [illegible]

for these [illegible]

N_p, N_d, and N_t be the [illegible]

trating [illegible]

empty [illegible]

x_2 g/cm² H_2O, [illegible]

[illegible] of light [illegible]

of penetrating [illegible]

a decreasing exponential [illegible]

Σ_1, then,

2) [illegible]

and [illegible]

3) where [illegible]

and [illegible]

From these above [illegible]

[illegible]

4) N_1/N_2 = exp [illegible]

[illegible]

If the depths of water are chosen such that

5) $$x_2/m_2 = x_1/m_1,$$

as was done for the main part of this experiment, (4) reduces to:

6) $$R_1/R_2 = \exp\left[2x_1(\sigma_{\bar{d}} - \sigma_{\bar{p}})/m_1\right],$$

from which one obtains

7) $$\sigma_{\bar{d}} - \sigma_{\bar{p}} = (m_1/2x_1)\ \ln(R_1/R_2).$$

From these above equations, one obtains:

8) $$L_{c1} = x_1/\ln(R_o/R_1) \quad \text{and}$$

9) $$L_{c2} = x_2/\ln(R_o/R_2).$$

Equations (7), (8), and (9) were used to calculate the results of this experiment.

The inefficiency of Tray E was determined in 24 runs which resulted in a total of 80,851 PS counts and 1,020 NPS counts. This gives $\varepsilon = 1{,}020/80{,}851 = 0.0126 \pm 0.0004$. Table I gives the magnitudes of the various corrections and the corrected values of the total NPS counts.

Table II gives the total time of running under each condition, the corrected total NPS counts, and the values of the corrected counting rates. All errors quoted represent standard deviations.

The logarithms of the corrected NPS counting rates observed with Σ_1 composed of light water are plotted in Figure 14 against depth of water for $\Sigma_2 = 0$ and for $\Sigma_2 = 6$ inches Pb. Both curves have the same slope within experimental

If the device [illegible]

5) [illegible]

as was done for [illegible]

dance for

6) [illegible]

from which one obtains [illegible]

7) [illegible]

From [illegible]

8) [illegible]

9) [illegible]

Equations (7), (8), [illegible]

results of this [illegible].

The [illegible]

which resulted in [illegible]

counts. This gives [illegible].

Table [illegible] gives the [illegible]

the corrected [illegible].

Table [illegible] gives [illegible]

condition, the [illegible]

of the corrected [illegible]

standard deviations.

The logarithm [illegible]

observed with Σ, [illegible]

Figure 14 against [illegible]

inches Pb. [illegible]

TABLE I

OBSERVED COUNTS AND CORRECTIONS

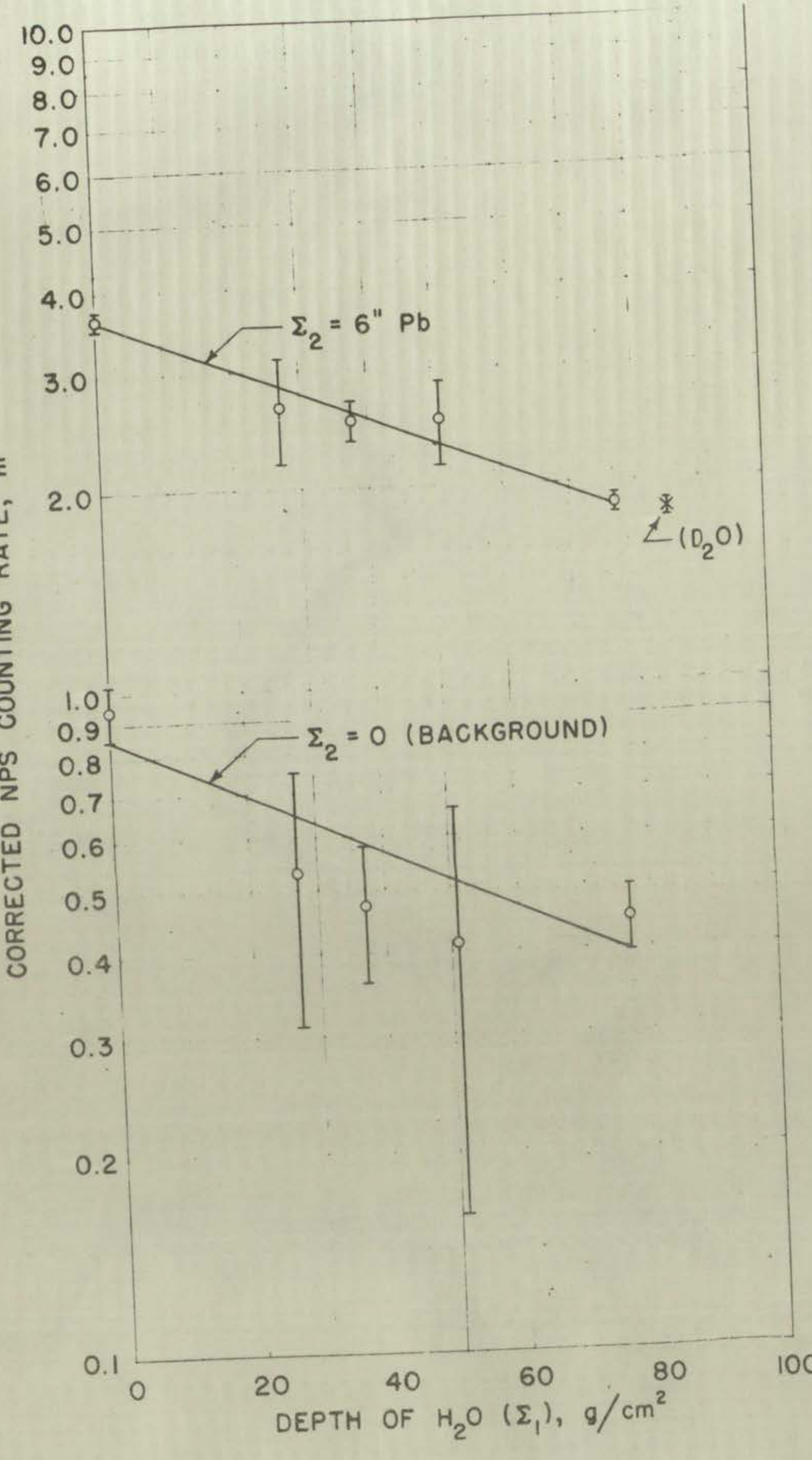
No. of runs	Σ_1 in g/cm^2	Σ_2	PS counts, obs.	NPS counts, obs.	Corrections to NPS counts N-S Ave.	Ineff.	Pressure	NPS corrected
45	85.09, D_2O	6" Pb	35,210	2,459	-4.05	-444.0	-8.86	2002.1
16	85.09, D_2O	0	15,824	386	-1.06	-199.3	+1.07	186.7
34	76.6, H_2O	6" Pb	28,035	1,962	-8.19	-354.0	-15.89	1583.9
15	76.6, H_2O	0	17,733	400	-2.09	-223.5	-0.10	174.3
11	0	6" Pb	9,868	1,068	+14.00	-124.5	-35.24	922.3
8	0	0	8,487	292	+5.11	-106.9	-8.85	181.4
4	37.6, H_2O	6" Pb	3,332	293	-5.12	-42.0	-7.32	238.6
4	37.6, H_2O	0	4,863	112	-1.96	-61.3	-3.26	45.5
1	50.8, H_2O	6" Pb	688	65	-1.14	-8.7	--*	55.2
1	50.8, H_2O	0	610	14	-0.24	-7.7	--*	6.1
1	27.0, H_2O	6" Pb	484	44	-0.77	-6.1	--*	37.1
1	27.0, H_2O	0	1,094	27	-0.47	-13.8	--*	12.7

*The barometric pressure was not read, but the correction is negligible compared with the statistical error for a small number of counts.

TABLE II

RATES OF PRODUCTION OF PENETRATING SHOWERS BY NEUTRAL N-RAYS

No. of runs	Σ_1 in g/cm^2	Σ_2	Total time in hours	Corrected total NPS counts	NPS counting rate in hr^{-1}
45	85.09, D_2O	6" Pb	1097.8	2002.1 ± 50	1.825 ± 0.045
16	85.09, D_2O	0	364	186.7 ± 20	0.512 ± 0.055
34	76.6, H_2O	6" Pb	855.6	1583.9 ± 44	1.851 ± 0.051
15	76.6, H_2O	0	392.4	174.3 ± 20	0.445 ± 0.051
11	0	6" Pb	253.7	922.3 ± 34	3.64 ± 0.13
8	0	0	193.4	181.4 ± 17	0.94 ± 0.09
4	37.6, H_2O	6" Pb	94.7	238.6 ± 17	2.52 ± 0.18
4	37.6, H_2O	0	96.4	45.5 ± 10.6	0.47 ± 0.11
1	50.8, H_2O	6" Pb	22	55.2 ± 8.1	2.51 ± 0.37
1	50.8, H_2O	0	15	6.1 ± 3.8	0.41 ± 0.25
1	27.0, H_2O	6" Pb	14	37.1 ± 6.6	2.65 ± 0.47
1	27.0, H_2O	0	24	12.7 ± 5.2	0.53 ± 0.22



10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
CORRECTED NPS COUNTING RATE, hr^{-1}
Σ_2 = 6" Pb
(D_2O)
Σ_2 = 0 (BACKGROUND)
0
20
40
60
80
100
DEPTH OF H_2O (Σ_1), g/cm^2

FIGURE 14

error. One interpretation of this fact is that most of the background counts ($\Sigma_2 = 0$) arise from rays incident through Σ_1, and that these rays are subject to the same absorption as the rays which produce the penetrating showers.

Examination of the data in Table II shows that, for $\Sigma_2 = 6$ inches Pb, the counting rate with $\Sigma_1 = 85.09$ g/cm^2 D_2O is slightly, but insignificantly less than that with $\Sigma_1 = 76.6$ g/cm^2 H_2O. These depths of heavy and light water contain the same amounts of oxygen per square centimeter, i.e., they satisfy equation (5). Thus, the small difference in these counting rates has a sign to correspond with the cross section of the deuteron being greater than that of the proton, even though this difference is less than its statistical error. The difference between the corresponding background rates ($\Sigma_2 = 0$) has the opposite sign, but it also is less than its statistical error. There is no obvious reason for the background to be less with the corresponding depth of heavy water and, possibly, the reverse might be expected. If the true background with light water is equal to or greater than that for heavy water, perhaps the best value of the background for the both cases would be the weighted average of the two values given in Table II. However, the statistical errors are sufficiently large to include the possibility that the true background values are

error. One [illegible]
the background [illegible]
through Σ_1, [illegible]
absorption [illegible]

Examination [illegible]
Σ_2 = 0 [illegible] the [illegible]
D_2O in [illegible]
Σ_1 = 76.[illegible]
contain the [illegible]
i.e., they [illegible]
in these [illegible]
cross section of the [illegible] being [illegible]
the proton, [illegible]
statistical error. The [illegible]
background rates (Σ_2 = [illegible]) [illegible]
also is less than [illegible]
reason for the [illegible]
depth of heavy [illegible]
expected. If the [illegible]
to or greater than [illegible]
value of the background [illegible]
weighted average of the [illegible]
however, the [illegible]
include the possibility [illegible]

equal, or even inverted in magnitude, and the value of $\sigma_{\bar{d}} - \sigma_{\bar{p}}$ has been calculated using the individual values of the background observed in the experiment.

Using the data of Table II, equation (7) gives:

$$\sigma_{\bar{d}} - \sigma_{\bar{p}} = 13 \pm 15 \text{ millibarns.}$$

(If the average value of the background had been used, as indicated in the previous paragraph, the result would have been

$$\sigma_{\bar{d}} - \sigma_{\bar{p}} = 4 \pm 12 \text{ millibarns.})$$

Similarly, equations (8) and (9) give the collision lengths as follows:

$$L_{c1} = 113 \pm 12 \text{ g/cm}^2 \text{ in } H_2O,$$

and $$L_{c2} = 123 \pm 13 \text{ g/cm}^2 \text{ in } D_2O.$$

III CONCLUSIONS

From the analysis of this experiment, one can see that an unambiguous measurement of the collision length is obtained only if the following conditions are true.

1) The first condition is that the radiation that produces the shower actually passes through the absorber. Considerable side shielding (as in Σ_3), and anticoincidence tubes well-removed from the equipment to discriminate against extensive air showers help in this matter. Extensive air showers, unless properly discriminated against,

equal, or even [illegible]

$\sigma_3 - \sigma_5$ has been [illegible]

the background [illegible]

Using the [illegible]

$\sigma_3 - \sigma_5 = [illegible] \pm [illegible]$

(If the average value of [illegible]

indicated in the previous [illegible]

been

$\sigma_3 - \sigma_5 = [illegible] \pm [illegible]$

Similarly, equations (3) and (4) [illegible]

as follows:

$k_{x1} = 115 \pm [illegible]$

and $k_{x2} = [illegible] \pm [illegible]$

III. [illegible]

From the analysis [illegible]

that an unambiguous [illegible]

obtained only if the [illegible]

1) The first condition is that the [illegible]

the [illegible]

[illegible]

that well-[illegible]

against [illegible]

tensive [illegible]

are the largest source of error in experiments that allow ionizing particles to initiate the shower.

2) The second condition is that some protection be established so that single particles at large angles from the zenith, local soft showers, and knock-on electrons do not register as penetrating showers. This requirement may be fulfilled by proper geometric considerations.

3) Background measurements must be made to eliminate the chance coincidences that would simulate showers. This requirement may not be very important, since, as was pointed out previously, the background counting rate seems to vary at the same exponential rate with depth of absorber as does the regular counting rate. However, the statistics upon which this conclusion is based are quite poor.

4) If the experiment measures showers produced by non-ionizing primaries, some precaution must be taken to take account of the inefficiency of the anticoincidence tray.

5) The experiment must have been conducted for a sufficiently long time to have cancellation of the errors introduced by short period variations in the incident flux.

are the l[illegible]

allow ionizing particles [illegible]

2) The record should [illegible]

lished so that [illegible]

the pending [illegible]

do not [illegible]

may be fulfilled by [illegible]

3) Background measurements [illegible]

chance-coincidences [illegible]

requirement [illegible]

pointed out previously, [illegible]

seems to vary [illegible]

of absorber [illegible]

the statistics [illegible]

are quite poor.

4) If the experiment [illegible]

ionizing primaries, [illegible]

take account of the [illegible]

tray.

5) The experiment [illegible]

long time to make [illegible]

by short period [illegible]

CHAPTER III

EVALUATION OF OTHER EXPERIMENTS

A. - COLLISION LENGTH OF THE NPSPR IN WATER.[9]

In 1951, Rollosson determined the collision length in water of the neutral component of the cosmic radiation which is capable of producing penetrating showers. The equipment is essentially the same as that used by Froman, Kenney, and Regener. The main changes which the latter made on the equipment used by Rollosson were of a geometric nature. Figure 15 shows two elevations of the experimental arrangement.

As one can see, there is a somewhat smaller amount of shielding in Σ_3, a slightly different shaped tank, and a change in Σ_2. In the experiment described in the previous chapter, Σ_2 was composed of 6 inches Pb, whereas in this experiment it was composed of 12 inches water. Thus, there was a different allowable solid angle in the two experiments, so that there was also a difference in the possible combinations of tubes in Trays A, B, C, and D to give allowable coincidences.

A value of the collision length of the NPSPR was given as:

$$L_c = 98 \pm 13 \text{ g/cm}^2 \text{ in water.}$$

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[9] Rollosson, op. cit.

4. - COLLISION [illegible] IN WATER.

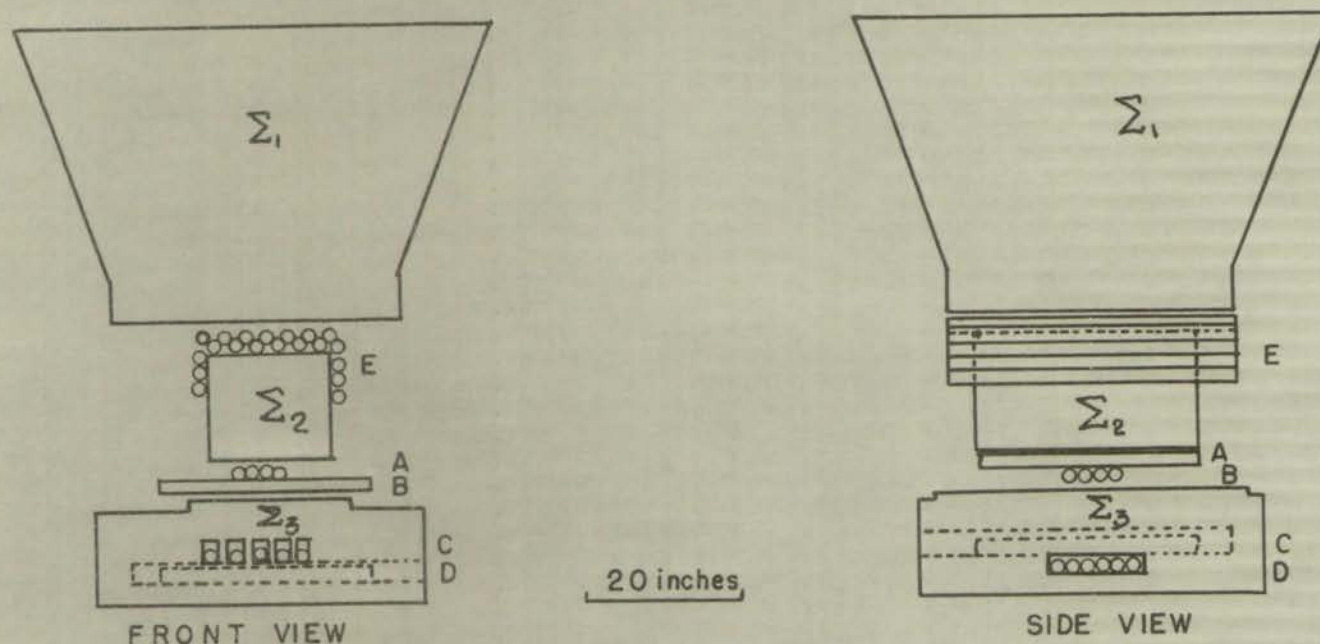
In 1951, [illegible] in water of the [illegible] which is capable of [illegible] equipment is [illegible] Kenney, and Heydenburg. [illegible] made on the equipment [illegible] nature. Figure [illegible] arrangement.

As one [illegible] of shielding in Σ_1, a [illegible] a change in Σ_1. [illegible] chapter, Σ_2 was [illegible] experiment it was [illegible] was a different [illegible] so that there was [illegible] tions of tubes [illegible] coincidences.

A value of the [illegible] as:

[illegible]

[9] Kollsman, [illegible]



EXPERIMENTAL ARRANGEMENT OF ROLLOSSON

FIGURE 15

This value agrees quite well with the value presented by Froman et al.. The experiment was performed at two altitudes, 2,770 m, and 1,570 m. From the difference in counting rates, the following value was deduced for the absorption length in air:

$$\lambda_{air} = 115 \pm 19 \text{ g/cm}^2.$$

The main difference in the treatment of data was that the calculated inefficiency was negligible in Rollosson's experiment, and was not included in the final calculation of the collision length.

B. - COLLISION LENGTH OF THE NPSPR IN PARAFFIN.[10]

This experiment performed by Pomeroy in 1950 is quite similar to those described previously. Two elevations of the experimental arrangement are given in Figure 16.

Neither the anticoincidence tray nor the side shielding were as extensive as in the experiments described above. Consequently, it is entirely possible that there were some extensive air showers that were included as local penetrating showers. The design of Σ_1 also left the possibility that particles inclined only somewhat from the vertical could cause a penetrating shower that would activate the detector, even though the incident particle traversed only a fraction of the

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10 Pomeroy, D., Phys. Rev., 87, 77 (1951)

This value agrees [illegible]

Froman et al.. The [illegible]

tudes, 2,770 m, and [illegible]

ing rates, the following [illegible]

tion length in [illegible]

λ [illegible]

The main difference [illegible]

the calculated [illegible]

experiment, and was not included in the [illegible]

of the collision lengths.

B. - COLLISION LENGTHS [illegible]

This experiment performed [illegible]

similar to those [illegible]

the experimental arrangement [illegible]

Neither the [illegible]

ing were so [illegible]

Consequently, it [illegible]

extensive air showers [illegible]

showers. The [illegible]

particles [illegible]

a penetrating [illegible]

though the [illegible]

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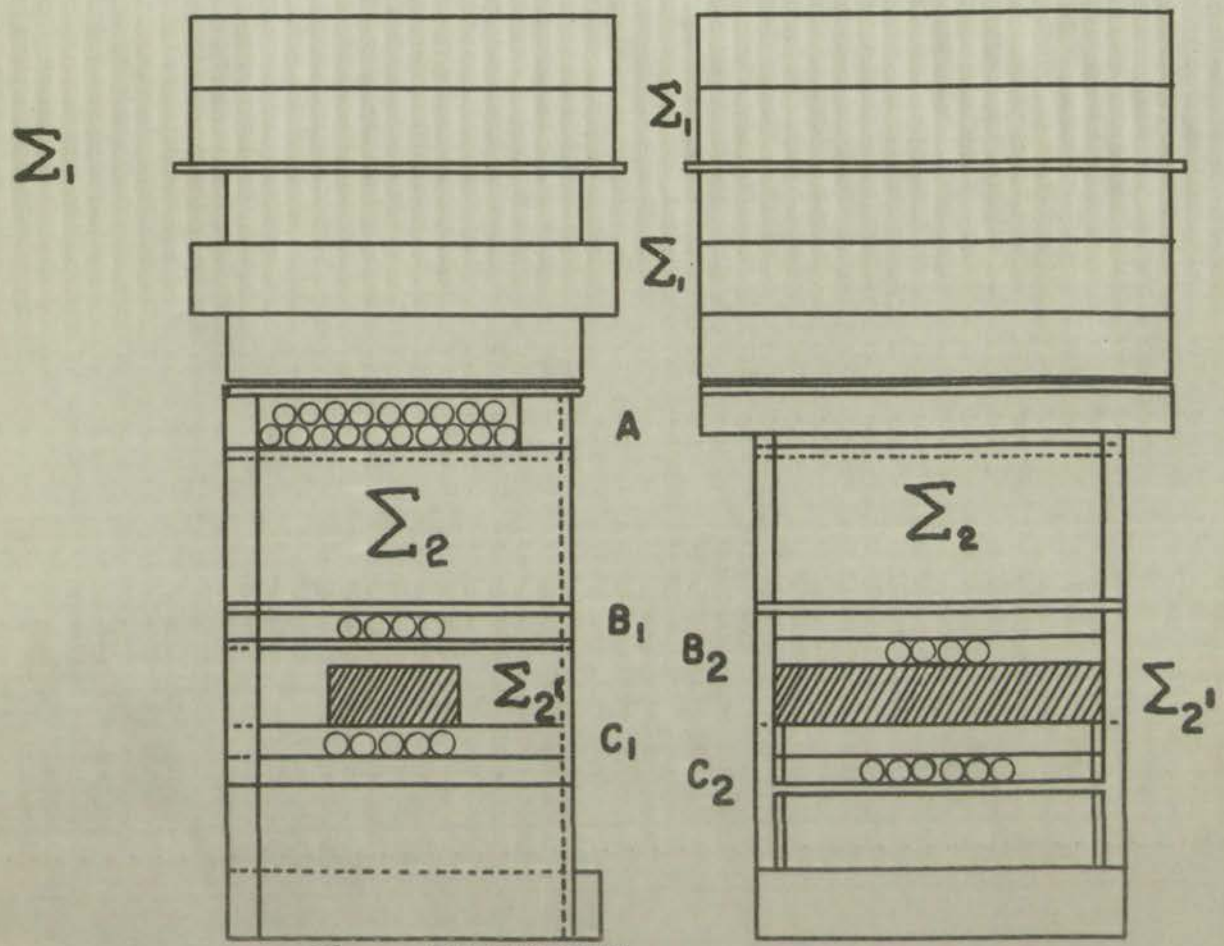
10 Froman, [illegible]



Σ_1 PARAFFIN
Σ_2 PARAFFIN
Σ_2' LEAD

EXPERIMENTAL ARRANGEMENT
OF
POMEROY

FIGURE 16

absorber. In general, the magnitude of these errors should be small, and the value given by Pomeroy is reasonably reliable.

The collision length of the NPSPR in paraffin as determined by Pomeroy is:

$$L_c = 61 \pm 6 \text{ g/cm}^2 \text{ at an altitude of } 2,770 \text{ m},$$

and

$$L_c = 75 \pm 19 \text{ g/cm}^2 \text{ at an altitude of } 1,570 \text{ m}.$$

From the difference in counting rates at the two altitudes, a value was deduced for the absorption length of the NPSPR in air which was given as:

$$\lambda_{air} = 104 \pm 6 \text{ g/cm}^2.$$

C. - COLLISION LENGTH OF THE IPSPR IN LEAD.[11]

Using the experimental arrangement of Figure 17, Sitte has investigated the collision length of the IPSPR in Pb. Using two separate values for the thickness of lead in the absorber Σ_3, the required penetrating power of the secondaries in the shower was changed. An increased penetrating power of the secondaries corresponds to an increased energy of the primary particle. The showers were produced in the lead of Σ_2. The required coincidences were those in which only one counter in Tray A, at least two counters in

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[11] Sitte, K., op. cit.

absorber. In general, [illegible] be small, and the value [illegible] reliable.

The collision length [illegible] termined by [illegible]:

L_c = 31 ± [illegible]

and L_c = [illegible]

From the difference in [illegible] a value was deduced for the [illegible] in air which was given as:

λ [illegible] = 100 ± [illegible]

C. - COLLISION LENGTH [illegible]

Using the [illegible] Fitte has investigated the [illegible] Pb. Using two [illegible] in the absorber Σ, [illegible] secondaries in the [illegible] trating power of the [illegible] energy of the primary particle. [illegible] in the lead of Σ. The [illegible] which only one counter [illegible]

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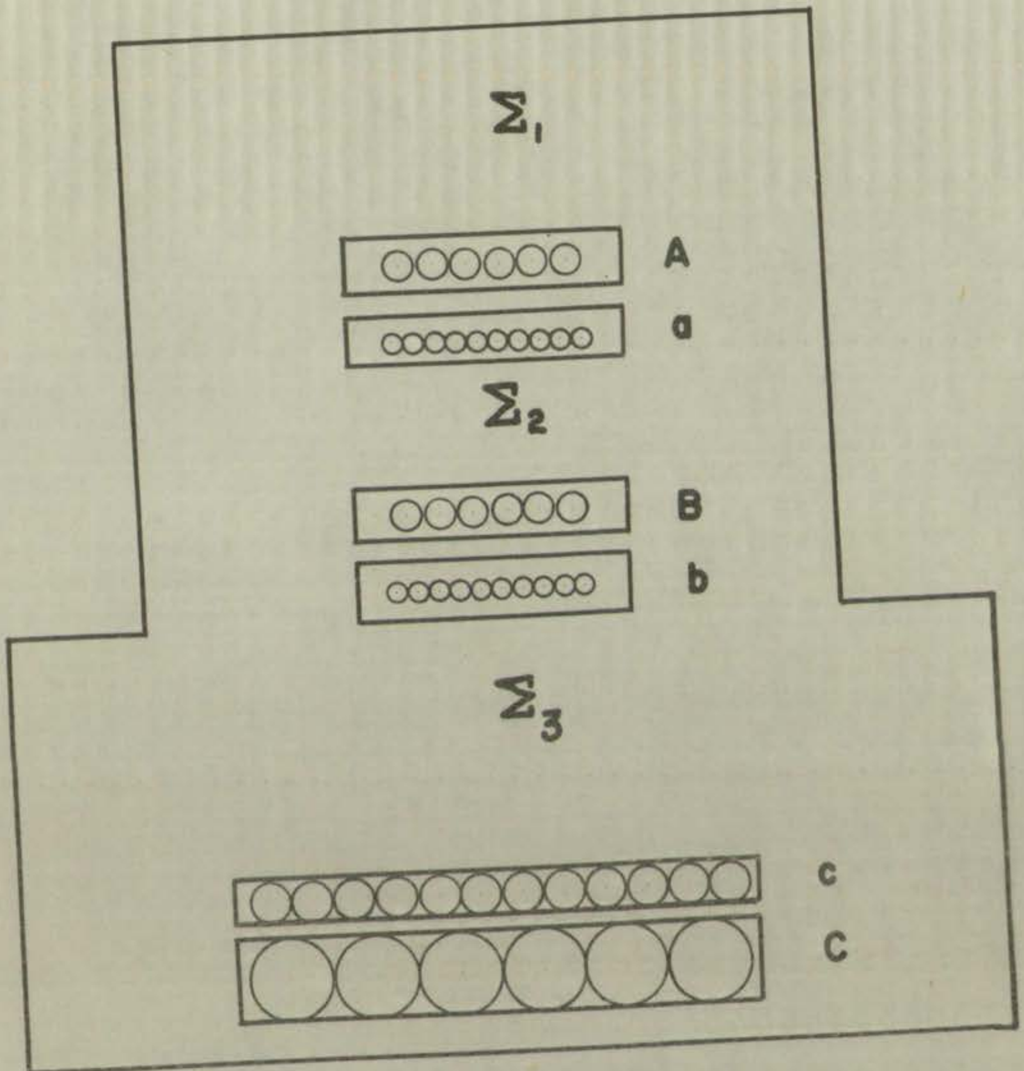
11 Fitte [illegible]



EXPERIMENTAL ARRANGEMENT
of
SITTE

FIGURE 17

Tray B, and at least three counters in Tray C were discharged. As the thickness of lead in Σ_1 was increased, showers would be formed in Σ_1 which would discharge more than one counter in Tray A. The count would then be rejected.

A bank of counter tubes in the near vicinity was also incorporated which registered a count every time one of these tubes was discharged in coincidence with a penetrating shower. This effectively records the number of showers that were produced by extensive air showers. The correlation between the number of penetrating showers and the number of air showers was less than 1%. This is, therefore, a good indication that this experiment actually measured the collision length of the IPSPR in lead. Hodoscope pictures were used to determine the actual number of secondaries in the shower.

The values obtained for the collision lengths of the IPSPR in lead are:

$$L_c = 162 \pm 10 \text{ g/cm}^2, \text{ where } \Sigma_3 = 200 \text{ g/cm}^2,$$

and

$$L_c = 196 \pm 13 \text{ g/cm}^2, \text{ where } \Sigma_3 = 100 \text{ g/cm}^2.$$

A criticism that applies to any experiment of this type is that a narrow or "collimated" shower could be formed in Σ_1 immediately above Tray A. This would discharge only one counter in Tray A, but still be registered as a penetrating shower produced in Σ_2. The hodoscope tray a, as used in this experiment, should minimize the error introduced by this effect.

Tray B, and at least three counter [illegible] as a [illegible]. As the thickness of [illegible] is [illegible] [illegible] be formed in Σ_1 which would [illegible] [illegible] in Tray A. The [illegible] would [illegible].

A [illegible] of [illegible] [illegible] incorporated [illegible] [illegible] tubes was [illegible] in [illegible]. This effectively [illegible] [illegible] duced by [illegible] [illegible]. [illegible] number of [illegible] [illegible] was less than [illegible]. This is, [illegible] [illegible] that this [illegible] [illegible] of the [illegible] [illegible] termine the actual number of [illegible].

The [illegible] [illegible] [illegible] [illegible] in [illegible]

$$[illegible]$$

and

$$[illegible]$$

A criticism [illegible] [illegible] type is that a [illegible] in Σ_1 [illegible] one counter [illegible] trating [illegible] used in this [illegible] by this effect.

D. - COLLISION LENGTH OF THE IPSPR IN LEAD AND IN IRON.[12]

Tinlot and Gregory measured the mean free path of the IPSPR in Pb and in Fe using the experimental arrangement of Figure 18. The recorded event was one in which at least one counter in each of Trays A, C, and D, only one counter in Tray B, and no counters in Tray E were discharged. This event was interpreted as a single ionizing particle traversing Σ_1 and Trays A and B, and then creating a shower in the lead separating Trays B and E from Trays C and D. If the shower were produced in the absorber Σ_1, then the count would be discarded because it would be impossible for such a shower to discharge both Trays C and D without discharging more than one counter in Tray B or one in Tray B and one in Tray E. This is also a sufficient condition to eliminate any air showers.

Since the primary particle passed through Tray B, the shower could have been initiated any place between Tray B and Trays C and D. If it were initiated near the top of Σ_2, then the shower would have been a genuine penetrating shower, because the secondaries would have had to penetrate about 4 inches of lead. If, however, the shower were initiated near the bottom of Σ_2, the secondaries would not need to

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[12] Tinlot, J., and Gregory, B., Phys. Rev., 75, 519 (1949).

D. - COLLISION [illegible]

Tinlot and Gregory [illegible] the IPSPR in [illegible] of Figure 16. The [illegible] event [illegible] one counter in each of Trays [illegible] in Tray B, [illegible] event was interpreted [illegible] ing Σ_1 and Trays A and B, and [illegible] lead separating Trays [illegible] shower were produced [illegible] would be discharged [illegible] a shower to discharge [illegible] more than one counter in Tray [illegible] Tray E. This is [illegible] any air showers.

Since the [illegible] the shower could have been [illegible] and Trays C and E. If [illegible] then the shower would have [illegible] because the [illegible] 4 inches of lead. [illegible] near the bottom of [illegible]

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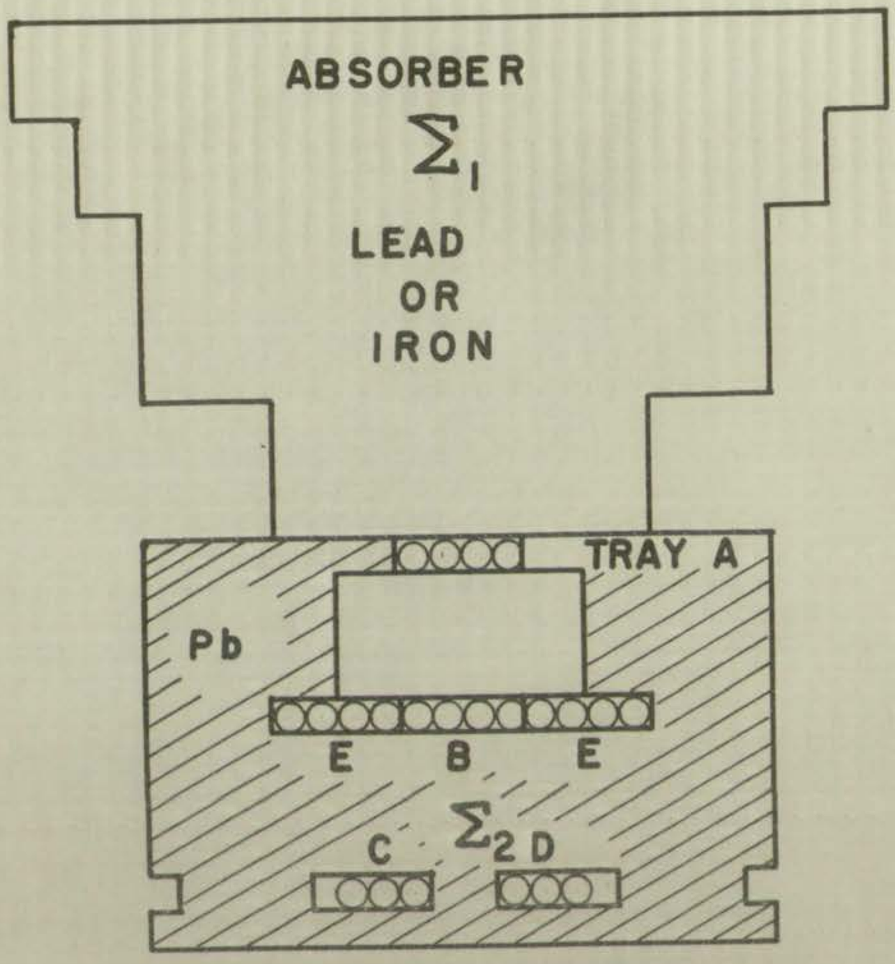
12 Tinlot, [illegible] (1949).



EXPERIMENTAL ARRANGEMENT
OF
TINLOT AND GREGORY

FIGURE 18

have been very penetrating to discharge both Trays C and D. The event recorded in this case may or may not be a penetrating shower. This is a rather serious objection to the validity of this experiment. The two inches of lead separating Trays C and D make it unlikely that any shower recorded was purely electronic in nature, or that the shower consisted of a knock-on particle and an electron shower. This helps to modify the objection to the validity of the experiment. The values for the collision length of the IPSPR presented in this paper are:

$L_c = 310 \text{ g/cm}^2$ where Σ_1 is composed of lead,

and $L_c = 200 \text{ g/cm}^2$ where Σ_1 is composed of iron.

E. - COLLISION LENGTHS OF THE IPSPR IN LEAD, IRON, AND CARBON.[13]

Using the experimental arrangement of Figure 19, Cocconi measured the absorption curve of the IPSPR in Pb, Fe, and C. The tubes in Tray A were all connected in parallel, as were the three tubes in each of Trays B, C, and D. The desired event was one in which Trays A, B, C, and D were discharged along with the discharge of only one tube in Tray E. This event was interpreted as due to a single ionizing particle passing through Σ_1', Tray A, Σ_1, Tray E, and then initiating a shower in Σ_2, the secondaries of which

---

[13] Cocconi, G., Phys. Rev., 75, 1075 (1949)

have been very penetrating [illegible]

The event recorded in this [illegible]

trating shower. [illegible]

validity of this experiment. [illegible]

separating Trays [illegible] it [illegible] that the [illegible]

recorded was purely a [illegible]

shower consisted of [illegible]

shower. This helps [illegible]

of the experiment. The [illegible]

of the [illegible] in [illegible]

L_c = 219 [illegible]

and L_e = [illegible]

E. - COLLISIONS [illegible] DARMONE.[13]

Using the experimental [illegible]

Gonnoni observed [illegible]

Fe, and C. [illegible]

parallel, [illegible]

D. The desired [illegible]

were discovered [illegible]

in Tray B. [illegible]

ionizing particle [illegible]

and then [illegible]

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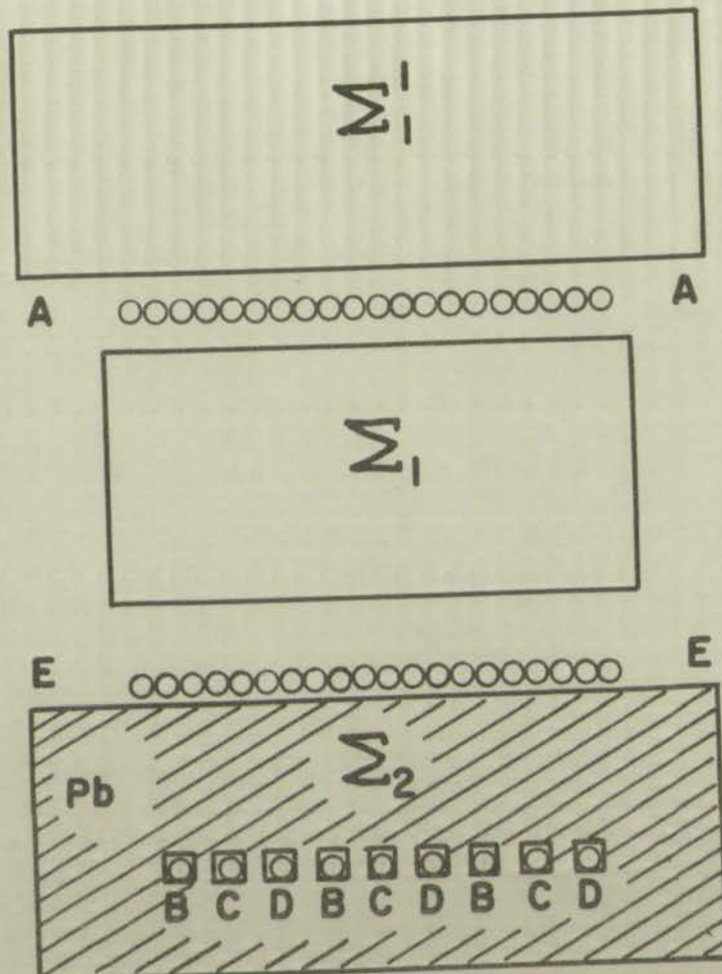
[13] Gonnoni, [illegible]



EXPERIMENTAL ARRANGEMENT
OF
COCCONI

FIGURE 19

would then discharge Trays B, C, and D.

The same criticism applies to this paper as did to the experiment of Tinlot and Gregory. That is, the penetration of the primary particle was well guaranteed, but not the penetrating power of the secondaries. Because of the wider separation of tubes in Trays B, C, and D in this experiment as contrasted with the separation of Trays C and D in the previously described experiment, the necessary penetration of the secondaries was somewhat greater. Therefore, the criticism is not to be taken as seriously as that pertaining to the experiment of Tinlot and Gregory. In this paper an absorption length was measured as a function of the thickness of the absorber, Σ_1' and Σ_1. The initial slope of this curve should be equal to the collision length of the IPSPR, and this is presented as:

$$L_c = 160 \pm 15 \text{ g/cm}^2 \text{ in lead,}$$
$$L_c = 135 \pm 15 \text{ g/cm}^2 \text{ in iron,}$$
and $$L_c = 100 \pm 5 \text{ g/cm}^2 \text{ in carbon.}$$

F. - COLLISION LENGTH OF THE IPSPR IN GOLD.[14]

Utilizing the combination counter tube and cloud chamber arrangement of Figure 20, Gottlieb investigated the

[14] Gottlieb, N. B., Phys. Rev., <u>82</u>, 349 (1951)

would then disappear [illegible]

The [illegible] of [illegible] the [illegible]

the experiments [illegible]

tion of the [illegible]

the penetrating [illegible]

which penetration [illegible]

pertinent [illegible]

in the proximity [illegible]

tration of [illegible]

the critical [illegible]

taining to the [illegible]

paper an absorption [illegible]

the thickness of the absorber, [illegible]

of this curve should be equal to the collision length of

the [illegible], and this is [illegible]

[illegible]

[illegible]

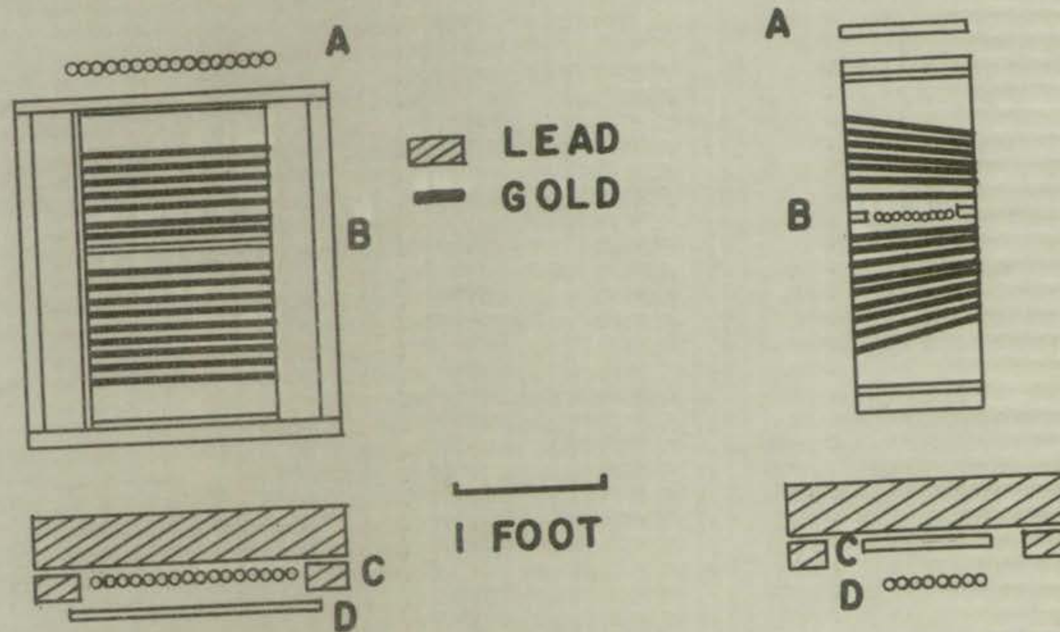
and [illegible]

F. - COLLISION LENGTH OF THE [illegible]

Utilizing the [illegible]

chamber arrangement of Figure [illegible]

[illegible], Phys. Rev., [illegible]



EXPERIMENTAL APPARATUS OF GOTTLIEB

FIGURE 20

collision length of the IPSPR in gold. As shown in the diagram, most of the plates were composed of gold. The required event was one in which an ionizing particle entered the chamber and created a shower in one of the gold plates. The secondary particles had to be sufficiently penetrating so that at least three tubes in Tray C were discharged along with one tube in Tray D. Since photographs were taken of each event, there should be little error for which compensation cannot be made. Gottlieb calculated all the errors, then added a certain amount to the statistical error in his determination of the collision length. The value which is presented in this paper should, therefore, be quite acceptable. This value is:

$$L_c = 145 \pm 15 \text{ g/cm}^2 \text{ in gold.}$$

In addition to this, the flux of particles entering the chamber that were capable of initiating high energy events in lead was compared with the flux of primary protons at the top of the atmosphere. From this, a value was computed for the absorption length in air of the particles that are capable of producing high energy events in lead. This value is:

$$\lambda_{air} = 77 \pm 5 \text{ g/cm}^2.$$

This value is not very reliable because not only protons, but also pi mesons are capable of producing high energy events in lead.

collision length of the [illegible] in [illegible] the [illegible]
diagram, most of the [illegible]
required event [illegible] the [illegible] of the
the chamber and [illegible] in [illegible]
The secondary [illegible]
so that at [illegible]
with one [illegible] (2) [illegible]
each event, there should [illegible]
pensation [illegible] errors,
errors, [illegible] in [illegible] error [illegible]
in his distribution [illegible] (4). [illegible]
which is [illegible] be
quite acceptable. [illegible]

[illegible]

In addition [illegible]
the chamber [illegible]
events in lead [illegible]
at the top of the [illegible]
puted for the [illegible]
are capable of [illegible]
value for

λ [illegible] + [illegible]

This value is not very reliable [illegible]
but also of [illegible]
events in lead.

G. - COLLISION LENGTH OF THE IPSPR IN LEAD AS A FUNCTION OF ENERGY.[15]

In 1949, Walker determined the mean free path in lead of the IPSPR as a function of energy using the experimental arrangement of Figure 21. The energies of the primary particles were not measured directly, but it was assumed that the showers of many penetrating particles were made by primaries of very high energy, while showers of fewer penetrating particles were initiated by primaries of lower energy. Absorber I was composed of four inches of lead, Absorber III was composed of eight inches of lead, and the thickness of lead in Absorber II was varied from zero to eight inches. A recorded event was one in which an ionizing particle passed through Absorbers I and II and initiated a penetrating shower in Absorber III. This means that only one tube in each of Trays A and B were discharged, no tubes in AS (air shower detector) were discharged, and N tubes in Tray C were discharged. After having subtracted the background, the curves of Figure 22 were presented as the results.

Thus, it would seem that as the energy of the primary particle increases, the mean free path decreases. Since nothing was said about the number of tubes discharged in

---

[15] Walker, W. D., Phys. Rev., 77, 686 (1950)

C. - COLLISION LENGTH [illegible] OF [illegible] PARTICLES [illegible] OF ENERGY.

In 1949, [illegible] of the IPSRS as a function of [illegible] arrangement of Figure 14. [illegible] particles were not [illegible] that the showers of [illegible] primaries of very high energy [illegible] trating particles [illegible] Absorber I was [illegible] was composed of [illegible] lead in Absorber II [illegible] A recorded event was [illegible] through Absorber I [illegible] in Absorber III. [illegible] Trays A and B [illegible] detector) [illegible] charged. After [illegible] of Figure 24 [illegible].

Thus, it [illegible] particle increase [illegible] nothing was said about [illegible]

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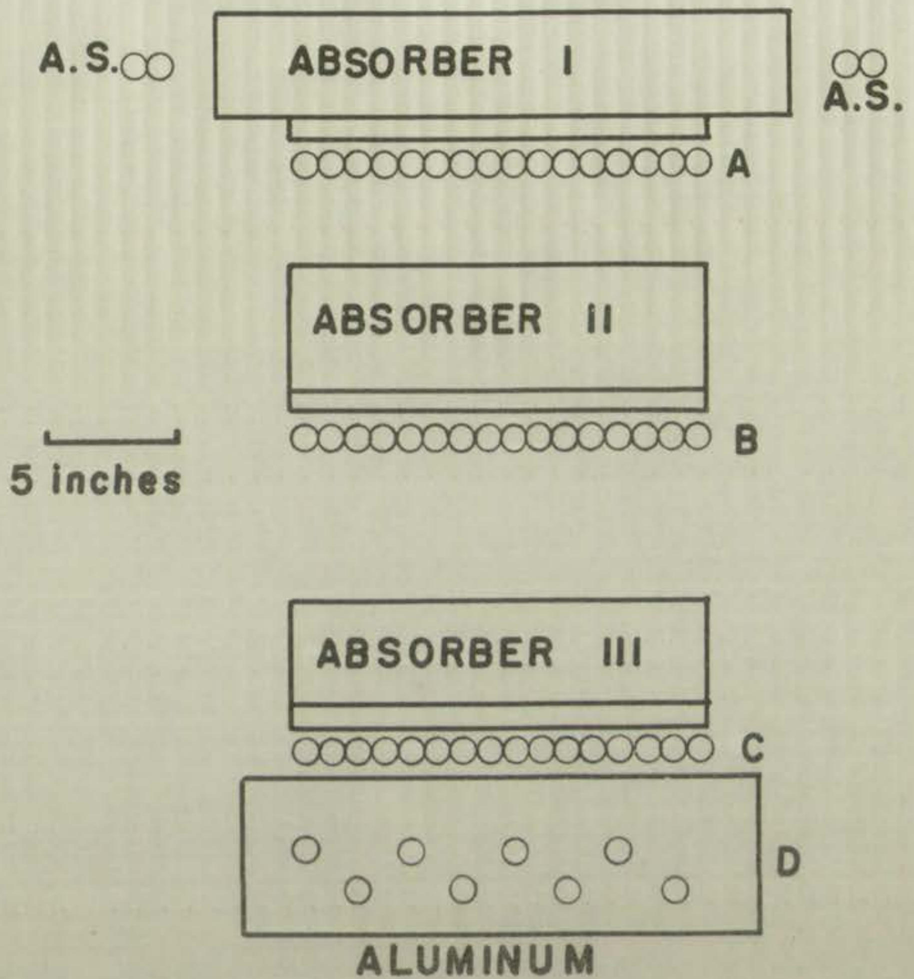
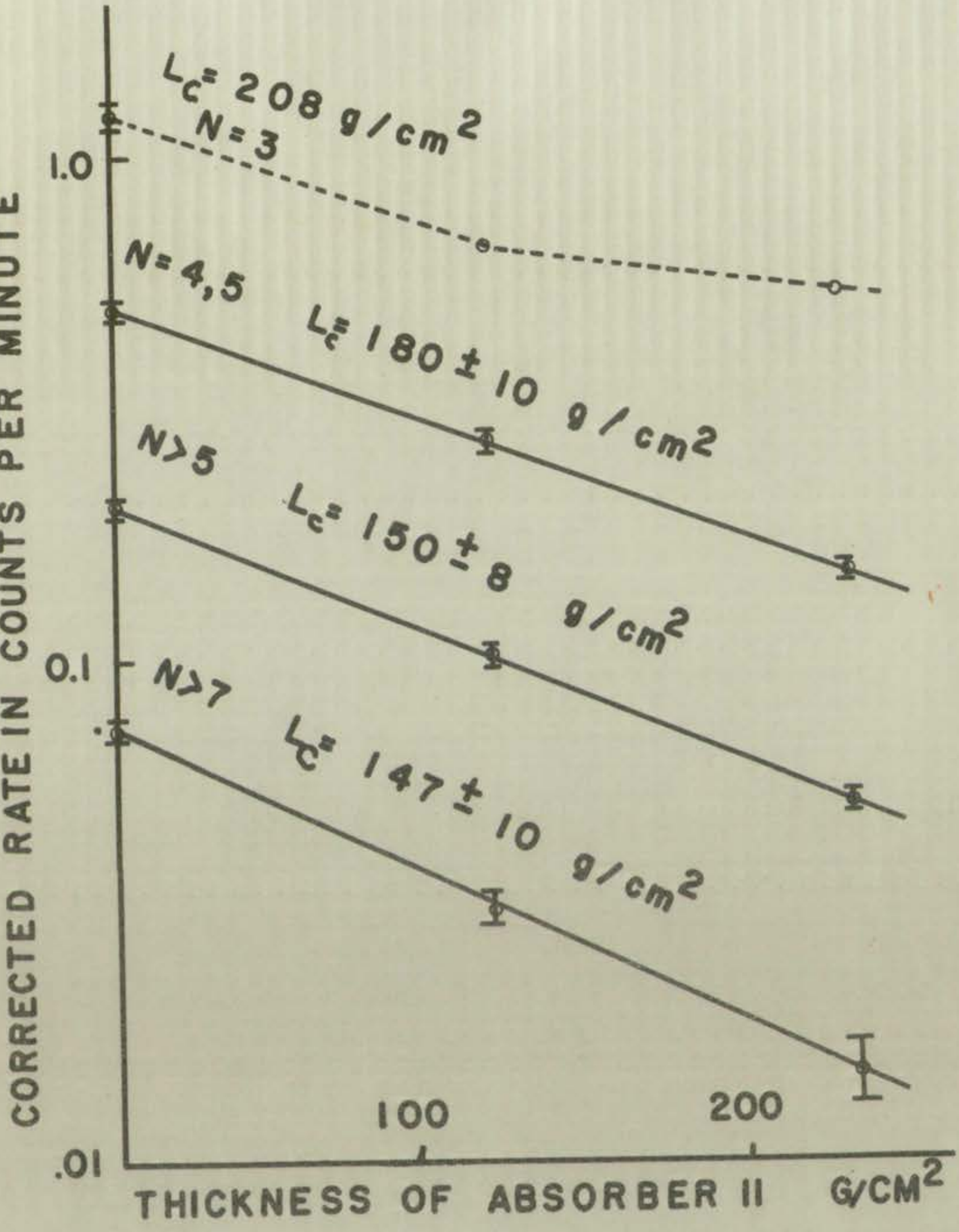
[15] Walker, W. D., Phys. Rev., [illegible]



EXPERIMENTAL ARRANGEMENT
OF
WALKER

FIGURE 21



DEPENDENCE OF COLLISION LENGTH ON ENERGY

FIGURE 22

Tray D, the penetration of the secondary particles may not have been guaranteed. However, because of the large number of tubes discharged in Tray C, it seems likely that in the two cases of $N > 5$, and $N > 7$, the mean free path is actually the collision length for the IPSPR in lead. These two values are:

$$L_c = 150 \pm 8 \text{ g/cm}^2 \text{ in lead for } N > 5,$$

and

$$L_c = 147 \pm 10 \text{ g/cm}^2 \text{ in lead for } N > 7.$$

A measurement of the zenith angle dependence of the primary radiation was determined to be $\cos^7 \theta$. From this, using the method of Greisen[16], the absorption length of the primary particles in air was calculated to be:

$$\lambda_{air} = 100 \text{ g/cm}^2.$$

H. - COLLISION LENGTHS IN LEAD AND CARBON FOR THE IPSPR AND THE NPSPR.[17]

Using the experimental arrangement of Figure 23, Walker, Walker and Greisen measured the collision lengths in lead and carbon for both the IPSPR and the NPSPR.

It was required that no more than one counter in Tray A_1, no more than one counter in Tray A_2, and at least two counters in each of Trays B, C, and D be in coincidence, and that this event be in anticoincidence with the unshielded

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16 Greisen, K. I., Phys. Rev., 61, 212 (1942)

17 Walker, W. D., Walker, S. P., and Greisen, I. I., Phys. Rev., 80 546 (1950)

Tray D, the penetration of the [illegible]

have been [illegible]

of tubes illustrated in Tray A, [illegible]

two cases of E > 5, and E > [illegible]

the collision [illegible]

values are:

and [illegible]

A new [illegible] of [illegible]

primary radiation [illegible]

using the method [illegible]

primary particles is [illegible]

E. - COLLISION [illegible]
THE [illegible]

Using the [illegible]

Walker, Walker and [illegible]

in lead and carbon [illegible]

It was [illegible] that [illegible]

Tray A_1, no more than [illegible]

two counters [illegible] of Tray [illegible]

and that [illegible]

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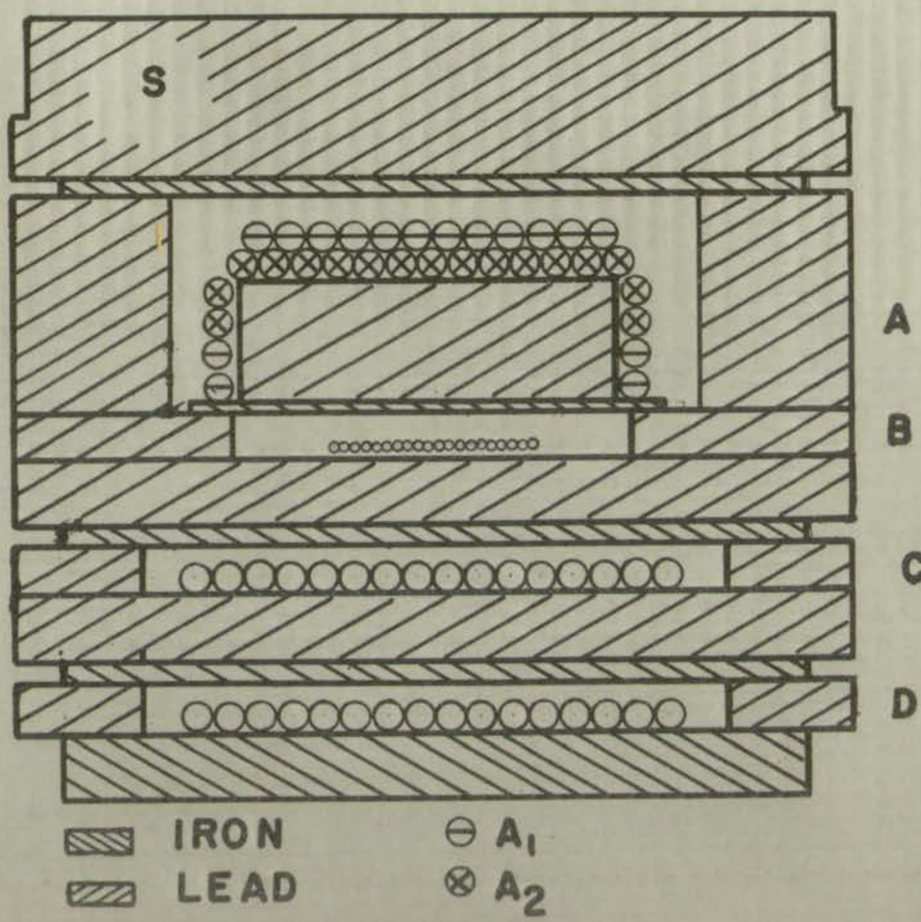
[24] [illegible], [illegible] Phys. [illegible]

[25] Walker, [illegible]

Phys. Rev., [illegible]



EXPERIMENTAL ARRANGEMENT
OF
WALKER WALKER AND GREISEN

FIGURE 23

air shower detector (not shown in the figure). Part of the time it was required that no tube in either Tray A_1 or Tray A_2 be discharged. The first case corresponds to an IPS event, and the latter to an NPS event. The apparatus was operated with various thicknesses of lead or carbon in the Absorber S. This should give the collision lengths of both the NPSPR and the IPSPR in lead and carbon.

The experiment is certainly valid for the collision length of the NPSPR, but there is an objection to the validity of the measurement of the IPSPR collision length. It is entirely possible that either a neutral particle or a charged particle could create a "collimated" shower in the Absorber S immediately above Trays A_1 and A_2. This would then be registered as an IPS event, and there would be an error introduced into the determination of the collision length of the IPSPR. However, since the tubes in Trays A_1 and A_2 were only one inch in diameter, and since they partially overlapped one another, it seems unlikely that many such showers were recorded. It is interesting to note that the collision lengths for both the neutral and the ionizing particles is the same within the statistical error of the experiment. The values presented are:

$L_c = 164 \pm 15$ g/cm^2 for neutral particles in lead,

$L_c = 157 \pm 12$ g/cm^2 for ionizing particles in lead,

$L_c = 80 \pm 7$ g/cm^2 for neutral particles in carbon,

and $L_c = 82 \pm 8$ g/cm^2 for ionizing particles in carbon.

air shower behavior (not shown in the figure). [illegible] thus it was required that [illegible] A_2 be discharged. [illegible] event, and [illegible] operated with various [illegible] Absorber S. This should [illegible] coincidence [illegible] the WPCCR and the [illegible].

The [illegible] is [illegible] length of the WPCCR, [illegible] of the measurement of the [illegible] tively possible that [illegible] particle could [illegible] C immediately above A_1 and A_2. This [illegible] registered [illegible] troduced into [illegible] the WPCCR. [illegible] were only [illegible] overlapped [illegible] showers were [illegible] collision length [illegible] particles [illegible] experiment. The [illegible]

[illegible]

and [illegible]

I. - COLLISION LENGTHS OF THE NPSPR IN LEAD AND IN CARBON.[18]

Using the experimental arrangement of Figure 24, Boehmer and Bridge investigated the collision lengths of the NPSPR in both carbon and lead. The theory and method of this experiment is again based on the Rossi-Regener method. The counters in Tray A were connected in parallel, as were the counters in each of Trays C and D. The counters in each of Trays B and E were connected to addition circuits so that the actual number of counters discharged in each of these trays was recorded for each event. Tray A was in anticoincidence. In order to discriminate against all air showers, Tray F was included to reject all events in which one or more tubes in Tray F were discharged. The efficiency of Tray A was about 99.5%, and there was no correction necessary for the small inefficiency.

For events of high multiplicity (many counters in Trays B and E discharged), which would correspond to very energetic primaries, the observed collision lengths were:

$$L_c = 143 \pm 30 \text{ g/cm}^2 \text{ for lead,}$$

and $$L_c = 85 \pm 12 \text{ g/cm}^2 \text{ for carbon.}$$

In discussing the apparent dependence of the collision length on the energy of the primary particle, the authors

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[18] Boehmer, H. W., and Bridge, H. S., op. cit.

I. - COLLISION LENGTHS [illegible]

Using the [illegible] arrangement [illegible], Boehmer and [illegible] investigated the [illegible] the EPSPR in [illegible] of this experiment [illegible]. The counters in [illegible] the counters in [illegible] of Trays [illegible] each of Trays [illegible] so that the actual number of [illegible] these trays was [illegible] anticoincidence. [illegible] showers, Tray [illegible] one or more tubes in [illegible] of Tray [illegible] was about [illegible] necessary for the [illegible].

For results of [illegible] Trays 2 and 3 [illegible] energetic primaries, the [illegible] were

$l_g = 1?? \pm$ [illegible] for [illegible],

and $l_g = 3? \pm$ [illegible].

In discussing the [illegible] length on the energy of the primary particle, the [illegible]

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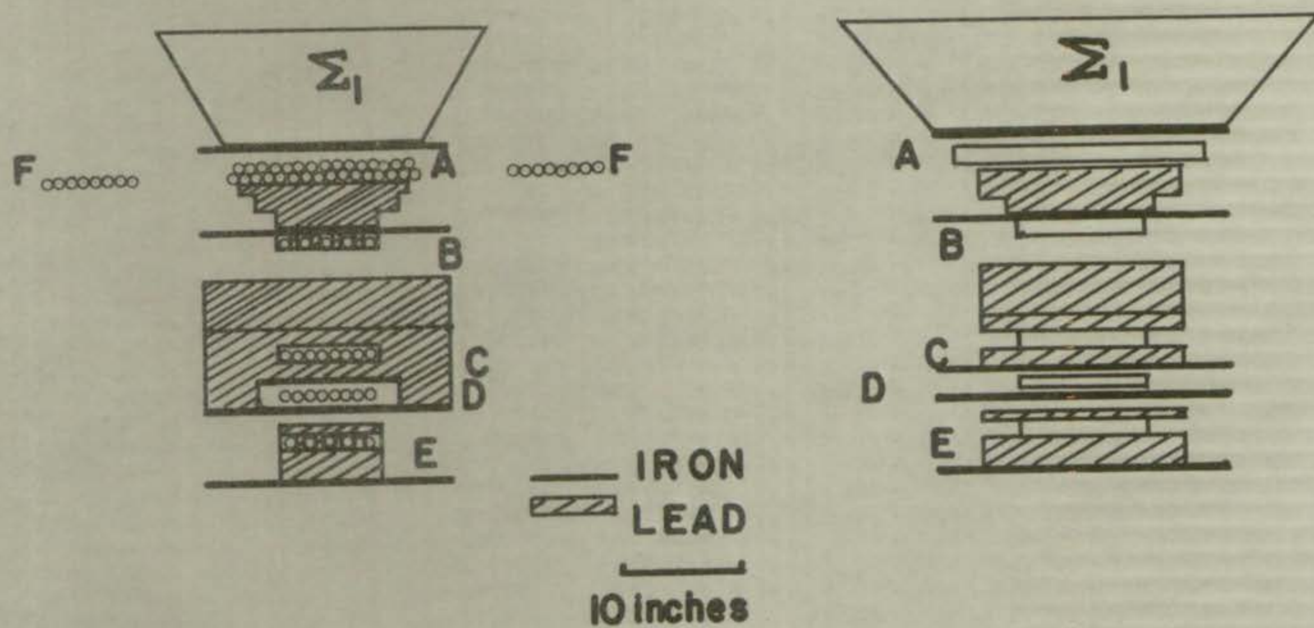
18 Boehmer, [illegible]



EXPERIMENTAL ARRANGEMENT
OF
BOEHMER AND BRIDGE

FIGURE 24

state:

> Thus the results, if taken at face value, would indicate that the mean free path decreases as the energy of the particle producing the nuclear interaction increases. It is important to notice, however, that this effect may be of an instrumental character. For example, a high energy neutron on traversing the absorber Σ_1 may undergo a nuclear interaction in which it loses only a small amount of energy and produces a few low energy charged particles. The charged particles may be stopped by ionization loss before they reach the anticoincidence tray A, while the neutron may go on to produce another nuclear interaction in the material below A. The occurrence of events such as the one described above would make the observed mean free path longer than the actual mean free path. It is reasonable to assume that this source of error is more effective at low neutron energies because, as the energy of the neutron increases, the penetration of the secondary charged particles produced in its nuclear interactions also increases. Thus, the effect described may possibly explain the energy dependence of the observed mean free paths.

In view of this, the values for the collision lengths which will be considered the most valid are those in which the greatest multiplicity is demanded. As mentioned previously, these are:

$$L_c = 143 \pm 30 \text{ g/cm}^2 \text{ in lead,}$$

and $$L_c = 85 \pm 12 \text{ g/cm}^2 \text{ in carbon.}$$

J. - COLLISION LENGTHS OF THE IPSPR IN CARBON, SULPHUR, AND IRON.[19]

Using the experimental arrangement of Figure 25,

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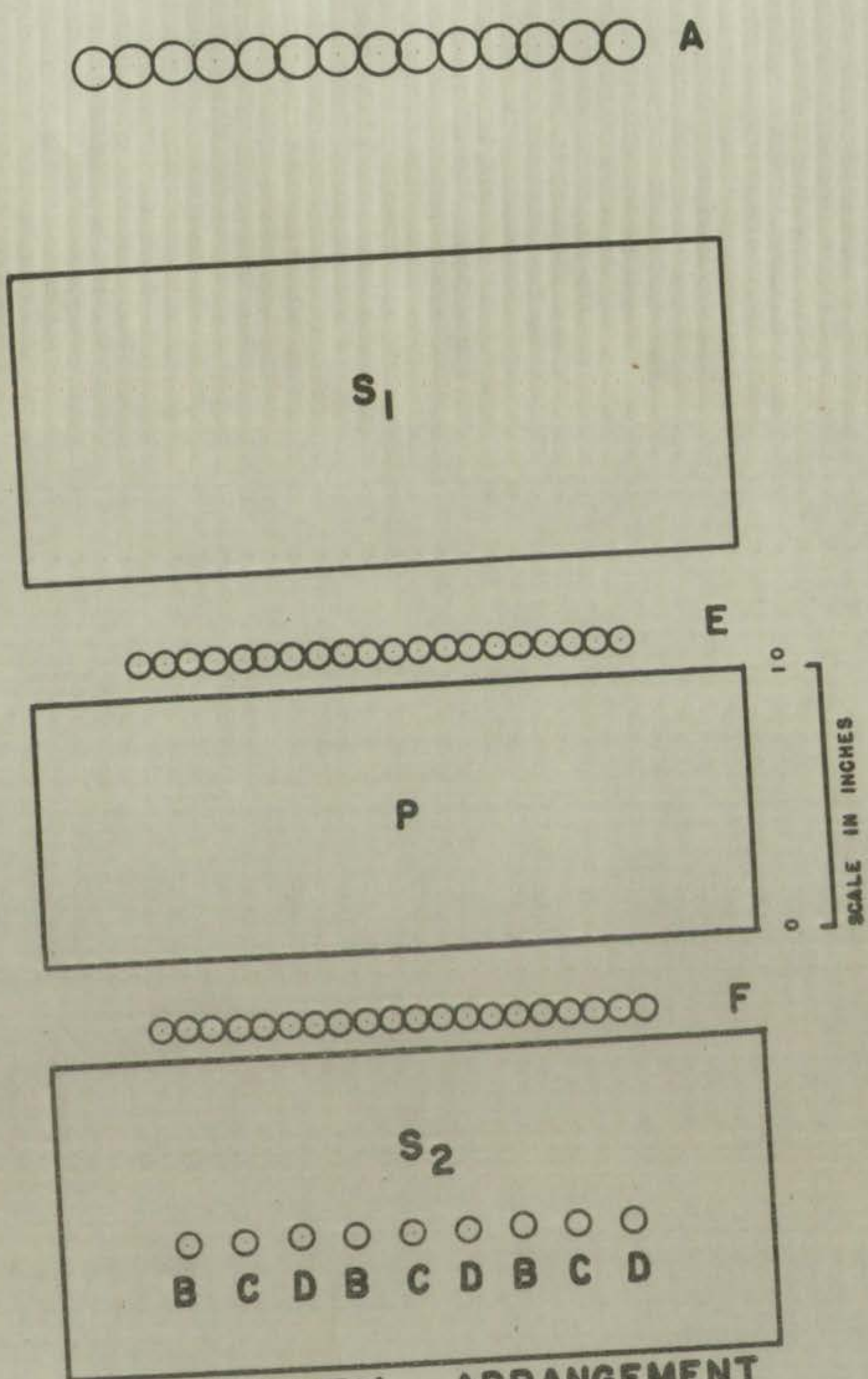
[19] Brown, R. R., Phys. Rev., 87, 999 (1952)



EXPERIMENTAL ARRANGEMENT
of
BROWN
FIGURE 25

Brown has investigated the collision length of the IPSPR in carbon, sulphur, and iron at an altitude of 2,765 m. The desired event was one in which an incident ionizing particle created a penetrating shower in P. The minimum requirement for a master pulse was that a counter in each of Trays A, B, C, and D be discharged. The further requirement that only one counter in hodoscope tray E, and at least three counters in hodoscope tray F be discharged ensured that the shower was initiated in the producer P. The producer, P, was composed of 38 g/cm^2 of graphite, while S_2 was composed of 170 g/cm^2 of lead. The nature and amount of absorber in S_1 was varied. For a part of the time, the experiment was conducted at an altitude of 130 m with S_1 composed of carbon. From the difference in counting rates at the two altitudes, an absorption length in air of the IPSPR was determined to be:

$$\lambda_{air} = 132 \pm 17 \text{ g/cm}^2.$$

The values for the collision lengths of the IPSPR were determined to be as follows:

At 130 m, $L_c = 89 \pm 12$ g/cm^2 in carbon.

At 2,765 m, $L_c = 65 \pm 5$ g/cm^2 in carbon,

$L_c = 76 \pm 7$ g/cm^2 in sulphur,

and $L_c = 115 \pm 12$ g/cm^2 in iron.

Brown has investigated [illegible]

in carbon, [illegible]

The desired [illegible]

particle [illegible]

requirement [illegible]

of Table A, [illegible]

ment that [illegible]

least [illegible]

ensure that [illegible]

The product [illegible]

while [illegible]

and about [illegible]

the time, [illegible]

130 x with [illegible]

counting rate [illegible]

eff of the [illegible] to be

λ_{eff} = 132 + 17 = [illegible]

The values for the calculated [illegible]

were determined to be [illegible]

At 130 e,

L_0 = [illegible]

At 2,765 e,

[illegible]

and [illegible]

The change in collision length at the two altitudes seems to suggest a dependence of the collision length on the energy of the primary particle. The author cautioned that there may be an additional error in the measurement of the collision length in sulphur. This is due to inability to measure accurately the thickness of the uneven sulphur blocks used.

A further criticism of this paper is to be found in the selection of events. As has been stated previously, it is very difficult to measure unambiguously the collision length of an ionizing particle. A possible event that would have been recorded on this equipment is the creation in the lower part of P of an electronic shower. This, if followed by a nuclear event in S_2, could simulate a penetrating shower, even though the penetration of the secondaries has not been guaranteed.

K. - COLLISION LENGTHS OF THE PSPR IN LEAD, ALUMINUM, AND PARAFFIN.[20]

The experimental arrangement of Figure 26 was used by George and Jason to obtain the collision length of the PSPR in several materials. The three main trays of tubes were di-

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[20] George, E. P., and Jason, A. C., Proc. Phys. Soc. London, A63, 1081 (1950).

The change in collision length of the two distinct seems to suggest a dependence of the collision length on the energy of the primary particle. The author realizes that there may be an additional error in the measurement of the collision length in sulphur. This is due to inability to measure accurately the thickness of the uneven sulphur blocks used.

A further criticism of this paper is to be found in the selection of events. As has been pointed out previously, it is very difficult to measure unambiguously a collision length of an ionizing particle. A possible event that could have been recorded on this equipment is the ejection in the lower part of P of an electronic shower. This, if followed by a nuclear event in G_2, could simulate a penetrating shower even though the penetration of the secondaries has not been guaranteed.

K. - COLLISION LENGTHS OF PENETRATING PARTICLES IN LEAD, ALUMINUM, AND PARAFFIN.[29]

The experimental arrangement of Figure 30 was used by George and Jason to obtain the collision lengths of the particles in several materials. The three main trays of counters were six

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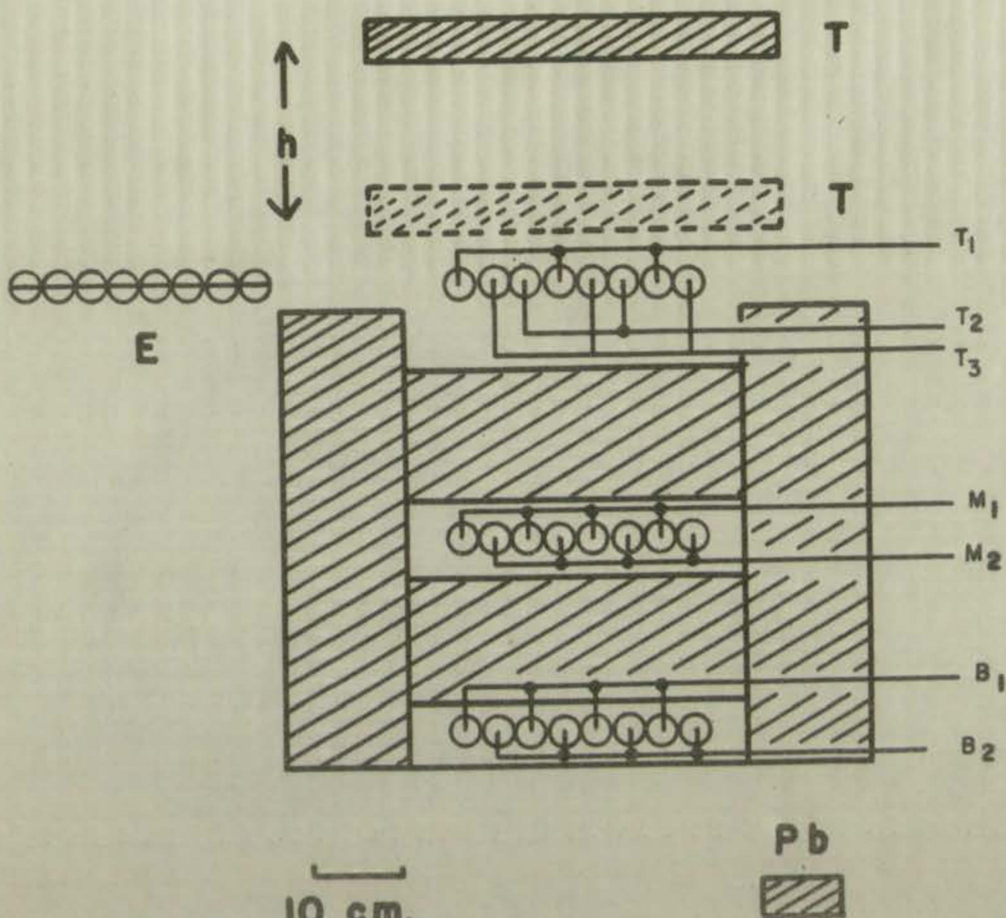
[29] George, E. P., and Jason, A. C., Proc. Phys. Soc. London, A63, 1081 (1950).



EXPERIMENTAL ARRANGEMENT
OF
GEORGE AND JASON

FIGURE 26

vided into seven sets as shown in Figure 26. A coincidence of at least one tube in each of the seven sets accompanied by no discharge from the tubes in the air shower detector was used to define a local penetrating shower produced in the upper absorber. By the transition difference, collision lengths in the upper absorber were measured. Using lead in the upper absorber, the equipment was operated at sea level and at 3,457 m altitude. The values for the collision length in lead were averaged for the two altitudes, and the result was:

$$L_c = 180 \pm 40 \text{ g/cm}^2 \text{ in lead.}$$

The values obtained at an altitude of 3,457 m for aluminum and for paraffin were:

$$L_c = 85 \pm 15 \text{ g/cm}^2 \text{ in aluminum,}$$

and $$L_c = 80 \text{ g/cm}^2 \text{ in paraffin.}$$

With this type of equipment, either a neutral particle or an ionizing particle could create a penetrating shower in the upper absorber that would register as an event. It is the feeling of this author that an inadequate protection against air showers was established.

In addition to the above experiments, several experiments have been performed by various groups which measured absorption or collision lengths, but not with sufficient accuracy to warrant a full description here. Therefore, a very brief statement of the results of these experiments will

be presented along with references to the original articles or letters.

L. - W. B. Fretter[21] measured the frequency of occurrence, the multiplicity, and the angular distribution of penetrating showers produced in lead at both sea level and 3,027 m. From these data, there was obtained a value of approximately 170 g/cm^2 for the collision length of the IPSPR in lead, and an absorption length of the IPSPR in air of 123 ± 10 g/cm^2.

M. - In an investigation of the correlation of local penetrating showers with air showers at various altitudes, Tinlot[22] derived an absorption length of the IPSPR in air of 118 ± 2 g/cm^2. For purposes of this calculation, there was no distinction made between local penetrating showers and air showers. There was also no correction made for inclination of the primary particle from the zenith.

N. - While investigating the latitude effect of the IPSPR at two altitudes, Walsh and Piccioni[23] obtained a value for the absorption length in air of the IPSPR. The value obtained

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[21] Fretter, W. B., Phys. Rev., 76, 511 (1949)

[22] Tinlot, J., Phys. Rev., 74, 1197 (1948)

[23] Walsh, W. D., and Piccioni, O., Phys. Rev., 80, 546 (1950)

be presented along with references to the original articles or letters.

L. - W. B. Fretter[21] measured the frequency of occurrence, the multiplicity, and the angular distribution of penetrating showers produced in lead at both sea level and 3,050 m. From these data, there was obtained a value of approximately 172 g/cm² for the collision length of the IPSPR in lead, and an absorption length of the IPSPR in air of 123 ± 10 g/cm².

M. - In an investigation of the correlation of local penetrating showers with air showers at various altitudes, Tinlot[22] derived an absorption length of the IPSPR in air of 118 ± 2 g/cm². For purposes of this calculation, there was no distinction made between local penetrating showers and air showers. There was also no correction made for inclination of the primary particle from the zenith.

N. - While investigating the latitude effect of the IPSPR at two altitudes, Walsh and Piccioni[23] obtained a value for the absorption length in air of the IPSPR. This value obtained

---

[21] Fretter, W. B., Phys. Rev., 76, 511 (1949)

[22] Tinlot, J., Phys. Rev., 74, 1197 (1948)

[23] Walsh, T. G., and Piccioni, O., Phys. Rev., 80, 546 (1950)

was 112 - 2 g/cm^2. An estimated correction for inclination of the primary particles was made by the authors, and the final result presented was about 140 g/cm^2.

O. - An investigation of the absorption of the N-component of the cosmic radiation using counter tubes and ionization chambers was carried out by Bridge and Rediker[24] at two altitudes. From a comparison of the counting rates at the two altitudes, a value was derived for the absorption length of the ionizing N-component of the cosmic radiation in air. This value is 119 $\pm$ 5 g/cm^2.

P. - Using equipment very similar to that of George and Jason at airplane altitudes, Hodson[25] obtained data on the absorption length for the IPSPR in air. The notation and experimental arrangement used by Hodson is the same as that used by George and Jason. Therefore, the reader is referred to Figure 26 and the paper of George and Jason for the proper notation. The absorption length in air was determined as follows: $\lambda_{air} = 126 \pm 2$ g/cm^2 for a P-E event with no lead, and $\lambda_{air} = 130 \pm 1.3$ g/cm^2 for a P-E event with 10 cm Pb absorber; and from the transition difference,

$$\lambda_{air} = 132 \pm 3.5 \text{ g/cm}^2.$$

An estimated best value is listed as 129 - 2 g/cm^2.

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[24] Bridge, H. S., and Rediker, R. H., Phys. Rev., 88, 206 (1952)

[25] Hodson, A. L., Proc. Roy. Soc., 65, 702 (19520

was 112 - 1 [illegible]. [illegible]
of the primary [illegible]
final result [illegible]

9. - An investigation [illegible]
of the counts [illegible]
chambers was [illegible]
tubes. From a [illegible]
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the ionizing [illegible]
This value is 113 ± [illegible]

P. - Using equipment [illegible]
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tion length for [illegible]
mental [illegible]
by [illegible]
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neutrons. The [illegible]
follows:

λ_{air} = [illegible]

and λ [illegible]

Pb absorbent and [illegible]

λ_{air} [illegible]

An estimate [illegible]

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206 (1952) [illegible]

Q. - Using a cloud chamber, Chang et al[26] investigated the penetrating showers produced by ionizing particles in beryllium. The definition of a penetrating shower used by the authors was not very rigid. This, coupled with the fact that there were not enough events recorded to give a very good statistical error, places the experimental value of the collision length in beryllium of the IPSPR in some doubt. However, since it is the only piece of data available on beryllium, the value, as presented by the authors, is listed below:

$$L_c = 85 \text{ g/cm}^2 \text{ in beryllium.}$$

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[26] Chang, W. Y., del Castillo, G., and Grodzins, L., Phys. Rev., 84, 582 (1951)

9. - Using a [illegible] penetrating [illegible] beryllium. The [illegible] by the authors was not [illegible] fact that [illegible] very good [illegible] of the collision [illegible] doubt. However, since [illegible] able on beryllium, the [illegible] is listed below:

l_e = [illegible]

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26 Cooper, [illegible] L., Phys. Rev. [illegible]

CHAPTER IV

DATA AND CALCULATIONS

The results of all of the experiments described in Chapters II and III are tabulated in Table III. The purpose of the next part of this paper is to obtain the best value for the collision length of the penetrating-shower-producing radiation in the various substances. As has been pointed out in Chapter III, some of these experiments were conducted under conditions that were favorable to the inclusion of a systematic error. It is also apparent from Table III, in the case of the absorption length in air, and in the cases of the collision lengths in lead and in carbon, that the external consistency of the data does not permit the probable error of the most probable value to be based merely on the statistical error shown by the internal consistency of the data. In certain papers, described in Chapter III, where this author has suspected the inclusion of a systematic error, he has changed the value of the error presented. The reasons for the systematic errors have already been pointed out in Chapter III, and the reader is referred to these discussions in the cases in which the error value has been changed. The errors were not reliable as originally given, and were therefore increased by

TABLE III

COLLISION LENGTH DATA

DATA POINT	REFER-ENCE	TYPE OF PRIMARY	ABSORBER	COLLISION LENGTH (g/cm²)
1	9	neutral	air*	115 ± 19
2	10	neutral		104 ± 6
3	15	ionizing		100
4	19	ionizing		132 ± 17
5	21	ionizing		123 ± 10
6	22	ionizing		118 ± 2
7	23	ionizing		140
8	24	ionizing		119 ± 5
9	25	ionizing		129 ± 2
10	26	ionizing	beryllium	85
11	13	ionizing	carbon	100 ± 5
12	17	neutral		80 ± 7
13	17	ionizing		82 ± 8
14	18	neutral		85 ± 12
15	19	ionizing		89 ± 12
16	19	ionizing		65 ± 5
17	10	neutral	paraffin	61 ± 6
18	10	neutral		75 ± 19
19	20	mixed		80
20	9	neutral	water	98 ± 13
21	4	neutral		113 ± 10
22	4	neutral	heavy water	123 ± 10
23	20	mixed	aluminum	85 ± 15
24	18	ionizing	sulphur	76 ± 7
25	12	ionizing	iron	200
26	13	ionizing		135 ± 15
27	19	ionizing		115 ± 12
28	14	ionizing	gold	145 ± 15
29	11	ionizing	lead	162 ± 10
30	11	ionizing		196 ± 13
31	12	ionizing		310
32	13	ionizing		160 ± 15
33	15	ionizing		150 ± 8
34	15	ionizing		147 ± 10
35	17	neutral		164 ± 15
36	17	ionizing		157 ± 12
37	18	neutral		143 ± 30
38	20	mixed		180 ± 40
39	21	ionizing		170

* In air the absorption length has been measured, not the collision length.

an amount which this author felt would take account of the systematic error in the experiment. The changes that were made are listed below. The data point number refers to the order in which these data are presented in Table III.

DATA POINT	VALUE PRESENTED g/cm^2	VALUE ACCEPTED g/cm^2
6	118 ± 2	118 ± 8
13	82 ± 8	82 ± 10
15	89 ± 12	89 ± 15
16	65 ± 5	65 ± 8
17	61 ± 6	61 ± 8
23	85 ± 15	85 ± 18
24	76 ± 7	76 ± 12
27	115 ± 12	115 ± 15

It is also apparent from the consistency of the accepted data, and in particular from the results of Walker, Walker, and Greisen, that there is no significant difference existing in the measurement of the collision lengths for neutral or ionizing primary particles. In view of this, the data that were actually used for a calculation of the collision length in the various materials are listed in Table IV.

In the cases of lead and carbon, where there are

TABLE IV

SELECTED COLLISION LENGTH DATA

DATA POINT	REFERENCE	MATERIAL	COLLISION LENGTH (g/cm^2)
1	9	air*	115 ± 19
2	10		104 ± 6
5	21		123 ± 10
6	22		118 ± 8
8	24		119 ± 5
9	25		129 ± 2
10	26	beryllium	85
11	13	carbon	100 ± 5
12	17		80 ± 7
13	17		82 ± 10
14	18		85 ± 12
15	19		89 ± 15
16	19		65 ± 8
17	10	paraffin	61 ± 6
18	10		75 ± 19
20	9	water	98 ± 13
21	4		113 ± 10
22	4	heavy water	123 ± 10
23	20	aluminum	85 ± 18
24	18	sulphur	76 ± 12
26	13	iron	135 ± 15
27	19		115 ± 15
28	11	gold	145 ± 15
29	11	lead	162 ± 10
30	11		196 ± 13
32	13		160 ± 13
33	15		150 ± 8
34	15		147 ± 10
35	17		164 ± 15
36	17		157 ± 12
37	18		143 ± 30
38	20		180 ± 40

* In air the absorption length has been measured, not the collision length.

more than two values given in the original data, the best values for the collision lengths are:

$$L_c = 87 \pm 3 \text{ in carbon,}$$

and
$$L_c = 160 \pm 4 \text{ in lead,}$$

provided that the errors are calculated from the data in Table IV on the basis of internal consistency.[27] Likewise, the best value for the absorption length in air is:

$$\lambda_{air} = 124 \pm 3 \text{ g/cm}^2.$$

If these results are determined in such a manner that one computes the errors on the basis of the external consistency[28] of the data presented in Table IV, the best values are:

$$L_c = 87 \pm 4 \text{ g/cm}^2 \text{ in carbon,}$$
$$L_c = 160 \pm 5 \text{ g/cm}^2 \text{ in lead,}$$

and
$$\lambda_{air} = 124 \pm 4 \text{ g/cm}^2 \text{ in air.}$$

From equation (1), $L_c = m/\sigma$ g/cm^2, one can obtain the cross section associated with each collision length. If one also assumes that a cross section is given by $\sigma = \pi R^2$* one can obtain from these cross sections the best experimental values for the nuclear radii, R. In order to determine the mass of a molecule of a substance, where the substance

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[27] Birge, R. T., Phys. Rev., 40, 207, (1932)

[28] Loc. cit.

* This concept will be discussed further in Chapter VI.

more than one [illegible]

values for the [illegible]

$$[illegible]$$

and [illegible] = [illegible]

provided that the weight and [illegible]

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the best value [illegible]

$$\lambda = [illegible]$$

If these [illegible] are determined in [illegible]

one compares the [illegible] of a plot of [illegible] tendency[26] of the data [illegible]

area

$$[illegible]$$

and λ [illegible]

From equation [illegible]

the cross section [illegible]

one also notes that [illegible]

one can [illegible]

values for [illegible]

the mass of [illegible]

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27 [illegible]

28 Ibid.

[illegible]

is a mixture, one may average over the composition of the mixture. Thus for air, which is composed of approximately 21% oxygen and 79% nitrogen, one may assume that the mixture is equivalent to a molecular substance having a formula of (0.79 N + 0.21 O). This is possible because in any high energy nuclear reaction, chemical binding energies are negligible. The mass of such a molecule would be 23.9 x 10^{-24} g. The final value of the collision length, the associated cross section, and the nuclear radius for each substance is given in Table V. In the case of poly-atomic molecules, the nuclear radius is the radius which a hypothetical nucleus would have if the cross section of the nucleus were equal to the sum of the cross sections of the nuclei composing the molecule.

is a mixture, one may [illegible]
mixture. Thus for [illegible]
21% oxygen and 79% [illegible]
is equivalent to a [illegible]
(0.79 N + 0.21 O). [illegible]
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TABLE V

AVERAGE VALUES OF THE COLLISION LENGTHS

MATERIAL	X	(g^m x 10^{24})	L_c (g/cm^2)	σ millibarns	R (cm x 10^{13})
air*	$N_{0.79}O_{0.21}$	23.9	124 ± 4	192 ± 6	2.48 ± .04
beryllium	Be	14.9	85	176	2.37
carbon	C	19.9	87 ± 4	229 ± 11	2.70 ± .07
paraffin	$CH_{2.2}$	23.5	62 ± 6	379 ± 37	3.43 ± .17
water	H_2O	29.9	107 ± 8	277 ± 21	2.99 ± .11
heavy water	D_2O	33.2	123 ± 10	270 ± 22	2.93 ± .12
aluminum	Al	44.8	85 ± 18	527 ± 112	4.10 ± .44
sulphur	S	53.1	76 ± 12	699 ± 110	4.72 ± .38
iron	Fe	92.8	125 ± 11	743 ± 65	4.88 ± .21
gold	Au	327.	145 ± 15	2250 ± 233	8.47 ± .44
lead	Pb	343.	160 ± 5	2140 ± 67	8.29 ± .13

* In air the absorption length has been measured, not the collision length.

CHAPTER V

NUCLEAR TRANSPARENCY

In all of the above work, the energy of the incident particle could at best only be estimated. Therefore, it is of interest at this point to present the results of an experiment performed at considerably lower energies where the energy was a well-defined quantity.

Using 95 Mev neutrons from the 184-inch cyclotron at the University of California, Cook et al[29] measured the total cross section for neutrons incident on several different materials. Assuming that the total cross section, σ_{tot}, is composed of half elastic scattering and half inelastic scattering, σ_{tot} can be represented by $\sigma_{tot} = 2\pi R^2$, where R is the nuclear radius. Using the above relationship, experimental values of the nuclear radius were determined for each absorber. A plot of the experimental value of the nuclear radius against the cube root of the atomic mass number (R vs $A^{1/3}$) is given in Figure 27. If one further assumes that the nuclear radius R, is given by $R = r_o A^{1/3}$*, where r_o is a constant, one can determine the best value of r_o to fit the data. The value used to obtain the straight

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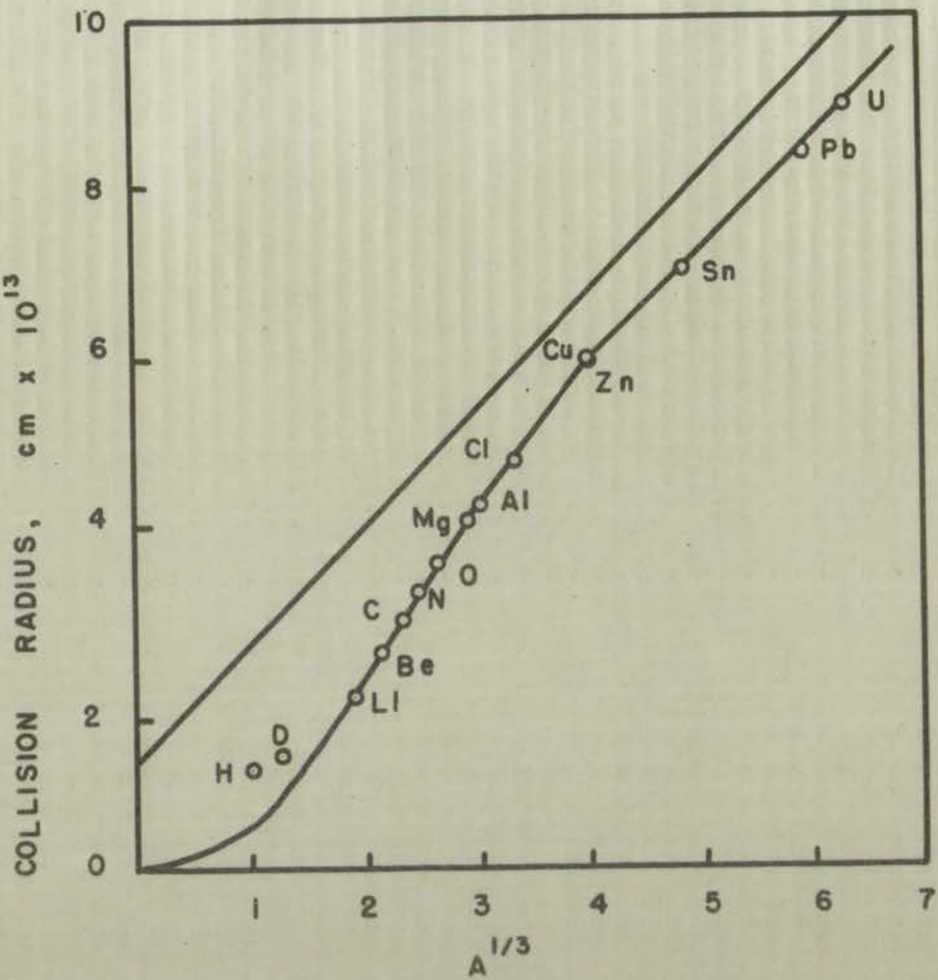
[29] L. J. Cook, E. M. McMillan, J. M. Peterson, D. C. Sewell, Phy. Rev. 75, 7, 1949.

*This concept will be discussed further in Chapter VI.



COLLISION RADII FOR

90 MEV

NEUTRONS

FIGURE 27

line in Figure 27 is $r_o = 1.37 \times 10^{-13}$ cm.

It is to be seen from the results of this experiment that a considerable transparency is to be expected for nuclear events taking place in materials of low atomic mass number. This will be discussed further in the next section of this paper. A plot of R vs $A^{1/3}$ obtained from the data presented in Table V is given in Figure 28. Using a value of r_o equal to 1.40×10^{-13} cm, it is indeed evident that there exists a transparency for the collision cross section of the PSPR with materials of low atomic mass number.

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It is [illegible]

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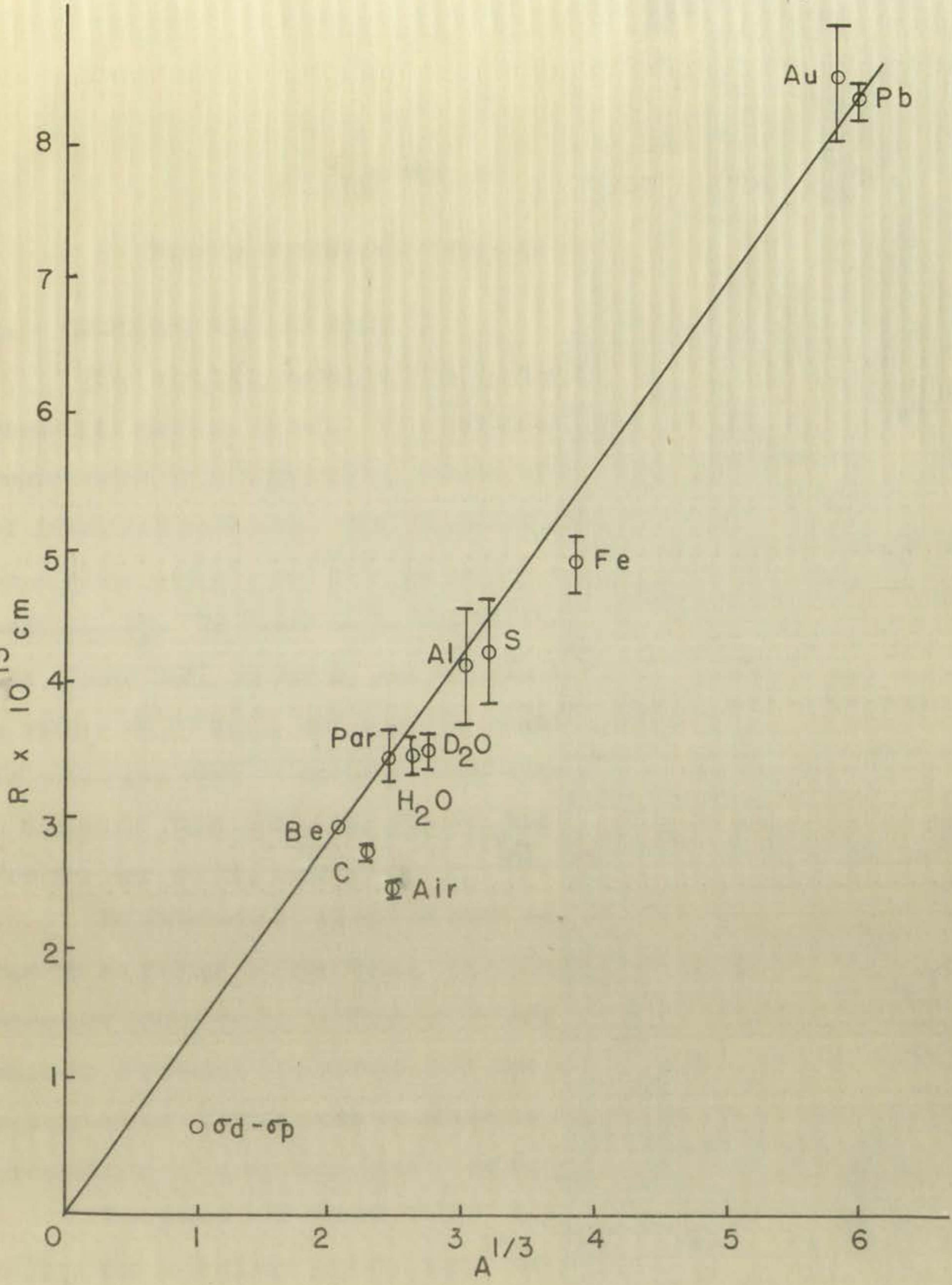


NUCLEAR RADII FROM THE GEOMETRIC MODEL

FIGURE 28

CHAPTER VI

VARIOUS THEORIES OF NUCLEAR COLLISIONS

A. - GEOMETRIC NUCLEAR MODEL

The simplest model of the nucleus is called the geometric nuclear model. In this model, the nucleus is represented by a homogeneous sphere of radius R, composed of identical nucleons. The projected area of this sphere on a plane is πR^2, and this is called the geometric cross section, σ_g. In order to calculate the dependence of R on the atomic mass number A, one assumes that each nucleon has a volume of $4\pi r_o^3/3$, and that the magnitude of this volume is unchanged when it combines with other nucleons to form a nucleus. From this, one obtains the familiar expression for nuclear radii, namely, $R = r_o A^{1/3}$.

In this model, there is only one parameter, r_o, that has to be fitted to the data. It is now evident that the straight lines drawn in Figures 27 and 28 of the previous chapter represent the curves that one would expect if the geometric cross section were an adequate description of the probability of a nuclear event taking place.

The geometric cross section does indicate the probability for a nuclear process quite well for large values of A if the constant r_o is properly chosen. However, for low

CHAPTER VI

VARIOUS THEORIES OF NUCLEAR COLLISIONS

A. - GEOMETRIC NUCLEAR MODEL

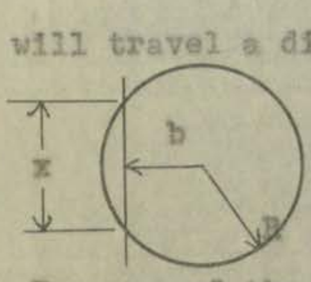
The simplest model of the nucleus is called the geometric nuclear model. In this model, the nucleus is represented by a homogeneous sphere of radius R, composed of identical nucleons. The projected area of this sphere on a plane is πR^2, and this is called the geometric cross section, σ_g. In order to calculate the dependence of R on the atomic mass number A, one assumes that each nucleon has a volume of $4\pi r_0^3/3$, and that the magnitude of this volume is unchanged when it combines with other nucleons to form a nucleus. From this, one obtains the familiar expression for nuclear radii, namely, $R = r_0 A^{1/3}$.

In this model, there is only one parameter, r_0, that has to be fitted to the data. It is now evident that the straight lines drawn in Figures 27 and 28 of the previous chapter represent the curves that one would expect if the geometric cross section were an adequate description of the probability of a nuclear event taking place.

The geometric cross section does indicate the probability for a nuclear process quite well for large values of A if the constant r_0 is properly chosen. However, for low values of A, it gives results that are too large. As one can see from Figures 27 and 28, there is a considerable transparency for small values of A. Therefore, this theory has to be modified to attain a transparency for nuclei of small atomic mass number.

B. - GEOMETRIC NUCLEAR MODEL WITH STATISTICAL TRANSPARENCY[30]

A slight modification of the above theory will include a transparency for nuclei of low atomic mass number. In this model, one makes the same assumption of a smooth, homogeneous sphere of radius R, where $R = r_0 A^{1/3}$ as one did in the geometric model. In addition to this, one also assumes a mean free path l_c, in nuclear matter. Then if a particle is incident upon a nucleus with an impact parameter b, it will travel a distance x in traversing the nucleus.



b = impact parameter,
R = radius of nucleus,
x = path length.

Because of the mean free path, the probability of no event taking place between the nucleus and a particle that travels a distance x through the nucleus is $\exp(-x/l_c)$. Therefore, the probability of an event taking place is

$$1 - \exp(-x/l_c).$$

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[30] Rossi, B., <u>High Energy Particles</u>, Prentice-Hall, Inc., New York: (1952).

values of A, it [illegible]

can see from Figures 47 and [illegible]

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E. - GEOMETRIC [illegible]

A slight modification [illegible] a transparency for [illegible] this model, one [illegible] homogeneous sphere of radius R, [illegible] in the geometric model. [illegible] assume a mean free path λ_0, [illegible] particle is incident upon [illegible] b, it will travel a distance [illegible]

b = [illegible]

R = radius [illegible]

x = [illegible]

Because of the [illegible] no events taking place [illegible] travels a distance [illegible] Therefore, the probability [illegible]

$1 - \exp(-x/\lambda_0)$ [illegible]

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[30] [illegible] Inc., New York [illegible].

Then the collision cross section, σ_{gt}, is given by

10) $$\sigma_{gt} = \int_0^R 2\pi b\, db \left[1-\exp(-x/l_c)\right] = \pi R^2 (1 - T),$$

where $$T = 1/\pi R^2 \int_0^R 2\pi b\, db\, \exp(-x/l_c)$$

Using the relationship $x = 2\sqrt{R^2 - b^2}$, one obtains

$$T = l_c^2/2r_o^2 A^{2/3} \left[1-\left(1 + 2r_oA^{1/3}/l_c\right)\exp\left\{- 2r_oA^{1/3}/l_c\right\}\right].$$

Then the expression for the geometric cross section with statistical transparency becomes:

12) $$\sigma_{gt} = \sigma_g (1 - T)$$

where T is given in equation (11). This cross section has the form

13) $$\sigma_{gt} = \sigma_g \left\{1 - \left[2d^{-2} \left(1 - (1 + 2d)\exp(-d)\right)\right]\right\}$$

where d is equal to $2r_oA^{1/3}/l_c$.

From this, one can immediately see that the transparency T increases as the atomic mass number decreases. Using the method of successive approximations, and the experimental data presented in Table V, the best values for r_o and for l_c have been determined to be:

$$r_o = 1.46 \times 10^{-13} \text{ cm},$$

and $$l_c = 3.80 \times 10^{-13} \text{ cm}.$$

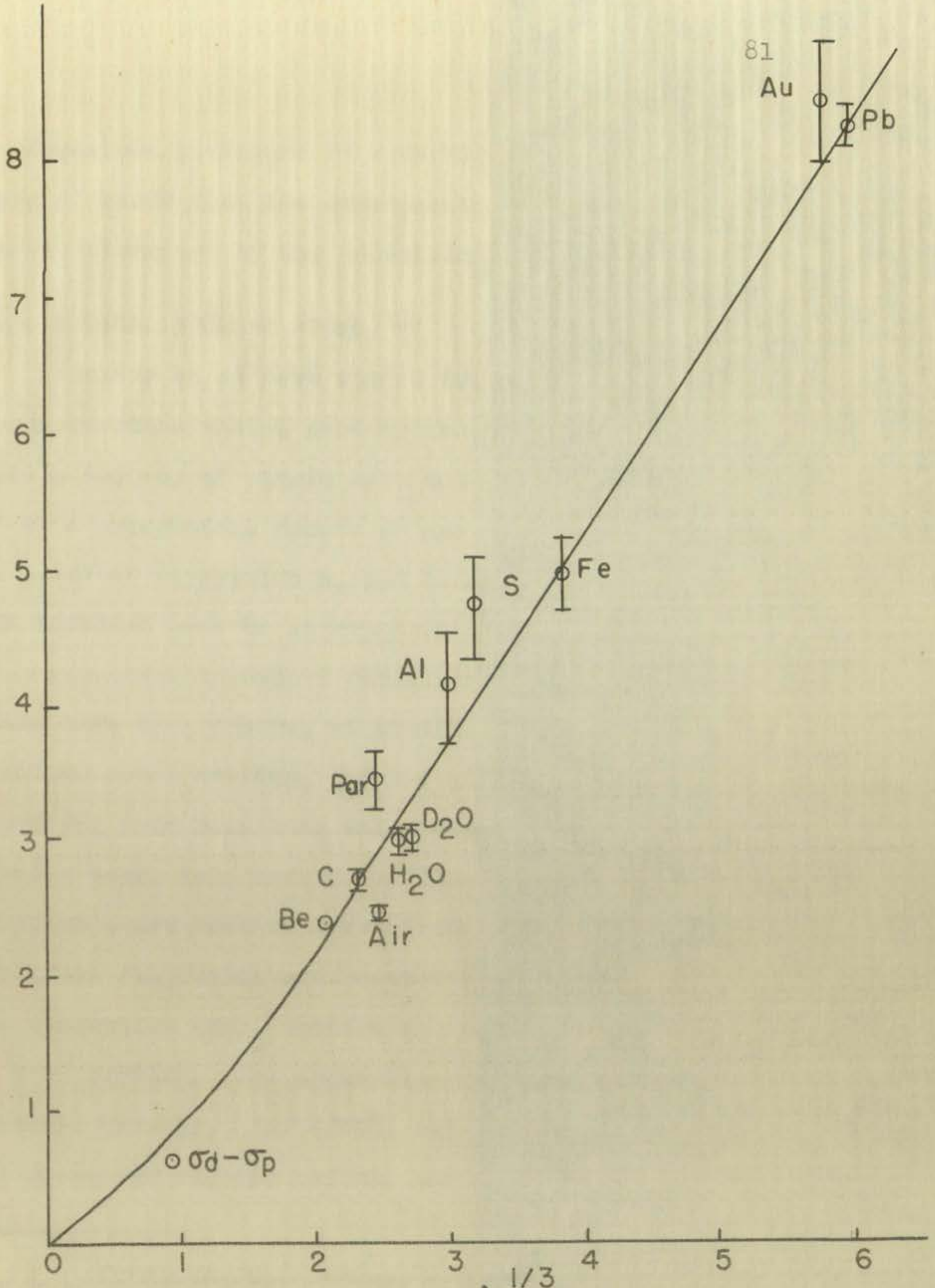
The data for air, water, heavy water, paraffin, and beryllium were not included in the calculation of r_o and l_c.

The nuclear radius R_{gt} described by this model is defined by the relationship

14) $$\sigma_{gt} = R_{gt}^2.$$

This radius is plotted against the cube root of the atomic mass number (R_{gt} vs $A^{1/3}$) in Figure 29. The experimental values of the nuclear radii are also plotted on this curve. In order to obtain an idea of how well this model fits the experimental data for poly-atomic materials such as water, a radius was calculated from both the experimental and the theoretical cross sections. The experimental radius, R_{ex}, is defined by the relationship $\sigma_{ex} = \pi R_{ex}^2$. The theoretical nuclear radius, R_{gt}, is described by equation (14), where σ_{gt} is taken to be the sum of the cross sections for all the nuclei composing the molecule. In the case of water, for example, σ_{gt} equals $2\,\sigma_H + \sigma_O$.

The experimental value of the nuclear radius for this case is not plotted on the abscissa value corresponding to $A^{1/3}$ where A is the sum of the atomic mass numbers of the nuclei composing the molecule, because the transparency is different for different values of A. R_{ex} is plotted on the graph with the same value of the abscissa as the theoretical nuclear radius. Therefore, if this theory were to describe the experimental data perfectly, R_{ex} would lie directly on the curve.



NUCLEAR RADII FROM THE GEOMETRIC MODEL WITH TRANSPARENCY

FIGURE 29

A comparison of Figure 29 with Figure 28 shows that this type of curve fits the experimental data better than a curve determined by the geometric model alone.

C. - OPTICAL NUCLEAR MODEL.[31]

Serber et al have worked out a nuclear model based on the assumption that Z protons and A - Z neutrons combine to form a nucleus of atomic mass number A, that may be represented as a homogeneous sphere of nuclear matter characterized by an index of refraction n, and by an absorption coefficient K. The incident neutron is represented as a plane wave.

Using the Kirchhoff formalism for the scattering of a plane wave by a sphere, an absorption cross section, a diffraction cross section, and the angular dependence of the scattered wave have been calculated. The diffraction cross section takes into account elastic scattering, and the absorption cross section takes into account true absorption, inelastic scattering and scattering with exchange. Therefore the absorption cross section is the one that is applicable to this problem. The absorption coefficient is given by the particle density, $3A/4\pi R^3$, multiplied by σ, where R is the geometric nuclear radius, and where σ is defined by the

[31] Fernbach, S., Serber, R., and Taylor, T. B., Phys. Rev., 75, 1352 (1949)

A comparison of [illegible] type of curve. [illegible] curve determined [illegible]

C. - [illegible]

[illegible] of [illegible] the assumption [illegible] Rose a nucleus [illegible] ed as a [illegible] an index of [illegible] The [illegible]

Using the [illegible] plane wave by a sphere [illegible] fraction [illegible] scattered wave [illegible] section taken [illegible] scattering [illegible] inelastic scattering and [illegible] the absorption [illegible] to this problem. The [illegible] particle density [illegible] the [illegible]

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[31] [illegible] Rev., 75, [illegible]

following:

$$\sigma = \left[Z \ \sigma_{np} + (A - Z) \ \sigma_{nn} \right] / A.$$

σ_{np} is the cross section for the event in question between an incident neutron and a proton bound in a nucleus; and σ_{nn} is the cross section for the same event between an incident neutron and a neutron bound in a nucleus.

In this treatment, all interactions between the nucleons inside the nucleus have been neglected. To make this a reasonable approximation, the binding energy of the nucleus must be small compared with the kinetic energy of the incident particle.

The absorption cross section, σ_a , is given by

$$\sigma_a = \pi R^2 \left\{ 1 - \left[1 - (1 + 2KR)\exp(-2KR) \right] / 2K^2R^2 \right\},$$

which has the form,

$$15) \quad \sigma_a = \sigma_g \left\{ 1 - 2d^{-2} \ \left[1 - (1 + 2d)\exp(-d) \right] \right\}.$$

This is the same form as the cross section described by the geometric nuclear model with statistical transparency.

Since this cross section has the same form as one previously described, it adds no new information to this particular problem. It does, however, offer a very elegant method of obtaining a transparency that is large for small

atomic mass numbers. It also gives additional information on elastic scattering, and about the angular dependence of scattered neutrons.

D. - THE THOMASONIAN MODEL.[32]

In all of the nuclear models proposed, one treats the interaction of an incident particle, or a wave that represents the incident particle, with the particles inside the nucleus. In most of these models, one assumes that the kinetic energy of the incident particle is high enough so that the binding energy of the nucleus may be neglected. One then is allowed to treat the interaction as a sum of nucleon-nucleon interactions instead of as a nucleon-nucleus interaction. (Note the definition of σ in the optical nuclear model, where $\bar{\sigma}_{np}$ and $\bar{\sigma}_{nn}$ are assumed to be constant despite the values of A and Z.)

In a radical departure from this type of treatment, Thomas has suggested that perhaps the way that one should look at this interaction is not on a nucleon-nucleon basis, but rather on the basis of the interaction between an incident particle and the meson field associated with the nucleus. The method employed in this treatment will be that of essentially neglecting the nucleons of the nucleus, and treat-

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[32] Thomas, Roy - Private communication to the author.

atomic mass numbers. It [illegible] and [illegible] elastic scattering, [illegible] the [illegible] scattered neutrons.

D. - THE T[illegible]IAN FORM.

In all of the analyses [illegible] the interaction of an incident [illegible] represents the incident particle [illegible] the nucleus. In most of these [illegible] kinetic energy of the incident [illegible] that the binding energy of the nucleons [illegible]. One then is allowed to treat the [illegible] nucleon-nucleon interactions [illegible] interesting. [illegible] nuclear model, where [illegible] constant through the values of [illegible].

In a critical [illegible] Thomas has suggested that perhaps [illegible] look at this interaction [illegible] but rather on the basis of the [illegible] particle and the more [illegible] The method employed in this [illegible] essentially [illegible] the [illegible].

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[1] Thomas, [illegible]

ing only the "nuclear glue", or meson field. The formula for the nuclear radius R, will then be given by:

$$R = R_o N^{1/3},$$

instead of $$R = r_o A^{1/3},$$

where N is the number of mesons associated with the nucleus.

However, the number of mesons associated with a nucleus will be equal to the binding energy of the nucleus divided by the rest energy of the pi meson.

16) $$N = (B.E. / M c^2)$$

Then the formula for the inelastic cross section will be given by:

17) $$\sigma_I = \pi R^2 = \pi R_o^2 N^{2/3} = \pi R_o^2 \, (B.E./M c^2)^{2/3}$$

Since N is a well-defined quantity, there is only one parameter that must be fitted to the data, and that is R_o.

This theory does not have an explicit energy dependence term associated with it, but if the proper energy dependence term is ever established, it can be included in this theory by making R_o a function of the energy. An interesting thing about this model is that it introduces a transparency of the proper order of magnitude on an entirely different physical basis than the usual theories.

One will also note that, since there is no binding energy for the hydrogen nucleus, there is also a zero cross section for the hydrogen nucleus according to this theory.

ing only the "nuclear field" or "meson field". The formula for the nuclear radius R_o will then be given by:

$$R = R_o N^{1/3},$$

instead of $$R = r_o A^{1/3},$$

where N is the number of mesons associated with the nucleus.

However, the number of mesons associated with a nucleus will be equal to the binding energy of the nucleus divided by the rest energy of the pi meson.

16) $$N = (B.E./M_\pi c^2)$$

Thus the formula for the inelastic cross section will be given by:

17) $$\sigma_i = \pi R^2 = \pi R_o^2 N^{2/3} = \pi R_o^2 (B.E./M_\pi c^2)^{2/3}$$

Since N is a well-defined quantity, there is only one parameter that must be fitted to the data, and that is R_o.

This theory does not have an explicit energy dependence term associated with it, but if the proper energy dependence term is ever established, it can be included in this theory by making R_o a function of the energy. An interesting thing about this model is that it incorporates a transparency of the proper order of magnitude on an entirely different physical basis than the optical theories.

One will also note that, since there is no binding energy for the hydrogen nucleus, there is also a zero cross section for the hydrogen nucleus, according to this theory.

If, however, there is actually a small cross section associated with the hydrogen nucleus, this can also be accounted for by a refinement to this model.

It is a generally accepted fact that part of the time, a proton exists in the neutron-pi meson state. Therefore on the average, there is a small fraction of the proton existing as a pi meson, and this fraction is equal to N, the number of pi mesons associated with the nucleus. Using equation (17), the best value of the parameter R_o was established by applying the method of least squares to the experimental data*. This value is:

$$R_o = (3.53 \pm .10) \times 10^{-13} \text{ cm.}$$

Using this value of R_o, the curve of R plotted against the cube root of the atomic mass number has been determined, and this is presented in Figure 30.

---

* The binding energies were determined from the following sources:

[33] Segre, E. H., Revised Segre Chart, Addison-Wesley Press, Cambridge, Mass., (1948)

[34] Mattauch, J., Nuclear Physics Tables, Interscience Publishers, New York. (1946)

If, however, there is actually a small cross section associated with the neutron capture, this can also be accounted for by a refinement of this model.

It is a reasonably [illegible] that part of the time, a proton exists in the neutron-proton [illegible]. Therefore on the average, there is [illegible] fraction of the proton existing as a pi meson, and this fraction is equal to K, the number of pi mesons associated with the nucleus. Using equation (17), the best value of the parameter E_a was established by applying the method of least squares to the experimental data. This value is:

$$E_a = (3.33 \pm .10) \times 10^{-3} \text{ ev.}$$

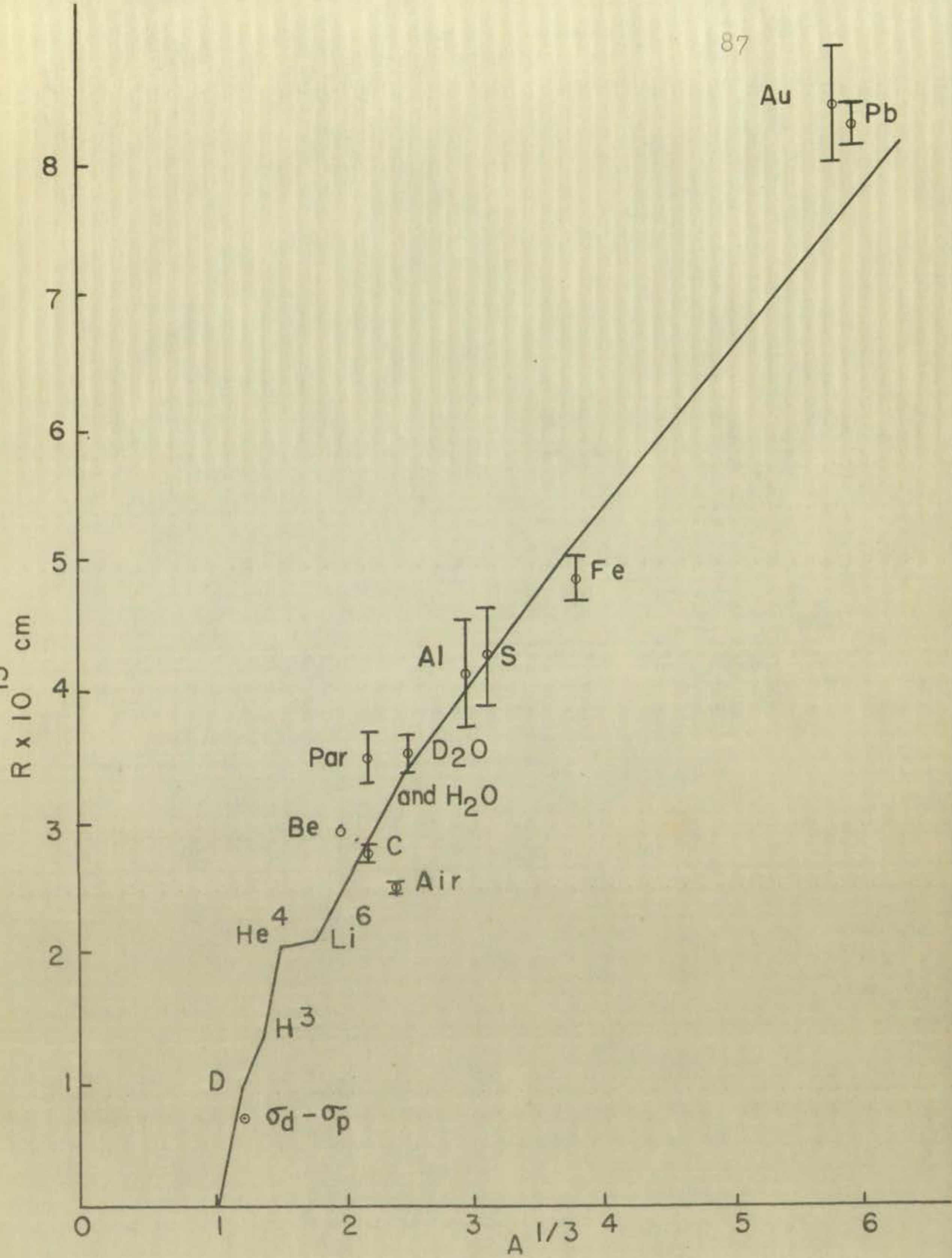
Using this value of E_a, the curve of K plotted against the cube root of the atomic mass number has been determined, and this is presented in Figure 34.

---

* The binding energies were determined from the following sources:

[33] Segre, E. E., Revised Segre Charts, Addison-Wesley Press, Cambridge, Mass., (1946)

[34] Mattauch, J., Nuclear Physics Tables, Interscience Publishers, New York, (1946)



NUCLEAR RADII FROM THE THOMASONIAN NUCLEAR MODEL

FIGURE 30

CHAPTER VII

EVALUATION OF THE THEORIES

A comparison of the experimental data listed in Table V with the results to be expected from the various theories is presented in Table VI. The accuracy of the data does not permit a reasonable evaluation of the relative worth of the various theories.

It is reasonable, however, to reject the geometric model on the basis of both the cosmic-ray results given in this paper and the results of experiments carried out at lower energies.

The geometric model with statistical transparency and the optical nuclear model both give the same results. These models are quite adequate for describing processes taking place in materials of large atomic mass number, but do not give a sufficiently large transparency for materials of low atomic mass number.

On the basis of the existing data, no selection can be made between the optical model and the Thomasonian model.

TABLE VI

EXPERIMENTAL AND THEORETICAL CROSS SECTIONS

MATERIAL	EXPERIMENTAL CROSS SECTION (millibarns)	GEOMETRIC CROSS SECTION (millibarns)	OPTICAL CROSS SECTION (millibarns)	THOMASONIAN CROSS SECTION (millibarns)
air*	192 ± 6	374	274	309
beryllium	176	265	186	202
carbon	229 ± 11	323	229	277
paraffin	379 ± 37	360	285	277
water	277 ± 21	422	351	344
heavy water	270 ± 22	452	391	390
aluminum	527 ± 112	503	481	500
sulphur	699 ± 110	620	515	570
iron	743 ± 65	908	805	843
gold	2250 ± 233	2090	2050	1810
lead	2140 ± 67	2150	2140	1860
$\sigma_d - \sigma_p$	# 13 ± 15	36	22	23

* In air an absorption cross section, not a collision cross section is presented.

This value is that given by Froman, Kenney, and Regener.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

The existing experimental data are neither sufficiently accurate nor consistent to obtain any really good comparison of the experimental data with the various theories. In the selection of experiments to be presented in this paper, the author has attempted to eliminate any experiments which measured events other than were claimed. In cases in which some doubt existed as to the validity of the experiment, that experiment was given a low weight in the calculation of average values of the cross sections. Even with this type of selection, the data are still not very consistent.

From the data that do exist, however, it seems that the collision length is the same for both the ionizing and the neutral component of the cosmic radiation that is capable of producing penetrating showers. To fit all the data chosen, the best value for the mean free path of the penetrating-shower-producing radiation in nuclear matter is:

$$l_c = 3.80 \times 10^{-13} \text{ cm.}$$

The experimental data permit no conclusions at all about the dependence of the cross section for penetrating shower production on the energy of the incident particle.

CHAPTER [illegible]

SUMMARY AND CONCLUSIONS

The existing experimental data are neither sufficiently accurate nor abundant to obtain any reliable comparisons of the experimental data with theoretical predictions. In the selection of experimental data presented in this paper, the author has attempted to eliminate any experiments which suffered more severely than those selected. In cases in which very little question as to the validity of the experiments, such experiments are given a low weight in the calculation of average values of the cross sections. Even with this type of selection, the data are still not very consistent.

From the data that is given, however, it seems that the collision radius is one near the bound the [illegible] and the natural boundary of the nuclear particles that are capable of producing penetrating showers. On the basis of all the data chosen, the best value for the mean free path of the penetrating-shower-producing radiation in nuclear matter is

$$\lambda_s = 3.80 \times 10^{-13} \text{ cm.}$$

The experimental data permit no conclusions at all about the dependence of the cross section for penetrating shower production on the energy of the incident particle.

Since the binding energies of light nuclei vary radically, the validity of the model suggested by Thomas could be checked easily. An experiment that would do this would be a measurement of the absorption cross section of high energy neutrons in helium and in deuterium. Because of the experimental difficulties entailed in working with liquid helium and liquid deuterium, this experiment would be best conducted with neutrons from a cycletron.

The author wishes to express his appreciation to Dr. D. K. Froman and Dr. V. H. Regener for their generous assistance and encouragement throughout the progress of this investigation. Special thanks are also due to Dr. Roy Thomas for invaluable discussions and for permission to treat, in this paper, the nuclear model suggested by him.

Since the binding energies of light nuclei vary radically, the validity of the model suggested by Kramer could be checked easily. An experiment that would do this would be a measurement of the absorption cross section of high energy neutrons in helium and in deuterium. Because of the experimental difficulties entailed in working with liquid helium and liquid deuterium, this experiment would be best conducted with neutrons from a cyclotron.

The author wishes to express his appreciation to Dr. D. K. Froman and Dr. V. M. Seymour for their generous assistance and encouragement throughout the progress of this investigation. Special thanks are also due to Dr. Roy Thomas for invaluable discussions and for permission to treat, in this paper, the nuclear model suggested by him.

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BIBLIOGRAPHY

BIBLIOGRAPHY

Birge, R. T., Phys. Rev., 40, 207, (1932)

______, Loc. cit.

______, Loc. cit.

Boehmer, H. W., and Bridge, H. S., Phys. Rev., 85, 863 (1952)

______, op. cit.

Bridge, H. S., and Rediker, R. H., Phys. Rev., 88, 206 (1952)

Brown, R. R., Phys. Rev., 87, 999 (1952)

Carlson, A. G., Hooper, J. E., and King, D. T., Phil. Mag. 41, 701 (1950)

Chang, W. Y., del Castillo, G., and Grodzina, L., Phys. Rev., 84, 582 (1951)

Cocconi, G., Phys. Rev., 75, 1075 (1949)

Cook, L. J., McMillan, E. M., Peterson, J. M., and Sewell, D. C., Phys. Rev., 75, 7 (1949)

Fernbach, S., Serber, R., and Taylor, T. B., Phys. Rev., 75, 1352 (1949)

Fretter, W. B., Phys. Rev., 76, 511 (1949)

Fretter, W. B., May, M. M., and Nakada, M. P., Phys. Rev. 89, 148 (1953)

Froman, D. K., Kenney, J. F., and Regener, V. H., (paper not yet published)

George, E. P., and Jason, A. C., Proc. Phys. Soc. London, A63, 1081 (1950)

Gottlieb, N. B., Phys. Rev., 82, 349 (1951)

Greisen, K. I., Phys. Rev., 61, 212 (1942)

BIBLIOGRAPHY

Argo, H. V., Phys. Rev., 80, 407, (1950)

______, loc. cit.

______, loc. cit.

Bonner, T. W., and Bridges, B. E., Phys. Rev., 82, 361 (1951)

______, loc. cit.

Bridges, B. E., and Bastian, R. H., Phys. Rev., 86, 300 (1952)

Brown, S. H., Phys. Rev., 87, 990 (1952)

Carlson, A. G., Hooper, J. E., and King, D. T., Phil. Mag. 41, 701 (1950)

Chang, W. Y., and Cantillo, S., and Goldstein, L., Phys. Rev., 82, 302 (1951)

Cocconi, G., Phys. Rev., 75, 1075 (1949)

Cook, L. J., McMillan, E. M., Peterson, J. M., and Sewell, D. C., Phys. Rev., 75, 7 (1949)

Feshbach, H., Serber, R., and Taylor, T. B., Phys. Rev., 75, 1352 (1949)

Fretter, W. B., Phys. Rev., 76, 511 (1949)

Fretter, W. B., May, M. M., and Nakada, M. P., Phys. Rev., 89, 168 (1953)

Froman, D. K., Kenney, J. P., and Regener, V. H., (paper not yet published)

Gerard, E. P., and Jason, A. C., Proc. Phys. Soc. London, A64, 1001 (1950)

Gottlieb, H. B., Phys. Rev., 82, 349 (1951)

Greisen, K. I., Phys. Rev., 61, 212 (1942)

Hodson, A. L., Proc. Roy. Soc., 65, 702 (1952).

Mattauch, J., Nuclear Physics Tables, Interscience Publishers, New York: 1946.

Pomeroy, D., Phys. Rev., 87, 77 (1951).

Regener, V. H., Rev. Sci. Instr. 18, 267 (1947).

Rollosson, G. R., Phys. Rev., 87, 71 (1952).

_______, op. cit.

Rossi, B., High Energy Particles, Prentice-Hall, Inc., New York: (1952).

Rossi, B., and Regener, V. H., Phys. Rev. 58, 837 (1940).

Segrè, E. H., Revised Segrè Chart, Addison-Wesley Press, Cambridge, Mass. (1948).

Sitte, K., Phys. Rev., 78, 714 (1950).

_______, op. cit.

Thomas, Roy, Private Communication to the author.

Tinlot, J., Phys. Rev., 74, 1197 (1948).

Tinlot, J., and Gregory, B., Phys. Rev., 75, 519 (1949)

Walker, W. D., Phys. Rev., 77, 686 (1950).

Walker, W. D., Walker, S. P., and Greisen, K. I., Phys. Rev., 80, 546 (1950).

Walsh, W. D., and Piccioni, O., Phys. Rev., 80, 546 (1950).

Hodson, A. L., Proc. R. [illegible] (19[illegible]).

[illegible], Oxford University Press, New York, 1954.

[illegible], Phys. Rev. [illegible] (19[illegible]).

Regener, V. H., Phys. Rev. [illegible] (19[illegible]).

[illegible], Phys. Rev. [illegible] (19[illegible]).

———, [illegible].

Rossi, B., High Energy Particles, Prentice-Hall, Inc., New York (1952).

Rossi, B., and Regener, V. H., Phys. Rev. 58, 837 (1940).

Segrè, E., [illegible], Addison-Wesley Press, Cambridge, Mass. (1953).

Sitte, K., Phys. Rev. 78, 714 (1950).

———, [illegible].

Thomas, Roy, Private Communication to the author.

Tinlot, J., Phys. Rev. 74, 1197 (1948).

Tinlot, J., and Gregory, B., Phys. Rev. 75, 519 (1949).

Walker, W. D., Phys. Rev. 77, 686 (1950).

Walker, W. D., Walker, S. P., and Greisen, K. I., Phys. Rev. 80, 546 (1950).

Walsh, T. G., and Piccioni, O., Phys. Rev. 80, 619 (1950).

APPENDIX

APPENDIX I

TABULATION OF THE COMPONENT PARTS OF THE EXPERIMENT OF FROMAN, KENNEY, AND REGENER

RESISTORS

NUMBER	OHMS	DESCRIPTION
R 208	5	2 watts
R 206	250	5 "
R 205	700	10 "
R 107 and R 108	750	5 "
R 207 and R 211	1250	100 "
R 202 and R 204	5K	potentiometer
R 115	10K	1 watt
R 212	10K	50 "
R 101 through R 106	11K	2 "
R 109	11K	2 "
R 201 and R 203	20K	50 "
R 110, R 111, R 116 R 117, R 122, and R 123	22K	1 "
R 114, R 126, R 128, R 132, R 360 through R 410, and R 547 through R 583.	47K	1 "
R 112, R 119 through R 121, R 129 through R 131, R 133 through R 136, R 149 through R 152, and R 601 through R 632.	100K	1 "
R 113, R 118, R 124, and R 127.	100K	2 "

RESISTORS

NUMBER	OHMS	DESCRIPTION
R 138, R 139, R 142 through R 146, R 301 through R 359, and R 501 through R 546.	220K	1 watt
R 209 and R 210	250K	potentiometer
R 147	470K	1 watt
R 125, R 137, R 140, R 141, R 148, and R153.	1M	½ "

CAPACITORS

NUMBER	MICROMICROFARADS
C 110 and C 112	10
C 601 through C 606	20
C 111, and C 122 through C 125	25
C 129, and C 113 through C 116	50
C 126 through C 128, C 301 through C 351, and C 501 through C 537	150
C 135	500
C 130	1000
	MICROFARADS
C 101 through C 109	0.1
C 117, C 118, C 131, and C 132	0.3

CAPACITORS

NUMBER	MICROFARADS	D. C. WORKING VOLTAGE
C 207 and C 208	8	450
C 119 through C 121, and C 211	10	450
C 205 and C 206	12	150
C 201 and C 202	20	150
C 212	20	450
C 203 and C 204	25	25
C 209 and C 210	100	25

INDUCTORS

NUMBER	VALUE
L 201 and L 203	250 henries
L 202 and L 204	20 henries (swinging choke)
L 205 and L 206	20 henries

VACUUM TUBES

NUMBER	TYPE
V 201, V 202, V 205 and V 206	5R4 GT
V 101, V 104, V 111, V 115, V 117, V 118, V 306 through V 315, V 331 and V 340, and V 510 through V 527.	6SA7
V 102, V 103 V 105 through V 108, V 116, and V 112 through V 114.	6SH7

VACUUM TUBES

NUMBER	TYPE
V 109, V 110, V 301 through V 305, V 316 through V 330, V 501 through V 509, V 528 through V 536, and V 601 through V 604.	6SL7
V 203 and V 204	6V6

TRANSFORMERS

NUMBER	MANUFACTURER	TYPE
T 201	U.T.C.	PA453
T 202	Thordarson	T19F76
T 203	Thordarson	T17R30
T 204	U.T.C.	CG431
T 205	U.T.C.	PA122
T 206	Thordarson	T19F79

MISCELLANY

NUMBER	DESCRIPTION	TYPE
Re 201 and R e 202	RELAY	SPST DC 5000 ohms
X 201, X 202, and X 601 through X 629.	CRYSTAL DIODE	1N34