A CLOUD CHAMBER FOR COSMIC-RAY STUDIES
AT SEA LEVEL

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Master of Science

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The undersigned, appointed by the Dean of the Graduate Faculty, have
examined a thesis entitled
"A Cloud Chamber For Cosmic-Ray Studies At Sea Level"

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ABSTRACT

The design, construction, and operation of an electronically controlled expansion cloud chamber to detect soft showers produced by mu-mesons is described. The cloud chamber is used in conjunction with a Geiger-tube telescope and an electronic energy-selecting trigger set for measuring the intensity of high-energy mu-mesons as a function of angle measured from the vertical direction.

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I. THE DESIGN OF THE EXPERIMENT

A. Introduction: the Experimental Problem

Since their discovery in 1913 by V. F. Hess, the investigation of cosmic rays has become a primary source of information about the nuclear structure of matter and the forces which characterize nuclear interactions.

Cosmic rays are believed to have their origin in the stars of stellar space. Of the primary particles impinging upon the earth's atmosphere, some 85-90 per cent appear to be protons; the remaining primaries are alpha particles and heavier ions ranging up to $Z \approx 30$. Primary radiation is quickly absorbed by the earth's atmosphere and can be studied effectively only with detectors sent aloft in high altitude balloons. However, the primary radiation produces some penetrating secondary particles, largely by collision with nuclei of atoms in the earth's atmosphere, which reach the surface of the earth in relative abundance.

One important component of the secondary radiation consists of pi-mesons. These particles have such a short half-life that those which are not absorbed by nuclear interactions decay before reaching the surface of the earth according to the following scheme:

The mu-mesons resulting from the decay of the pions are sufficiently long-lived and penetrating to reach sea-level in abundance great enough for study in the laboratory.

Details of the production and propagation of high-energy mu-mesons are currently being investigated by the cosmic-ray group at the University of Missouri. Theoretical studies of the problem have been made. The theory is now being carefully refined, and the analytical expressions have not yet been set in final form. However, a first-approximation theory has been given.¹ It is based upon a number of assumptions which are to be tested by experimental investigation. A very brief outline of the theory will be given here.

The first step in the development is the derivation of the diffusion equation of pi-mesons in the earth's atmosphere; it has the following differential form:

$$\frac{\partial N_{\pi}(E, l, \theta)}{\partial (l/\cos \theta)} = \left[AE^{-2.7} e^{-\frac{l}{\lambda_p \cos \theta}} \right] - N_{\pi}(E, l, \theta) \left[\frac{1}{\lambda_{\pi}} + \frac{m_{\pi}}{\rho p T_0} \right] \quad (1)$$

The first term on the right is the production term due to incident primaries. A is a proportionality constant, l is the depth in grams/cm² in the earth's atmosphere, θ is the angle of the incident primaries, measured from the zenith, λ_p is the absorption mean-free-path of the primaries. The two

¹ J. A. Smith, University of Missouri. Private communication.

remaining terms on the right are removal terms. The first of these gives the absorption of pi-mesons by interactions in the atmosphere. λ_π is the absorption mean-free-path of pi-mesons. The second of these terms gives the removal by decay of pi-mesons in flight. m_π is the mass of the pion, ρ is the density of the earth's atmosphere at depth l , p is the momentum of the pion, and τ_0 is the proper lifetime of the pion in the frame of reference at rest with respect to its center of mass.

The difference of the production and removal terms then gives the total rate of change of the pi-meson intensity with distance in the earth's atmosphere. A simple solution of the equation may be had if one assumes $\lambda_\pi = \lambda_p$. The solution is

$$N_\pi(E, l, \theta) = \frac{AE^{-2.7} l e^{-\frac{l}{\lambda_\pi \cos \theta}}}{\left[\frac{m_\pi l_0}{\tau_0 \rho_0 p} + 1 \right] \cos \theta} \quad (a)$$

The function N_π is an intensity of the usual kind encountered in cosmic-ray physics. It has units of number of particles per cm^2 per steradian per second in direction θ , per unit energy at E . ρ_0 is the density of the earth's atmosphere at depth l_0 . The differential energy spectrum, $f(E, \theta)$ of mu-mesons as a function of zenith angle at sea level is obtained by integrating the decay of pi-mesons over l .

$$f(E, \theta) = \int_0^{l_0} \frac{N_{\pi}(E, l, \theta) m_{\pi} dl}{\rho P T_0 \cos \theta} \quad (3)$$

The result of integration gives

$$f(E, \theta) = \frac{K_0 E^{-2.7}}{[1 + K_1 E \cos \theta]} \quad (4)$$

where K_0 and K_1 are combinations of the constants in the preceding equations.

The integral mu-meson spectrum measured experimentally is given by

$$F(\theta) = \int_{E_0}^{\infty} f(E, \theta) dE \quad (5)$$

where E_0 is some lower limit, (to be specific, say 75 Bev). The resulting expression for $F(\theta)$ is quite complicated and is not easily interpreted directly, although numerical results which display the zenith angle dependence have been obtained by J. A. Smith.¹ This dependence is more clearly observed in equation (4). The constant K_1 is approximately $1/(100 \text{ Bev})$ and the $\cos \theta$ term becomes important for $E \gtrsim 100 \text{ Bev}$.

The validity of equation (5) and the assumptions upon which it is based are to be investigated by experimental measurement of the integral intensity of mu-mesons as a function of zenith angle. If η is the efficiency of the counting

mechanism and is independent of energy,² the detector will then measure the quantity

$$G(\theta) = \eta F(\theta) \quad (6)$$

provided the theory outlined above is correct.

It is the purpose of this thesis to present an account of the design, construction, and operation of an experimental set-up to be used in this investigation.

B. The Geiger-counter Telescope

Since $G(\theta)$ is to be measured as a function of zenith angle, provision must be made in the apparatus for selecting only those particles which are incident upon the detectors (Geiger tubes) from a given angle and excluding all others. This is accomplished by an array of Geiger counters shown schematically in Figure 1.

In order that an incident particle be accepted by the telescope, it is required to pass through one of the Geiger tubes in tray 1 and one in tray 2. The capacity of a Geiger-counter telescope to accept particles is known as its acceptance factor. This factor is determined by two quantities: a) the total solid angle subtended by the telescope about the

² This assumption is being studied by the cosmic-ray group.

FIG. 1 THE GEIGER-COUNTER TELESCOPE.

direction θ , and b) the total area of a cross section through the lower tray of Geiger counters perpendicular to the axis of the telescope. Analytically the acceptance factor, C , is given by

$$C = \int_{\Omega} \int_A dA d\Omega \quad (7).$$

In any real case the acceptance factor of a telescope may be determined by breaking the area of the lower tray of counters into unit squares ΔA_i and determining the solid angle Ω_i subtended at each by the upper tray. Then

$$C = \sum_i (\Delta A_i) \Omega_i \quad (8).$$

The intensity $I(\theta)$ of particles at θ accepted by the telescope is given in units of

$$I(\theta) = \frac{\text{number of particles}}{\text{cm}^2 - \text{steradian} - \text{sec}}$$

and $N(\theta)$, the total number of particles per unit time recorded by instruments operating in conjunction with the telescope, is

$$N(\theta) = CI(\theta)$$

Because of the finite dimensions of the Geiger-counter trays, particles enter the telescope from a spread of angles, $\Delta\theta$. θ then represents an average direction of incident particles recorded at a given inclination of the telescope. By reducing the width of the Geiger-counter trays or increasing

the axial distance between them, the angular spread may be made smaller. However, this has the compensating effect of reducing the acceptance factor ~~as well~~, with a resultant decrease in counting rate at the recorder. The intensity $I(\theta)$ of high energy particles is generally low and it is necessary to make C large enough to provide good statistics in $N(\theta)$.

A compromise between counting rate and angular spread is thus one of the prime considerations in using a Geiger-counter telescope.

C. The Cloud Chamber as an Energy Discriminator

The selection of angle is thus determined. The next problem is to measure $G(\theta)$, the integral intensity of high energy mu-mesons in the direction θ . $G(\theta)$ is to be the total intensity of particles that enter the telescope with energy above a fixed minimum E_0 . That is, $G(\theta)$ is that fraction of $N(\theta)$ with $E \geq E_0$.

The integral intensity is to be measured by use of the apparatus shown in Figure 2. This equipment is located between the two trays of Geiger tubes shown in Figure 1, and together with the telescope is tilted through an angle θ for a particular measurement.

An energetic mu-meson passing through a sufficient thickness of lead (the production layer) has a high probability of producing an energetic secondary particle which is

**INCIDENT
PARTICLES**

**PRODUCTION
LAYER 5" PB**

GEIGER COUNTERS (TRAY 3)

LEAD PLATES

CAMERA

CLOUD CHAMBER

FIG. 2 THE ENERGY DISCRIMINATOR

capable of initiating a soft shower of electrons in the lead.

There are three mechanisms by which a mu-meson can produce shower-initiating particles: bremsstrahlung radiation, direct pair production, and knock-on collisions with electrons. If the mu-meson emits bremsstrahlung radiation, this in turn produces pairs which emit more bremsstrahlung, leading to a cascade of electrons. Or if the initiating particle is a knock-on electron, it emits bremsstrahlung which again leads to a cascading effect. The soft shower so generated then passes through the tray of Geiger tubes and into the cloud chamber where it can be photographed and analyzed.

Since the multiplicity of electrons in the shower at a given level, say at the Geiger-tube level, tends to be proportional to the energy of the shower-initiating particle, the number of Geiger tubes triggered by the shower is a rough measure of the energy of the initiating particle. By requiring a minimum number of tubes to be triggered, a lower limit is placed on the energy of the particles which are counted at the recorder. All particles of greater energy are then counted. This mechanism is used in the first analysis for screening out the lower-energy initiating particles.

A more precise determination of the energy of the initiating particles is made by shower-theory analysis of the tracks which are photographed in the cloud chamber.

The next problem is to correlate the energy of the particle which initiated the shower with the energy of the mu-meson that produced the initiating particle. The energy discrimination afforded by the probabilities of three shower-producing processes in lead can be investigated in terms of the integrals of the differential collision probability, the differential radiation probability, and the differential pair-production probability. Rossi³ has put these three expressions in convenient and consistent notation. For example, the differential radiation probability gives the probability per gram per cm² that a mu-meson with energy E will emit radiation with energy between E' and $E' + dE'$.

Integration of this expression⁴ over all energies above E'_0 gives the total probability that a mu-meson of energy E will emit radiation of energy E' or greater. This integral and the integral pair-production probability show that bremsstrahlung and direct pair-production are increasing functions of mu-meson energy and are sufficiently energy sensitive to afford fair discrimination between medium- and high-energy mu-mesons. The integrated probability of the collision process is less energy sensitive and offers less hope for effective discrimination.

³ Bruno Rossi, High Energy Particles (Prentice-Hall: New York, 1952), Chapter 2.

⁴ R. W. Sheldon, University of Missouri. Private communication.

To be more specific, these integrated probabilities show that for a given lower limit, the total probability $\Phi_{\text{rad}} + \Phi_{\text{pp}} + \Phi_{\text{col}}$ that all recorded showers were produced by high energy mu-mesons is several times greater than the probability that they were produced by lower-energy mu-mesons. For example, the probability that all showers of 2 Bev or more are produced by mu-mesons of 400 Bev is approximately 8 times as great as the probability of production by 50 Bev mu-mesons. Furthermore, the ratio of probable production by high energy mu-mesons to probable production by lower-energy mu-mesons increases with increasing E'_0 . A proper selection of E' thus gives reasonable assurance that the recorded particles are high energy mu-mesons.

A possible source of contamination of the data should be mentioned here. The apparatus is also subject to penetrating showers of pi-mesons produced by nuclear-active particles (protons, pi-mesons) colliding with nuclei in the lead. If these showers meet the minimum-energy requirements, they will be recorded. However, they can be eliminated from the data because of their appearance in the cloud-chamber photographs. Pi-mesons are distinguished by the fact that they are penetrating particles and do not scatter and multiply in lead as readily as do electrons. Three plates of lead, each 1/4" thick, are placed in the chamber to make use of this feature. A pi-meson track appears as a straight line, passing

undeflected through the lead sheets. An electron, being about 300 times less massive, generally is deflected by interaction with the nuclei of the lead. This deflection produces bremsstrahlung radiation which frequently leads to electron multiplication. Consequently, an electron track is often accompanied by the cascading effect which characterizes soft-showers. Thus either track deflection or the cascading of tracks may be used as a valid criterion for distinguishing soft showers from penetrating showers.

II. THE APPARATUS

A. The Cloud Chamber and Associated Equipment

A simplified diagram (top view) of the equipment discussed in this section is shown in Figure 3. Figures 4, 5, and 6 are photographs of portions of this equipment.

The cloud chamber is of the volume-defined type. It consists of essentially two sections, front and back, separated by a moveable $1/8$ "-thick neoprene diaphragm whose limits of motion are fixed by two stops made of perforated metal through which gases may pass easily. The front section of the chamber is the active volume in which tracks are formed. A gas-vapor mixture in this section is compressed and saturated. When a particle which has been selected to be photographed passes through the chamber the mixture is allowed to expand adiabatically. The tracks formed in the active volume are illuminated by lights located on the sides of the chamber. The sides are made of transparent lucite. Photographs of the tracks are taken through the plate-glass window in the front of the chamber.

The active volume of the chamber is filled with a mixture of high Z gas (argon) for ionization by charged particles, and ethyl-alcohol-water vapor for condensation on the ionized gas.

FIG.3 THE CLOUD CHAMBER & ASSOCIATED EQUIPMENT

The filling procedure is as follows. With the alcohol-water input in the top of the chamber open, 8 cubic feet of argon are flushed through the chamber to remove most of the air in the active volume. Then 35 cc of 75% alcohol-25% water mixture by volume are poured into the chamber. The liquid passes down a small tube and flows into a trough at the bottom of the chamber, from which it will evaporate and diffuse evenly throughout the active volume in a few hours. After the liquid is poured in, another 2 cubic feet of argon are flushed through the chamber. Then the alcohol-water input is closed and the argon pressure is increased to the final value (see below).

The usefulness of the chamber depends upon the fact that, under supersaturation conditions, vapor condenses more readily on charged particles than on neutral particles. Both types of condensation centers exist in the chamber. Background condensation on the uncharged centers must be minimized if clear tracks are to be seen. The expansion ratio for prohibitive background condensation is about 0.01 greater than the expansion ratio for clear track formation. It has been shown by Flood⁵ that this spread in critical expansion ratios decreases rapidly for water-alcohol mixtures of less than about 15% alcohol by volume. Consequently it is impor-

⁵ H. Flood, *Z. phys Chem.*, 170, 286, (1934).

tant that the expansion ratio as well as the percentage of water to alcohol be controlled carefully.

In addition to the uncharged centers, there is another source of background condensation, which cannot be controlled by the expansion ratio. When a rapid expansion occurs, turbulence of the gas produces ionization. These ions are of the same nature as those produced by the tracks, and vapor condenses on them at the same rate. Most of these ions are produced after tracks have already been formed in the chamber and so do not produce visible drops until after the tracks have been photographed. However, these ions will be centers of condensation in subsequent photographs unless they are removed. A clearing field of 20v/cm is maintained in the chamber, and by making a number of slow expansions lasting about five seconds each, these ions are cleared from the gas. Four such expansions have been found sufficient to clean the chamber. Slow expansions also serve another purpose. Besides the uncharged gas atoms, dust particles are always present in the chamber. Because of their large radii, vapor condenses on these neutral particles as readily as on ions. In a slow expansion these centers filter out of the gas under their own weight.

Another item concerning background condensation should be mentioned. Cosmic rays are continuously passing through the chamber, producing ions. The clearing field is maintained

in the chamber almost constantly to remove these ions. Only immediately before the chamber makes a fast expansion is the clearing field turned off, and then just long enough for the tracks to be photographed. The tracks consist of both positive and negative ions and the electric field rapidly tears them apart. If the clearing field is not removed, the photographed tracks will appear abnormally diffused.

The adiabatic expansion process is achieved in the following manner. The pressure in the front section of the chamber is raised to about 14 cm. Hg. above atmospheric with the pressure in the back section at atmospheric pressure. Under the excess pressure in the front section, the diaphragm is pushed backward against the back stop. The chamber is then in the expanded state. The pressure in the back section is raised to 5 lbs/in² above atmospheric and the excess pressure in the back pushes the diaphragm against the front stop, compressing the gas in the active volume. Pressure in the back is suddenly reduced to atmospheric pressure as explained below, and an adiabatic expansion of the gas in the front section occurs.

Pressure in the back section is controlled by four valves, two pop-valves for rapid expansion, and two solenoid valves for slow expansion. (See Figures 3 and 6.)

Each pop-valve consists of a sliding, non-magnetic shaft fitted in a hole drilled along the axis of an iron

cylinder. The axis of the shaft is perpendicular to the back of the chamber. On the end nearest the chamber is mounted an aluminum cap which seals a hole in the back of the chamber when the pop-valve is closed. On the other end of the shaft is an iron cap which is magnetically attracted to the iron cylinder when the valve is closed. Two coils of wire are wrapped around the cylinder. One supports a holding current to magnetize the cylinder and attract the iron cap. When the holding current is turned off, the pressure in the back of the chamber causes the valve to pop open. The second coil is used as a bucking coil to assist in reducing the magnetism and make the valve respond more rapidly. A small spring is inserted between the cylinder and aluminum cap to return the iron cap to the cylinder after the valve has opened.

Slow expansions are controlled by the solenoid valve between the pop-valves. The rate of flow of air through this valve can be controlled accurately. When the chamber is in a state of slow expansion, it is desirable to cut off the flow of air into the back of the chamber. This is achieved with another solenoid valve which closes a port in the air line. The air is supplied by a reservoir tank which is filled by a compressor. A reduction valve in the line controls the pressure.

The next problem to consider is illumination and pho-

tography of the tracks. On either side of the chamber (see Figures 3 and 5) are located two vertically-oriented xenon-filled gas-discharge tubes. Each tube is connected to a 100-micro-farad bank of oil-filled capacitors charged to 2000 volts by a common high voltage power supply. The cathode of each tube is grounded and around this end is wrapped a tickler coil to trigger the tube. This coil is connected to the secondary high potential lead of an ignition transformer. The other side of the secondary is grounded. A 0.75 micro-farad capacitor charged to 200 volts is discharged through the primary, generating a voltage pulse of about 15,000 volts in the secondary.

Light from the tube is collimated by a pair of molded lucite plates which form a cylindrical lens system. Collimation is necessary because the tracks are photographed against a sheet of black velvet mounted on the front stop, and light on the background velvet must be kept to a minimum for good track definition. The tubes and lenses are housed in a frame of 3/4" angle-iron, with the ignition transformers mounted on top of the frame.

It has been shown by Webb⁶ that the intensity of scattered light by droplets in a cloud chamber increases rapidly as the angle between axis of camera lens and direction of

⁶ C. G. Webb, Phil. Mag., 19, 927, (1935).

light beam decreases. Thus it is desirable to make this angle as small as possible. But decreasing this angle has the disadvantage of reducing the amount of active volume falling in the beam of light. It has been found that an angle of about 70° is a satisfactory compromise between intensity and volume illumination.

Light from the sources enters the chamber through transparent lucite plates which form the sides of the active volume. The interior of each plate is coated with transparent "Varnition" V-21B, a varnish-like compound which is resistant to alcohol. Lucite crazes readily when exposed to alcohol.

The illuminated tracks are photographed by a DeVry 35mm motion picture camera which is provided with a single-frame exposure mechanism. The single-frame mechanism is driven by a solenoid which operates on a three-ampere pulse of current from a special selenium rectifier power supply. The camera is provided with a wide-angle $f/4.5$ Wollensac lens which has the desirable property of a depth of focus as great as the depth of the active volume of the chamber at less than four feet and at large stop openings. The shutter of the camera is normally open (for reasons to be discussed later), and this necessitates operating the chamber in darkness. A light shield to keep room light out is to be built later so that lights in the room may remain on.

Although the light sources are shielded against emission of light in all directions except toward the sides of the chamber, the room is well lighted (largely by reflection from the sides of the chamber) by the discharging tubes. To prevent the front glass plate from mirroring objects in the room, a black cloth is draped over the camera and the front of the chamber.

The cloud chamber must be operated in surroundings which are maintained at constant temperature for two reasons. First, any free liquid in the chamber tends to distill to the coolest part. Eventually this will be the front window. Tracks will then be obscured by light scattered from the liquid on the window. Second, if the room temperature fluctuates extensively, the various interior surfaces of the chamber will change temperature at different rates, producing thermal gradients in the active volume. These gradients set up convection currents which distort the tracks. The chamber is operated in an air-conditioned room where the temperature is held at $24 \pm 1^\circ \text{C}$.

Even at constant room temperature it is possible for the vapor to condense on the glass, that is, if the temperature is low and the pressure in the chamber is sufficiently high for condensation. This problem is treated by directing a stream of warm air on the glass. Overheating the glass must be avoided to prevent thermal gradients.

B. The Geiger Counters

The Geiger counters used in the apparatus are made of 1" diameter brass tubing, 18" long, with center wires of 5-mil tungsten. The total pressure of the filling mixture is 11 cm. Hg. This consists of 1 cm. Hg. of ethyl-alcohol vapor and 10 cm. Hg. of argon gas. The tubes have a threshold voltage of about 1000 volts and a plateau length of at least 150 volts. The output pulses are approximately 2 volts when the tubes are operated 25 volts above the threshold voltage.

High voltage for a given tube is obtained in the manner shown in Figure 7. The positive terminal of a supply of 825 volts is grounded, and the negative terminal is connected through a 2.2 megohm resistor to a variable voltage supply, the low potential side of which is grounded.

The 825-volt source is used as a common supply for all the tubes. But each tube is provided with a potentiometer so that its total voltage may be regulated separately. This is necessary because the threshold voltage varies slightly from tube to tube.

For a given tube, the portion of the circuit shown inside the dashed square in Figure 7 is located in the mixer circuit (see Section II, C) if the tube is in tray 1 or 2, or is in the addition circuit if the tube is in tray 3.

FIG. 7 THE GEIGER COUNTER

C. The Electronic Triggering System

A block diagram of the electronic triggering system is shown in Figure 8. The equipment shown in Figures 1 and 2 is included in this diagram. The cloud chamber and camera are, strictly speaking, not included in the triggering system, but they are shown here for clarity. Pulses shown in the diagram are as they appear on an oscilloscope. The left-hand edges thus occur first in time.

The basic function of the triggering system is to select the cosmic-ray events which are photographed by the camera. This system produces an output pulse (known as the master pulse) only when certain specified input conditions are satisfied. Thus the triggering system effectively analyzes the particles which pass through the array of Geiger counters.

There are five basic units in this system: two mixer circuits, an addition circuit, a discriminator, and a triple-coincidence circuit. The multivibrators (MV) and cathode followers (CF) are used for pulse shaping and impedance matching.

The heart of the selection mechanism is the triple-coincidence circuit. It produces an output pulse only if three pulses, one at each of its inputs, occur simultaneously. The coincidence circuit, as its name implies, is thus a time discrimination unit which requires that three events happen

at the same time.

The nature of these three events is determined by the selection requirements of the circuitry that pulses from the Geiger tubes must pass through before reaching the coincidence circuit. Pulses from the first and second trays of Geiger tubes (the telescope) pass through identical mixer circuits. Each mixer requires only that one or more of its inputs be triggered in order for it to produce an output pulse. This, in conjunction with the coincidence circuit requirement of simultaneity, constitutes the zenith-angle measurement discussed in Section I, B.

The requirements placed upon the input pulse to the third channel of the coincidence circuit are somewhat more restrictive. Pulses from tray 3 are fed to an addition circuit which has an output pulse height proportional to the number of input pulses that occur simultaneously. Thus, in view of the discussion in Section I, C, the output pulse height is proportional to the energy of the shower-initiating particle. The output of the addition circuit is then fed to a discriminator which is biased to respond only to pulses with heights greater than a certain minimum value. When an input pulse of sufficient amplitude occurs, the discriminator feeds a pulse to the third channel of the coincidence circuit.

The addition and discriminator circuits constitute

INCIDENT
PARTICLES

TRAY 1

MIXER

MV

CF

PRODUCTION LAYER

TRAY 3

ADDITION

CF

DISC

MV

CF

CAMERA

CLOUD CHAMBER

TRIPLE
COINC

SMALL
RC INP.

MV
CF

MASTER
PULSE

TRAY 2

MIXER

MV

CF

825V

FIG. 8 THE ELECTRONIC TRIGGERING SYSTEM

the energy measurement discussed in Section I, C. And the simultaneity requirement of the coincidence circuit correlates the energy measurement timewise with the angle measurement of the telescope.

A more detailed description of the circuitry will now be given. Three of the circuits so far discussed--coincidence, mixer, and addition--are variations of a single type of circuit which uses several tubes connected in parallel to a common plate resistor. Each circuit, by means of a properly selected load line, exploits the properties of a certain region of the family of plate characteristic curves generated by 1, 2, 3, ..., n tubes connected in parallel. One important feature of the set of curves is that for a given plate voltage, two tubes conduct twice as much current as one tube, and in general, r tubes conduct r times as much current as one tube. Other important features will be discussed with the respective circuits in which they are used.

Figure 9 shows a circuit diagram of the coincidence circuit. The operation of this circuit may most easily be described in terms of its load line and the plate characteristic curves of the tubes. See Figure 10. The diagram is not drawn to scale, since the horizontal portions of the characteristic curves actually lie much higher above the load line. The numbered curves correspond respectively to 1, 2, and 3 tubes connected in parallel. Since the plate resistor

FIG. 9 THE COINCIDENCE CIRCUIT

FIG. 10 THE COINCIDENCE CIRCUIT LOAD LINE AND CHARACTERISTIC CURVES

is the same, the load line is the same in each case. Under normal static conditions all three tubes are conducting, their grids being grounded. When a single tube is cut off by an input pulse, an output pulse occurs corresponding to the plate voltage change between the intersections of the load line with curves 3 and 2. When two tubes are cut off simultaneously, an output pulse occurs corresponding to the voltage change between the intersections of the load line with curves 3 and 1. On the other hand, when all three tubes are simultaneously cut off, the plates rise to B_+ . This pulse is clearly many times larger than the output pulse for single or doubly-coincident input pulses. The difference in pulse height may easily be made a factor of ten or more by making the plate resistor sufficiently large.

Although an ideal coincidence circuit produces an output pulse only for triple coincidences, any real coincidence circuit produces small, though detectable, pulses for single-pulse and double-coincidence inputs. These small pulses are readily eliminated by feeding the output to a multivibrator biased to accept only pulses of a certain minimum size or larger.

Although the size of the small pulses is reduced by increasing the plate resistance, this has the compensating effect of increasing the RC rise time of each tube. If the length of the input pulses is sufficiently short, the tubes

will not have time to reach B+ before they are cut off again and the output pulse height will be made correspondingly smaller. A very satisfactory compromise between these effects is achieved with a 75K resistor.

An explanation should be given here of what actually constitutes a triple coincidence. Input pulses to the coincidence circuit are 20 micro-seconds long. If, during the 20 micro-seconds that any one tube is cut off, the other two tubes are cut off also, the circuit registers a triple coincidence. "Simultaneity" thus is actually a 20 micro-second interval. Particles passing through the apparatus require somewhat less than one micro-second to pass through all three trays. Thus three pulses, one from each tray, may readily occur within the required time of the coincidence circuit.

Of course, chance coincidences may occur also, but they happen very rarely compared to actual coincidences. The rate of chance coincidences can be reduced by making the input pulses shorter. The rise time of the pentodes effectively determines how short the input pulses can be made. Fast pentodes are thus preferable to triodes which have a longer rise time.

SPST switches are provided in the plate circuit of each tube. Any one channel may thus be operated by itself. This is particularly convenient when one is checking the circuitry with an oscilloscope. Also, any two channels may be

operated together as a double coincidence circuit. For example, if desired, the telescope can be used independently of the energy selecting system.

A diagram of a section of the mixer circuit is shown in Figure 11. The complete circuit consists of four such units, using the common 10K, 10W plate resistor. There are eight input channels, each using one-half of a 6J6 double triode. This circuit can also be explained most easily in terms of a diagram showing the load line of the entire circuit and the characteristic curves of the tubes. See Figure 12. The diagram is not to scale. The characteristic curves should be separated by only about one-third of the distance shown in the diagram.

The only requirement for an effective mixer is that it produce an output pulse of sufficient amplitude to trigger other electronic components whenever one or more of its inputs receives a pulse. The smallest output pulse clearly occurs when only one channel is triggered. A 10K resistor in the plate circuit makes this pulse approximately 5 volts, which is adequate for triggering the components following the mixer circuit. A 10K resistor is nearly an optimum value, since a larger or smaller resistor begins to decrease the pulse height. This can be seen from Figure 12. As the slope of the load line is decreased the characteristic curves begin to converge. At larger slopes the load line becomes more

FIG. II A SECTION OF THE MIXER CIRCUIT

FIG.12 THE MIXER CIRCUIT LOAD LINE AND CHARACTERISTIC CURVES

nearly parallel to the characteristic curves.

Since the output pulse is only about five volts, a triode has a sufficiently short rise time for this circuit.

A section of the addition circuit is shown in Figure 13. There are 8 such units in the complete circuit, giving a total of 16 channels, all using the common 5K plate resistor. (Although the third tray of Geiger counters presently contains but three tubes, more are to be added later.) The addition circuit is quite similar to the mixer circuit. But the slope of the load line is made larger so as to intersect the various characteristic curves where they are nearly straight lines. If the characteristic curves were exactly parallel in this region, the output pulse would be linearly proportional to the number of tubes triggered. Although the curves have slightly different slopes, the difference is not great, and the output pulses are nearly proportional to the number of triggered inputs. Strict linearity may be achieved by using pentodes and operating well above the knees of the characteristic curves.

Each channel is provided with a cathode resistor to allow fine control of the output pulse height of that particular channel. This is necessary because the input pulses from the Geiger tubes may not be of the same height.

The discriminator circuit is shown in Figure 14. The analysis of this circuit is quite complicated and will not be

FIG. 13 A SECTION OF THE ADDITION CIRCUIT

FIG. 14 THE DISCRIMINATOR

undertaken here. It can be found in any standard text on electronics. The function of the discriminator is to select only pulses greater than a certain minimum height that reach it from the addition circuit. The discriminator is provided with two variable resistors in the grid circuit. They are grid bias controls used to determine the minimum pulse height which will trigger the discriminator. One of these is a coarse control; the other is a fine control.

The remaining elements in the circuit--multivibrators, and cathode followers--are used for pulse shaping and impedance matching.

Circuits such as the mixer, addition, discriminator, and coincidence circuits frequently produce output pulses that are poor for use in triggering other electronic elements. This may be because the output pulses are too large or too small, too long or too short, or because their leading and trailing edges have undesirable slopes which lead to poorly defined triggering properties.

Two kinds of "one-shot" multivibrators, one for positive input pulses and one for negative input pulses (see Figures 15 and 16) are used extensively throughout the circuitry to produce square pulses of desirable length, with sharp leading and trailing edges. These multivibrators are standard cathode-coupled circuits. The output pulses are about 25 micro-seconds long and have an amplitude of approximately 60 volts.

FIG. 15 THE MULTIVIBRATOR FOR POSITIVE INPUT PULSES

FIG. 16 THE MULTIVIBRATOR FOR NEGATIVE INPUT PULSES

The outputs of the multivibrators (either positive or negative, depending upon which plate is used) are fed to cathode followers (see Figures 17 and 18). Variable resistors in the latter circuits are used to control pulse heights. The outputs of the cathode followers can be made to give pulse heights from zero to about 0.9 the height of the multivibrator pulse. The cathode followers also are used for impedance matching. They serve principally to prevent loading of the multivibrators by units such as the coincidence circuit and by long coaxial cables.

If the multivibrators are to have pulse lengths determined by their own RC times, they must be triggered by pulses which are very short compared to the length of the output pulse. They perform best if triggered by a sharp spike pulse. In some cases the input pulse is of the same length as the multivibrator pulse. For example, the output pulse of the coincidence circuit is approximately the same length as the RC time of the multivibrator following it. Consequently the coincidence circuit output is differentiated by coupling it to a cathode follower with a very short RC input (20K, 25 μ f).

Whenever the input pulse to a multivibrator is one of the spikes from a differentiated pulse, the other spike must be eliminated or it will bias the multivibrator in the reverse direction and more than likely turn it off before it has completed its cycle. This undesired spike is eliminated

FIG. 17 THE CATHODE FOLLOWER FOR POSITIVE INPUT PULSES

FIG. 18 THE CATHODE FOLLOWER FOR NEGATIVE INPUT PULSES

by means of a IN34 crystal diode connected in the grid circuit in such a manner as to give a very low impedance to ground to the unwanted spike.

The master pulse from the trigger system, having been generated and shaped in the manner described above, is then fed to another system of electronics, the control system described in the next section.

D. The Electronic Control System

A block diagram of the control system is shown in Figure 19. The function of this system is to initiate and coordinate the operations necessary for recording the data represented by any master pulse which triggers it. It should be mentioned here that not all master pulses trigger the control system. After being activated, the system requires five minutes to go through its complete cycle of operations. During this time additional master pulses are blocked from the system by a mechanism known as a gate. This is an electronic device which, with the exception of a very short transition time, is always in one of two possible states. On the one hand it may be "open"; it will then allow a master pulse to pass through it to the next element of the control system. On the other hand, it may be "closed," in which case a master pulse is stopped at this point and does not reach any of the following elements in the control system.

Suppose the system has just completed a control cycle. The gate is now open and ready to receive a master pulse. As soon as one occurs, it passes through the gate and triggers a series of events which take place within the first second of the control cycle. These events are the following: first, two relays in the relay circuit are closed. One turns on the motor and closes the gate. The other is used in opening the relay circuit again at the end of the cycle, as described later. Second, the clearing field is briefly cut off. Third, the pop-valve holding current is momentarily turned off and the bucking current momentarily turned on. The pop-valves then open, the chamber expands and the valves close again. Fourth, the lights are flashed.

Because of mechanical and electronic delays, these four events occur at different times within the first second of the cycle. The first three are triggered by pulses that occur immediately after the gate receives a pulse. However, the mechanical delay of the pop-valves (including the effects of both hysteresis and inertia) is greater than that of the relays and the latter close before the pop-valves open. The clearing field is controlled by the same type of relay as the motor and gate, and it is also cut off before the pop-valves open.

The pulse which fires the lights is electronically delayed because tracks are not immediately formed in the chamber.

This delay is actually a combination of three delays. The first is the mechanical delay of the pop-valves. The second is a delay due to the time required for the chamber to reach supersaturation. The third is the time required after supersaturation is reached for the tracks to grow to sufficient size to be photographed clearly. The sum of these three is about 0.1 second.

The light triggering pulse must not be delayed much more than 0.1 second because turbulence in the chamber rapidly distorts the tracks. A compromise between track size and track distortion must be made in selecting the optimum delay time.

It was mentioned previously that the camera shutter is normally open. This is desirable for two reasons. First, because of the various delay times involved, it is difficult to synchronize the opening of a normally-closed shutter with the peak intensity of the light flash from the xenon tubes. Second, when the chamber is initially set into operation, the optimum delay time for flashing the tubes must be determined experimentally. This involves varying the delay time over an interval of about one second. If the shutter is left open, this avoids the problem of synchronizing the shutter opening with the different delay times.

At the end of the first second of the control cycle, the clearing field is restored in the chamber. The motor-

driven cam system now completes the control cycle by operating three microswitches. One of these is used to carry the chamber through four cleaning expansions spaced forty seconds apart. Each expansion lasts five seconds and is followed by a ten-second interval in which the chamber remains expanded to allow the droplets to be removed.

Halfway through the series of cleaning expansions a second microswitch is triggered. This activates the single-frame mechanism of the camera. Finally, eighty seconds after the last cleaning expansion, the third microswitch is used to turn off the motor and open the gate, thus terminating the control cycle.

A detailed description of the control system will now be given. All diagrams show the system as it exists immediately before a control cycle is to begin.

Figure 20 shows the gate circuit. It employs a 6AS6 pentode, with the suppressor grid used as a second control grid. The conventional control grid is biased 30 volts negative and the tube is normally off, whether the gate is open or closed. The suppressor controls the gate action. When it is grounded the gate is open. When it is heavily biased, the gate is closed. The bias level is controlled by connecting the suppressor through a relay (see Figure 24) to -200 volts and through a parallel circuit to ground. When the relay is open the suppressor is grounded. When it is closed the sup-

FIG.20 THE GATE

pressor is connected to -100 volts. (The two 2.2-megohm resistors are then in series and form a voltage divider.)

A manual switch is also provided for controlling the gate. This switch is normally in the "on" position as it is shown in the diagram. In the "off" position the suppressor is connected to -100 volts regardless of whether the relay is open or closed.

Since both positive and negative pulses are needed for triggering purposes in subsequent parts of the system, the gate is followed by a multivibrator from which both polarities can be obtained. The outputs of the multivibrator plates are fed to two cathode followers. They are essential at this point because the pulses from the multivibrator are used to trigger several other components which would seriously load a multivibrator if connected directly to it.

A pulse from one of the cathode followers triggers the holding current circuit shown in Figure 21.

This circuit consists of two channels, one for each valve, with a single input. Each channel has a variable bias voltage to control the holding current and a milliammeter to register it. The holding current for each valve must be separately variable for two reasons. First, the holding current in each valve must be made small so that the valves will respond as rapidly as possible after being triggered. Because of magnetic hysteresis, larger currents produce greater

FIG. 2i THE HOLDING - CURRENT CIRCUIT

residual magnetism in the valves and more time is required for the bucking current to reduce this magnetism to the point where the valve will open.

Second, since the valves are not geometrically identical, each has a different minimum holding current. If the currents in the valves are not simultaneously the same amplitude above their respective minimum values, the valve in which the current differs most from its minimum value may fail to open. This is due to the fact that the valves are opened by pressure in the chamber. If the magnetism in one of the valves is bucked out before it is in the other, the first valve will open and allow the pressure to drop before the second valve has a chance to respond.

One of the valves has a minimum holding current of 8 milliamps and the other, 11 milliamps. Both valves are operated 3 milliamps higher than their minimum values.

The bucking circuit is shown in Figure 22. This circuit also consists of two channels, one for each pop-valve, with a common input. The SN4 thyratron is fired by establishing a sufficient potential gradient between grids 1 and 2. The bias on grid 2 is set about 20 volts below breakdown potential and the tube is non-conducting. A bank of four 80 micro-farad capacitors connected in parallel to the plate is charged to B+. (This bank is shown as a single 320 micro-farad capacitor in Figure 22.) When an input pulse occurs,

FIG. 22 THE BUCKING - CURRENT CIRCUIT

grid 2 rises above the breakdown potential and the tube turns on momentarily, discharging the bank of capacitors through the cathode circuit. One side of the bucking-current coil in the pop-valve is connected to the cathode through a current limiting inductance. (This consists of about 15 turns of #20 gauge wire wound on a 1/4" diameter form, 1 1/2" long.) The other side is grounded. This surge of current bucks out the residual magnetism in the pop-valve.

Figure 19 shows a multivibrator and cathode follower immediately preceding the bucking-current circuit. The multivibrator is used to form the pulse which triggers the SN4. A pulse of at least 25 micro-seconds and 50 volts is necessary to cause the tube to fire.

The cathode follower is used to isolate the SN4 from the rest of the electronics. When a thyatron fires, a large quantity of charge is suddenly dumped into the tube. A portion of this charge strikes the control grid, inducing on it a large and very irregular pulse. If the grid were not isolated by the low output impedance of the cathode follower, this pulse would be fed back to the multivibrator and its operation would be distorted.

Figure 23 shows the clearing-field circuit. It consists essentially of a relay whose solenoid is connected into the plate circuit of one-half of a 6SN7 triode. This tube is normally conducting and the relay is normally closed. One

FIG.23 THE CLEARING FIELD CIRCUIT

side of the relay switch is connected to the center tap of a variable potentiometer, the outside terminals of which are connected across -200 volts. The other side of the switch connects through a 100K resistor to two of the clearing field plates. (The other two plates are grounded.) When the switch is closed, the potential difference between any two adjacent plates is 200 volts. A potentiometer is provided so that the clearing field may be reduced if 200 volts proves to be too large. A high potential gradient can lead to conduction in the gas of the chamber. The 100K resistor serves as protection against such conduction.

The pulse which cuts off the 6SN7 and opens the relay is formed by a multivibrator whose output pulse is one second in length. The long pulse is obtained by replacing the 220K grid resistor in Figure 15 with a 2-megohm resistor and replacing the 1000 micro-micro-farad feedback capacitor with a 0.1 micro-farad capacitor. The output must be coupled through a 1 micro-farad capacitor to avoid differentiation of the long pulse.

The relay circuit is shown in Figure 24. The micro-switch shown in the diagram is actually in the microswitch system, but it is so closely associated with the relay circuit that it is shown here for clarity.

The tube in this circuit is normally cut off by the bias voltage on the grid. An input pulse turns the tube on

FIG. 24 THE RELAY CIRCUIT

momentarily and both relays are activated, closing the three relay switches. The gate is then closed and the motor turned on. Although the tube is cut off again as soon as the input pulse passes, the relay switches remain closed, since a new path to ground has been established through the 56K resistor.

The second relay and the microswitch are used to open the relay circuit at the end of the control cycle. This will be discussed later.

The circuit for delaying the light-triggering pulse consists of three units. The first is a long-pulse-length multivibrator, the positive output of which is differentiated by the small RC input of a cathode follower. This multivibrator is the same as the one discussed in connection with the clearing-field circuit, except that the 2-megohm grid resistor here is a potentiometer to make the output pulse variable in length. The delayed negative spike of the differentiated pulse then triggers another multivibrator which forms the pulse required to trigger the ignition transformer circuit, shown in Figure 25.

This is a thyatron circuit which operates in essentially the same manner as the circuit shown in Figure 22. A 2D21 is used here because smaller currents are involved. The primaries of all four ignition transformers are connected in parallel in the plate circuit. The tube is normally biased off by the 5.6K resistor. The 0.75 micro-farad capacitor tied to the plate through the primaries of the ignition trans-

FIG. 25 THE IGNITION TRANSFORMER CIRCUIT.

formers is then charged to 200 volts. A negative pulse of about 50 volts and 20 micro-seconds fires the thyatron and the 0.75 micro-farad capacitor discharges through the tube. The surge of current through the transformer primaries generates a pulse of 15,000 volts in each secondary, causing breakdown in the xenon flash tubes.

Figures 26 and 27 show two views of the cam and microswitch system. The first is a top view; the second is a view along the axis of rotation of the cams. The cams rotate clockwise. A time scale is superimposed upon the cams in Figure 27. Microswitches 1 and 3 shown in Figure 26 are superimposed in Figure 27 and appear as a single switch.

Switch 1 is in the plane of cam 1, which is a circular disc with four lobes spaced around the circumference. Switches 2 and 3 are in the plane of cam 2, which is a long, thin lever.

The system is shown immediately before receiving a triggering pulse. Forty seconds after a pulse occurs, the first lobe of cam 1 activates microswitch 1 by pressing against the microswitch slider and depressing the pin. After fifteen seconds the slider is released and the switch is deactivated. Lobes 2, 3, and 4 repeat this process.

Halfway through the control cycle, cam 2 activates microswitch 2, which triggers the camera circuit shown in Figure 28. This circuit consists essentially of a power sup-

**FIG. 26 THE CAM & MICROSWITCH SYSTEMS
(TOP VIEW)**

**FIG. 27 THE CAM & MICROSWITCH SYSTEM
AXIAL VIEW**

FIG. 28 THE CAMERA CIRCUIT

ply and a heavy-duty relay for carrying the large current drawn by the camera. A microswitch would burn out immediately if three amperes passed through it. The microswitch is required to carry only enough current from the power supply to close the heavy-duty relay.

The final step in the control cycle occurs 80 seconds after the last cleaning expansion is completed. Cam 2 then activates microswitch 3. The basic operation here is to open the relay circuit so that the motor will turn off and the gate will open. This operation is accomplished by opening microswitch 3 long enough for the relay circuit to open and then closing the microswitch again. Since the 6SN7 is not conducting and relay 2 is now open, the circuit remains open.

Actually, this operation requires two steps. First, relay 1 is opened, then relay 2 is opened. This is necessary because of the small but finite time that the microswitch remains open. If relay 2 opens as soon as the microswitch, the microswitch fails to close again, and a permanent break in the relay circuit exists at the microswitch. This is due to the fact that when relay 2 opens, the motor stops and the inertia of the system is insufficient to carry the slowly-moving cam past the microswitch slider before it comes to rest. Consequently, the "normally-open" terminal of the microswitch is used to provide a temporary path to ground

for relay 2. When the microswitch is activated, relay 1 opens, but relay 2 remains closed. When the microswitch is deactivated, relay 2 then has no path to ground, and it opens.

A large portion of the electronics discussed in Sections C and D is shown in Figure 29.

Figure 25. The electronics

CHAPTER III

SOME RESULTS

The pictures shown in this section are some preliminary photographs of tracks taken in the apparatus described above. An expansion ratio of 1.10 was used in all cases.

The first two pictures were taken without the lead plates in position. Figure 30 is probably a low-energy electron shower, while Figure 31 is probably a high-energy electron shower. However, because of the absence of clear scattering or track multiplication, there is no positive means of identifying these tracks as electrons rather than pi-mesons. In Figure 31, the slight scattering of the tracks by the gas is indicative of electrons; however, convection currents could produce the same effect. (The white strips are orientation markers.)

The remaining photographs were taken with the lead plates in position. There are four plates shown in these pictures. The upper- and lower-most are made of a hard insulating material with strips of brass mounted on them; they alone were used in maintaining a clearing field in the chamber before the two middle plates were added.

In Figures 32-34, a 1/4" layer of lead is laid on the top insulator. Each of the two middle plates consists of

Figure 30

Figure 31

Figure 32

Figure 33

Figure 34

1/4" of lead supported by a 1/4" sheet of aluminum.

Figure 32 shows a clear example of electron deflection in a low-energy shower. An electron entering almost vertically is scattered sharply to the left in the second layer of lead. At the point where it leaves the plate, a very low-energy electron emerges and is scattered greatly by the gas.

Figures 33 and 34 show the second method of electron identification. In Figure 33 electrons multiply in passing through the second plate. Most of these are absorbed in the third plate. Figure 34 shows a high-energy electron shower. Extensive multiplication occurs in the first plate. As the electrons progress downward, absorption in the plates removes all but the most energetic of these. Scattering by the gas is very prominent in some of the tracks.

In all of these pictures, a number of tracks appear that are unrelated to the showers. These tracks are due to particles that naturally and unavoidably pass through the chamber at essentially the same time as the showers. Many of these particles are electrons, as is shown by the extensive scattering of their tracks by the gas in the chamber.

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