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A preliminary search for subionizers

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A PRELIMINARY SEARCH FOR SUBIONIZERS

BY

JOSEPH B. HUGHES

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A

THESIS

submitted to the faculty of

THE UNIVERSITY OF MISSOURI SCHOOL OF MINES AND METALLURGY

in partial fulfillment of the work required for the

Degree of

MASTER OF SCIENCE, PHYSICS MAJOR

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1959

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Approved by

James L. Kassner Jr. (Advisor)

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I. INTRODUCTION

A number of physicists of recent years have been attempting to explain the basic nature of the universe in terms of particles. A few particles have been predicted theoretically, and some of these, along with many others have appeared experimentally. Searches for them have presented some interesting experimental problems and brought forth some invaluable experimental apparatus. One of these devices is the Wilson cloud chamber, with which this thesis is concerned.

Of the particles that have been discovered thus far, only the electron and the proton appear to be stable. The rest ultimately decay by the emission of photons and electrons, and possibly neutrinoes, until they reach the state of the electron or proton. The stability of the neutrino is still controversial[1], but its rest mass is generally accepted to be zero[2]. It is the only particle believed to have less mass than the electron.

Another property of particles which aids greatly in describing the nature of matter is charge. Spin and magnetic moment also hold interesting possibilities, but this discussion will be confined to charge. All of the particles which are charged appear to have a

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[1] Lee, T. D. and Yang, C. N., "Parity Nonconservation and a Two-Component Theory of the Neutrino," Physical Review, 105, 1676, (1957).

[2] Sakurai, J. J., "Rest Mass of the Neutrino," Physical Review Letters, 1, 40, (1958).

charge numerically equal to that of the electron. This is somewhat difficult to prove experimentally; and, since at present there is no theoretical basis for the quantization of charge, there is reasonable room for doubt. If charge values other than integral multiples of the accepted electronic charge do exist, ionization measurements of tracks in a Wilson cloud chamber (the most sensitive of all ion detecting instruments) should expose them if their values lie within certain limits imposed by the apparatus.

There is also some theoretical basis for the possible existence of a magnetic monopole.[1] The experimental observation of a magnetic monopole would be of considerable theoretical interest. It should be recognizable by a careful study of its ionization in a Wilson cloud chamber.

In searching for nonstandard electric charge values by ionization methods, it is necessary to avoid confusion with standard electronic charge values. Since the ionization of an electric charge passes through a minimum with increasing velocity, it would seem advisable to restrict early experiments to charge values which would produce minimum ionizations well below the minimum ionization of an electron. It is possible that other types of particles such as magnetic monopoles could produce ionization rates in the region below the minimum ionization of the electron. There is also the possibility that there are neutral particles with unusual magnetic moments which could give rise to very small ionization rates. All such particles shall be defined as subionizers.

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[1] Dirac, P. A. M., "The Theory of Magnetic Poles," Physical Review, 74, 817, (1948).

This work, then, will be concerned with establishing the techniques and performing a preliminary search with our apparatus for any particles which ionize more lightly than the minimum ionization rate of the electron. It is expected that particles having ionization rates between one ion pair per cm of path length and fifteen ion pairs per cm can be definitely distinguished from light trails of droplets produced by poor chamber conditions. This corresponds to a sub-charge between 1/7 e and 1/2 e.

II. PREVIOUS WORK

In 1917, Millikan determined the charge of the electron by studying the motion of charged oil droplets between the large parallel plates of a capacitor. His work was subject to certain minor inaccuracies, but it is universally accepted. He determined that the smallest quanta of charge is the electronic charge, e (4.8×10^{-10}esu).

Dirac then proposed the existence of isolated magnetic poles and showed by the symmetry of the electrodynamic field equations that, if charge is quantized in units of e, it follows from quantum mechanics that pole strength is likewise quantized in units of g ($\frac{137e}{2}$ emu). Anderson's discovery of the positron, which was also predicted by Dirac, led Tuve[1] to suggest certain deflection experiments for the detection of free magnetic monopoles. He stated that it would be unlikely that high speed monopoles would have the same type of interactions with matter as similar charged particles. He felt that their ionization rates might be too small for them to be detected.

Cole[2] and Bauer[3] computed independently the ionizations of poles of various masses. Cole worked with particles of mass equal to that

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[1] Tuve, M. A., "Search by Deflection-Experiments for the Dirac Isolated Magnetic Pole," *Physical Review, 43*, 770, (1933).

[2] Cole, H. J. D., "The Theoretical Behavior of a Magnetic Monopole in a Wilson Cloud Chamber," *Proceedings of the Cambridge Philosophical Society, 47*, 196, (1951).

[3] Bauer, E., "The Energy Loss of Free Magnetic Poles in Passing Through Matter," *Proceedings of the Cambridge Philosophical Society, 47*, 777, (1951).

of the proton or greater. Bauer made his calculations for particles with masses in the neighborhood of the electronic mass. Both of them assumed the Dirac value for the pole strength. Cole found that the ionization of the heavier particles would be nearly constant at higher velocities and then would drop off rapidly as the particle nears the lower end of its velocity. Bauer found that monopoles with masses near the mass of the electron would lose their energy so rapidly through bremsstrahlung radiation processes that they would not very likely be observable.

Ehrenhaft[4] claims to have observed both subcharges and monopoles in an oil drop type of apparatus. In his study of photophoresis, he says he has observed both electric and magnetic ions being produced by strong light. The particles he was dealing with, however, were stable at rest. This would be highly unlikely for particles of the pole strength Dirac suggested. Although Enrenhaft's work is not generally accepted, it would be most unscientific to say that he and his co-workers did not observe a subelectron or isolated pole.

Certain experiments have been performed to try to produce stable resting monopoles artificially, or to collect them. Benedikt and Leng[5] subjected a colloidal suspension of Fe_2O_3 to an intense magnetic field, and observed the drift of the colloidal particles. They concluded

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[4] Ehrenhaft, F., "The Microcoulomb Experiment," Philosophy of Science, 8, No. 3, (1941), and "Photophoresis and Its Interpretation by Electric and Magnetic Ions," Journal of the Franklin Institute, 233, 235, (1942).

[5] Benedikt, E. T., and Leng, H. R., "On the Existence of Single Magnetic Poles," Physical Review, 71, 454, (1947).

that no monopoles of pole strength greater than 1.5×10^{-12}emu existed in their apparatus. Others, such as Kane[6], have tried to duplicate Ehrenhaft's work, but they were either unable to obtain comparable results, or they interpreted their results differently.

At the suggestion of Teller, Malkus[7] searched for magnetic monopoles in the secondary radiation from cosmic rays. His assumption was that if these particles were created in pairs, they would lose their energy and wander for a long time before they would find another particle to annihilate with. His intention was to accelerate these particles in a vacuum in a field of 250 gauss, and detect them with a photographic emulsion. He used a long solonoid of large cross-sectional area, and operated it continuously for two weeks. There were no heavy tracks except a few randomly oriented alpha particles. He, too, assumed the Dirac value for the pole strength, and thus was only looking for heavy tracks. It is possible that he ignored the lighter tracks, or was not able to differentiate them from electron tracks.

In 1953, Ruark[8] began a search at the University of Alabama for subionizing particles of any description. He suggested that both particles of charge smaller than that of the electron, or monopoles

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[6] Kane, G., "Magnetic Ions and Magnetic Currents," Physical Review, 71, 458, (1947).

[7] Malkus, W. V. R., "Interaction of the Dirac Magnetic Monopole with Matter," Physical Review, 83, 899, (1951).

[8] Ruark, A. E., "A Cloud Chamber Search for Free Magnetic Poles," A proposal to the National Science Foundation, (1953) (Unpublished).

of low pole strength traveling at high velocities, would ionize less than the minimum ionization rate of the electron. Fitz[9], Good[10], Kassner[11], Shuskus[12], and Tyler[13] worked under him in this research.

Fitz was the first to work on this project. He laid the theoretical ground work for the project. He generalized the equations for ionization and scattering for particles of nonstandard charge and mass, and exhibited relations governing the production cross-sections. He made similar calculations for monopoles.

Good used the Bearden chamber to search for subionizers in the flux from a radioactive source, and Tyler used it to search in the cosmic ray flux. Both observed tracks with low drop counts per cm of length, but they were unable to identify these with a possible subionizer. They concluded that all such tracks were produced by abnormal chamber conditions or recombination phenomena occurring prior to the expansion.

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[9] Fitz, H. C., "Apparatus and Methods for a Search for Particles Ionizing More Lightly than the Electron," Master's Thesis, University of Alabama, (1955) (Unpublished).

[10] Good, W. B., "A Search for Particles Ionizing More Lightly than the Electron," Ph.D. Dissertation, University of Alabama, (1956) (Unpublished).

[11] Kassner, J. L., "A Search for New Particles in Cosmic Rays with a Large Cloud Chamber," Ph.D. Dissertation, University of Alabama, (1957) (Unpublished).

[12] Shuskus, A. J., "Apparatus for Scintillation Counting of Cosmic Rays in a Search for Particles Ionizing More Lightly than the Electron," Master's Thesis, University of Alabama, (1957) (Unpublished).

[13] Tyler, W. C., "A Cloud Chamber Search for Anomalously Charged Particles in the Cosmic Ray Flux," Master's Thesis, University of Alabama, (1957) (Unpublished).

Kassner used a tall cloud chamber to investigate cosmic radiation. This type of chamber has the disadvantage of excessive turbulence and background. His results were also inconclusive.

Shuskus developed a geiger counter telescope including a scintillation tank to study the nearly vertical cosmic radiation. His apparatus was ingenious, but the minimum subionizer flux which he could detect was too high (about 5 percent of the total flux).

Mettenburg[14] and Rinker[15] worked under Kassner at the University of Missouri School of Mines and Metallurgy. They constructed and operated a Wilson cloud chamber with a sensitive time in the neighborhood of three seconds, and an average background density of about 0.05 drops per cubic centimeter. Mettenburg assembled the chamber in its original form and determined the optimum operating conditions. Rinker made a study of chamber background and its causes and effects. Rinker obtained the best photograph of a subionizer suspect observed to date. However, the photograph was taken as a single frame of an individual expansion without stereoscopy which made its indentification impossible.

Haque[16], in continuing the work at the University of Alabama, with the Bearden chamber, also obtained some excellent photographs of subionizer suspects.

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[14] Mettenburg, C. W., "An Improved Long Sensitive Time Cloud Chamber," Master's Thesis, from the University of Missouri School of Mines and Metallurgy, (1958) (Unpublished).

[15] Rinker, D. A., "A Study of Background in a Long Sensitive Time Cloud Chamber," Master's Thesis, University of Missouri School of Mines and Metallurgy, (1958) (Unpublished).

[16] Haque, B., "A Cloud Chamber Search for Subionizing Particles," Ph.D. Thesis, University of Alabama, (1958) (Unpublished).

All those investigators who used the Bearden chamber for a search for subionizers made use of incandescent lights for photography. The exposures were of the order of 0.1 sec which could considerably reduce the resolution of droplets in ordinary tracks. It is doubtful whether this lack of resolution was damaging in instances where subionizer suspects were involved. Eight or ten photographs were taken at a rate of about four frames per second. It is not known whether Good, Haque, and Tyler required the suspected subionizer track to appear well in the center of the sensitive period in order to qualify as a bona fide suspect.

It was thought that the maximum possible photographic resolution should be obtained, and that this might best be achieved using flash-tube illumination. It was also concluded that a longer sensitive time and a more rapid framing rate would be required to insure positive identification of real subionizer suspects. The techniques required to successfully obtain 22 successive flashes at rather high energy inputs required further major developments at the onset of this investigation. A stereoscopic movie camera which would be capable of photographing the chamber under the desired conditions was in the process of development.

The aim of this investigation is to try to detect a subionizer suspect which enters the chamber well in the center of the sensitive period, and which does not appear too close to the chamber walls. The multiple photography will give information with regard to the approximate time the track enters the chamber while stereoscopy will determine its initial position in the sensitive volume.

III. THEORETICAL CONSIDERATIONS

General

As stated previously in the introduction, this search is being confined to particles which ionize less than the minimum ionization of the electron. It would be difficult to distinguish between a charge of 1.5 e at minimum ionization and 1.0 e at slightly greater than minimum ionization. For this reason, we will not attempt a search for anomalous charges larger than e. In principle, it would be possible to differentiate between these particles at minimum ionization; however, it is experimentally difficult to determine which particles produce minimum ionization.

If subcharges or magnetic monopoles exist in a stable state, in concentrations as high as 10^{-5} per cm^3, they would likely not have been detected by spectroscopic techniques. By investigating the ionization rates of high energy particles, it is believed that if subionizers do exist their tracks can be positively identified provided their ionization rates lie within certain limits. When subionizer tracks are found, it must be shown that these could not be attributed to experimental ambiguities. A discussion of these difficulties and methods of resolving them will be presented below. Once the validity of the subionizer tracks has been established, they can then be classified as to charge or pole strength as the case may be.

Energy Loss by Rapidly Moving Electric Charges

A charged particle, in its passage through matter, ionizers or excites the atoms or molecules in the region through which it passes. It does so by one of the following energy transfer processes:

1. Inelastic collisions with atomic electrons: This is the primary method by which a bombarder loses its energy. Each collision results in one or more transitions to excited or unbound states. The individual collisions can be treated by use of the Rutherford scattering equation.

2. Inelastic collisions with a nucleus: In a near collision with a nucleus, a bombarder will be deflected, and sometimes a quanta of Bremsstrahlung radiation is emitted and the kinetic energy of the particle is reduced by the same amount. There is a certain small probability of nuclear excitation in such collisions, but it is small compared to the radiative probability.

3. Elastic collisions with a nucleus: The bombarder loses just enough energy to take care of the momentum changes. No radiation is emitted, and the nucleus is not excited.

4. Elastic collisions with atomic electrons: These are the low energy collisions. The bombarder is deflected by the electron's field, but the energy exchange is less than the excitation energy. The effect, therefore, is the same as an interaction with the atom as a whole.

Since the major portion of the energy loss is from inelastic collisions with atomic electrons, the rate of energy loss can be measured by measuring the ionization. This ionization results from two types of inelastic collisions: those of large impact parameter or soft collisions (impact parameters larger than atomic distances), and those of small impact parameter or hard collisions (impact parameters smaller than atomic distances). The soft collisions give rise to small angle scattering. This type of collision accounts for the major portion of the ionization observed. If a track is seen to pass straight through a chamber, or wander aimlessly with no sharp changes in direction, the ionization is primarily due to small angle scattering. Because of the interplay of the coulomb forces in the surroundings, the calculation of the ionization from such collisions is not simple. It has been done by Bethe[1], however, whose results will be exhibited below. The hard collisions are the near collisions or large angle scattering with impact parameters on the order of atomic distances. Hard collisions can be treated to a first approximation as free body collisions in the theoretical computation of ionization rates. It is from such collisions that delta rays results. A delta ray is normally the track of an electron which was ejected in an ionization process with sufficient energy that it can ionize a number of atoms or molecules before coming to rest. A delta ray attached to a very lightly ionized track constitutes rather convincing evidence for the existence of subionizers, since both are subject to identical chamber conditions. A statistical study of clumps of secondary ionization of sufficiently low energy that their probability of occurrence would be reasonable would suffice to give information toward the classification of the particle's charge or pole strength.

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[1] Bethe, H., "Quantenmechanik der Ein-und Zwei-Elektronenproblems," Handbuch der Physik, 24/1, 518, (1933).

The differential cross-section per atomic electron for an energy transfer between Q and Q + dQ is:

$$d\sigma = 2\pi x dx = \frac{2\pi z^2 e^4}{m_o v^2} \frac{dQ}{Q^2} \quad \frac{\text{cm}^2}{\text{electron}} \tag{1}$$

Where x is the impact parameter, m_o is the rest mass of the electron, v is the initial velocity of the bombarder, ze is the charge on the bombarder, and Q is the energy transferred. It is interesting to note that the probability of an energy transfer Q varies as $\frac{1}{Q^2}$ and as $(ze)^2$. Therefore, one would expect to find fewer delta rays of a given length along the track of a subionizer of small z than one finds along the tracks of ordinary particles with identical mass. Secondary ionization will appear as small clumps of droplets well within the confines of the track. The average energy loss per unit path length, taken from the differential cross-section, is

$$\frac{dT}{ds} = \frac{N_o}{A} \rho Z \int_{Q_{min}}^{Q_{max}} Q\, d\sigma = \frac{2\pi z^2 e^4}{m_o v^2} \frac{N_o \rho Z}{A} \ln \frac{Q_{max}}{Q_{min}} = \frac{N_o \rho Z}{A} \frac{4\pi\ z^2 e^4}{m_o v^2} \ln \frac{1.123\ m_o v^3 M}{2\pi \bar{\nu} Z e^2} \tag{2}$$

where $\bar{\nu}$ is the average frequency of electronic rotation in the Bohr orbits, and A is the atomic mass number. Q min is chosen in such a way that very large impact parameter collisions are excluded so that the energy loss will remain finite. Q max is determined by the relative masses of the particles.

Before proceeding further in a discussion of ionization, a few terms should be defined. A discussion of these terms is found in Rossi.[2] The primary specific ionization of a high speed ionizing particle is the average number of collisions per gm cm^{-2} that result in the ejection

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[2] Rossi, B., "High Energy Particles," Prentice-Hall, (1956).

of an electron from an atom or molecule. This includes collisions of both large and small angle scattering types. It does not include the ionization due to the ejected electrons. The primary specific ionization has been computed by Bethe for a particle of charge ze:

$$j_p = \frac{2Cm_ec^2}{\beta^2} z^2 \frac{r}{I_o} \left[\ln \frac{2m_ec^2\beta^2}{(1-\beta^2)I_o} + s - \beta^2 \right] \qquad (3)$$

where $C = \pi N_o \frac{Z}{A} r_e^2$ (Z is the atomic number; A, the atomic weight of the target; N_o, Avogadro's number; and r_e, the classical radius of the electron), z is the multiple of the electronic charge borne by the bombarder, c is the speed of light, m_e is the electronic mass, β is the velocity of the bombarder divided by the speed of light, and I_o is the ionization potential of the outer electron of the target material. r and s are constants and have been computed for hydrogen to be $r = 0.285$ and $s = 3.04$. s is believed to vary but slightly with atomic number, and to a first approximation can be considered independent. The reason the primary specific ionization is computed for a point charge, and the spin and magnetic moment neglected, is that the majority of the interactions are large impact parameter collisions, and the spin and magnetic moment are short range effects. The close collisions, in which the structure of the particle comes into play, can be neglected when computing the number of collisions. Referring again to the equation, it should be noted that the primary specific ionization is independent of the mass of the bombarder. In a known substance the ionization varies as the square of the charge of the bombarder. The ionization is nearly constant at high bombarder velocities.

The ionization produced by electrons which have been ejected in ionization processes is called secondary specific ionization. An electron seldom receives enough energy to cause further ionization, except in the somewhat rare large angle scattering collisions. These collisions account for the clumps of droplets and the occasional branches observed in cloud chamber tracks. The branches produced by ejected electrons are called delta rays. The differential cross-section for the production of delta rays with initial energy between T_1 and T_2 is:

$$\frac{2\pi z^2 e^4}{m v_o^2}\left(\frac{1}{T_1}-\frac{1}{T_2}\right) \qquad (4)$$

The <u>total specific ionization</u> is the average total number of ion pairs per gm cm^{-2}. This includes all of the unlikely long delta rays. It is found by the following formula:

$$j_t = \frac{2C m_e c^2 z^2}{V_o \beta^2}\left[\ln \frac{4m_e^2 c^4 \beta^4}{(1-\beta^2)I^2} - 2\beta^2\right] \qquad (5)$$

where V_o is the average energy expended per ion pair produced, and I is the average ionization potential of the absorber.

The most <u>probable specific ionization</u> is the average number of ions per gm cm^{-2} produced by the primary particles and secondary electrons ejected with energy less than E' (10^4 to 10^5 ev). The equation is:

$$j_{E'} = \frac{2C m_e c^2 z^2}{V_o \beta^2}\left[\ln \frac{2m_e c^2 \beta^2 E'}{(1-\beta^2)I^2} - \beta^2\right] \qquad (6)$$

It is obvious that the heavy ionization of the long delta rays weights the average ionization heavily; and, since their occurrence is improbable, they are eliminated from the probable specific ionization. This amounts to simply ignoring the long delta rays when counting droplets to get the specific ionization.

In equation (6), above, it can be seen that the ionization rate varies with velocity (where $v = \beta c$) in such a manner as indicated in Figure 1. The energy imparted to an atomic electron is dependent on the impulse, the force of the electric field times the time it is acting on the electron. At low velocities, a bombarder spends more time in a particular vicinity, and, therefore, has a greater chance of causing ionization. Therefore, as a particle slows down, its ionization rate increases until it is going too slow to ionize at all. The slow increase of the ionization at very large velocities is attributed to relativistic effects. As the velocity approaches the speed of light, the Lorentz contraction causes the radial electric field to be compressed toward a plane through the particle perpendicular to the velocity. Since the field is compressed, the force it will exert is greater; and, at relativistic velocities, this increased force overcompensates the decrease in reaction time and gives an increased impulse. Between these two effects, there is a region of minimum ionization rate. It occurs at about ninety-five percent of the speed of light for the electron. The electron has the lowest minimum ionization rate observed thus far (about 50 ion pairs per cm in air). Our laboratory is concerned with searching for possible particles whose specific ionizations lie below the minimum specific ionization of the electron. Figure 2 shows the effect of varying the charge. It should be noted that the minimum

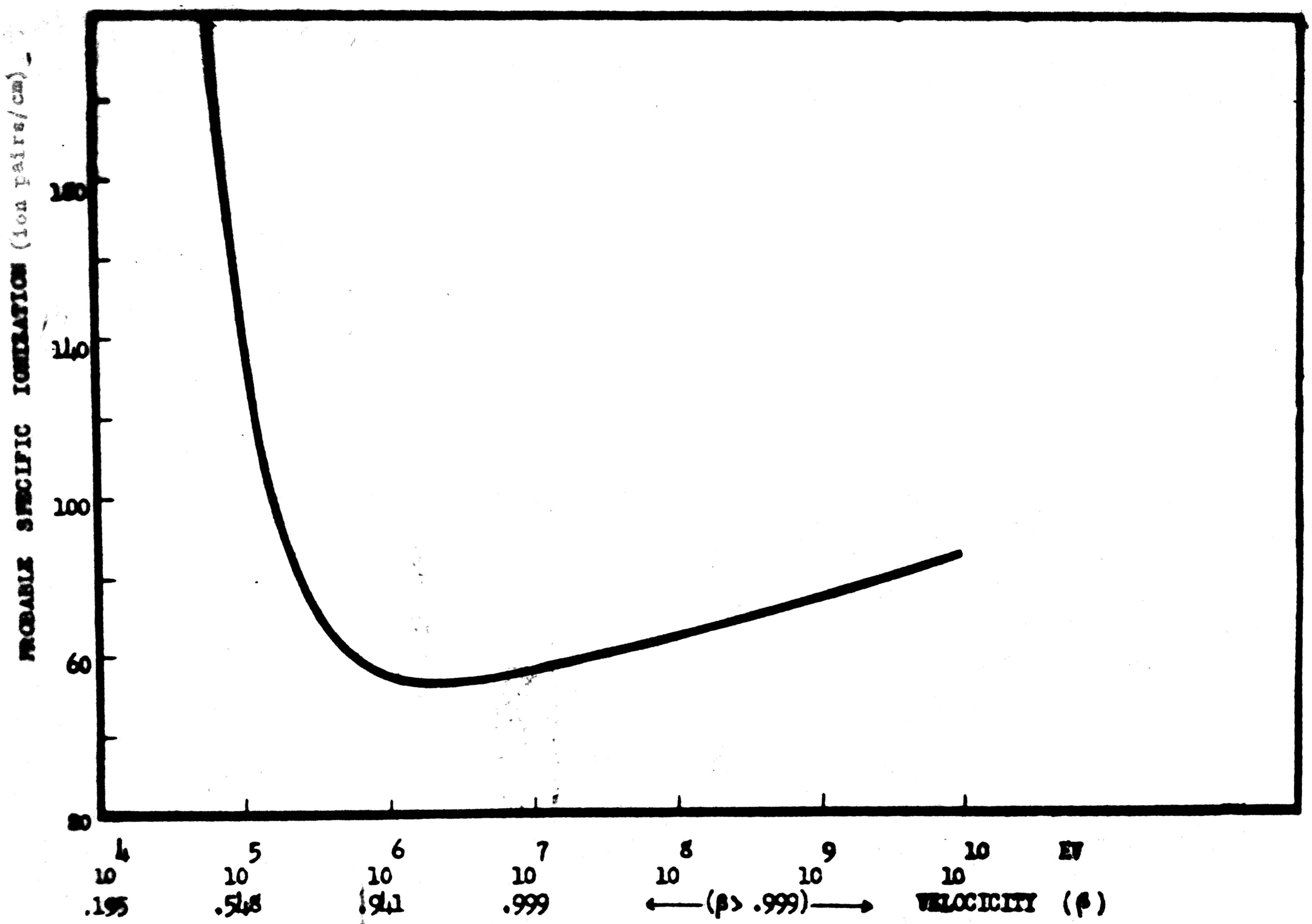
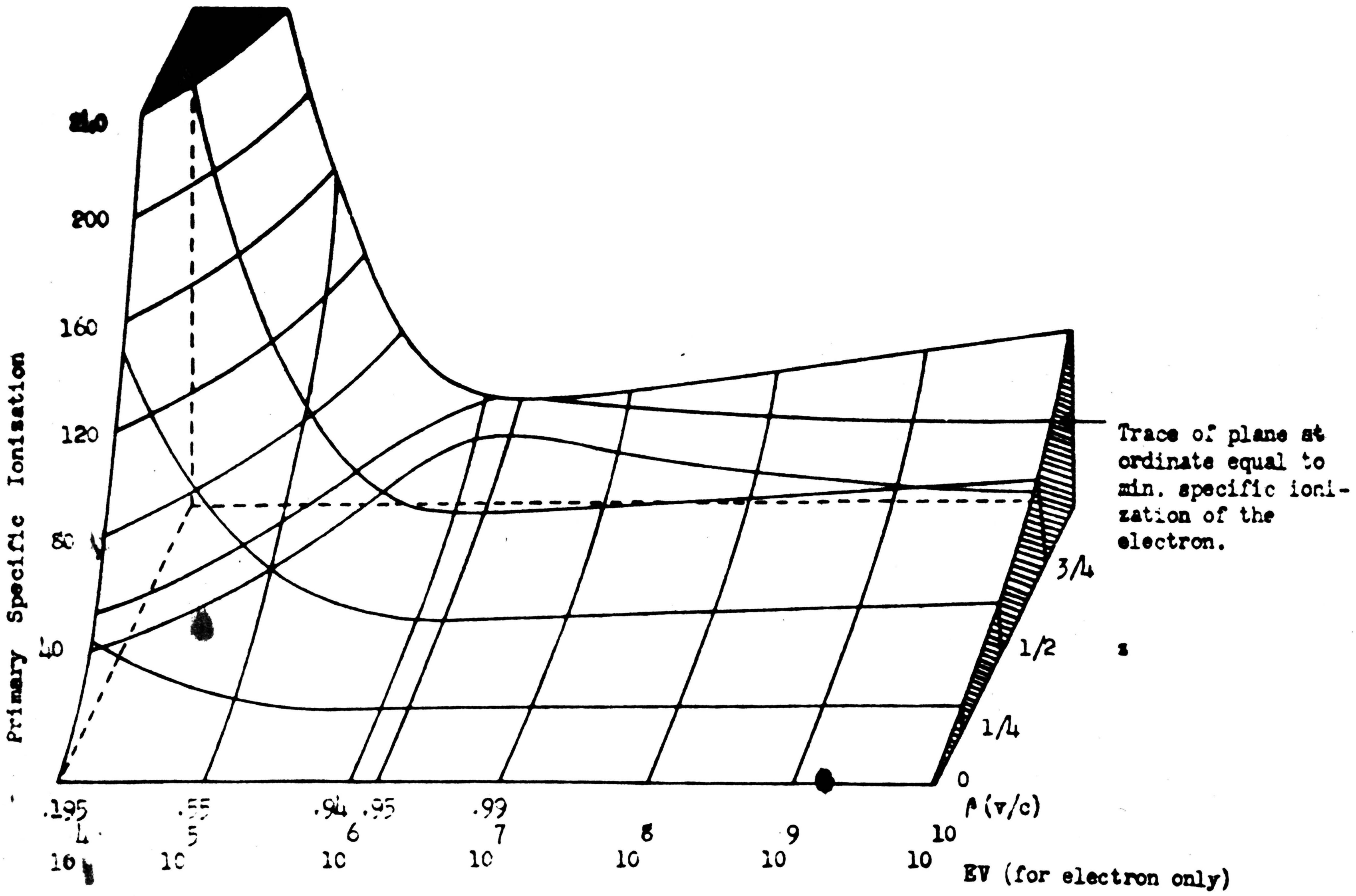


Fig. 1 **Probable Specific Ionization of an Electron in Air as a Function of Velocity.**



Trace of plane at ordinate equal to min. specific ionization of the electron.

Fig.2 Primary Specific Ionization of a Charged Particle, in air, as a Function of Charge and Velocity.

stays at ninety-five percent of the speed of light for particles with the electronic mass. A decrease of mass would merely displace the graph to the right.

Since the relativistic increase in the specific ionization is rather small, one finds that by restricting a search to nearly straight tracks with occasional large angle scatterings is equivalent to considering particles with very nearly minimum ionization over a wide range of energies.

Kassner[3] points out that when the number of droplets per centimeter is two or more, it is possible to unmistakably associate the droplets with a track even though they may not fall in a relatively straight line. In other words, the search would no longer be restricted to consideration of strictly relativistic particles. This could conceivably lower the minimum detectable charge considerably; but, at the same time, one loses the ability to determine the charge from the ionization rate without resorting to other techniques.

Energy Loss by Rapidly Moving Magnetic Monopoles

By the symmetry of the Maxwell equations, the electric field of a moving monopole (pole strength g), should be analogous to the magnetic field of a moving charge. Then, by analogy with Ampere's law:

$$\vec{E}_p = \frac{g\,\vec{v}\times\vec{r}}{cr^3}$$

Now in the case of a charge, the field is:

$$\vec{E}_c = \frac{ze\vec{r}}{r^3}$$

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[3] Kassner, <u>op. cit.</u>

Therefore, for a charged particle interacting with an electron, there will be a certain energy exchange as the particles are repelled apart. But when a pole interacts with a charge, the force is no longer directed along the line joining the centers of the particles; and there will be a greater energy exchange, since, in the laboratory system, the pole would swing around the charge in a path similar to an expanding helix, thus allowing the pole a greater impulse time in the region of stronger field than for a charge of the same impact parameter. However, for particles moving at relativistic velocities, where the impulse time becomes very small, the energy exchange would be the same for a monopole as for a charge with the same magnitude of electric field. The electric field magnitudes being:

$$E_p = \frac{g\beta}{r^2} \frac{1-\beta^2}{(1-\beta^2 \sin\theta)^{\frac{3}{2}}}$$

$$E_c = \frac{ze}{r^2} \frac{1-{}^{2}}{(1-\beta^2 \sin\theta)^{\frac{3}{2}}}$$

where θ is the angle from the direction of motion. For very short impulse times, the directions of these fields will make no difference in the amount of energy transferred. Therefore, since it is the interaction of the fields which gives ionization, the expression g can be substituted for ze, and the analogous equations for energy loss and ionization due to a monopole should appear. The primary specific ionization of a monopole would be:

$$j_p = \frac{2Cm_o c^2}{e^2} \frac{g^2 r}{I_o} \left[\ln \frac{2m_e c^2 \beta^2}{(1-\beta^2) I_o} + s - \beta^2 \right]$$

Now that $\frac{1}{\beta^2}$ has disappeared from the multiplicative term, the ionization will decrease nearly logarithmically, as shown in Figure 3.

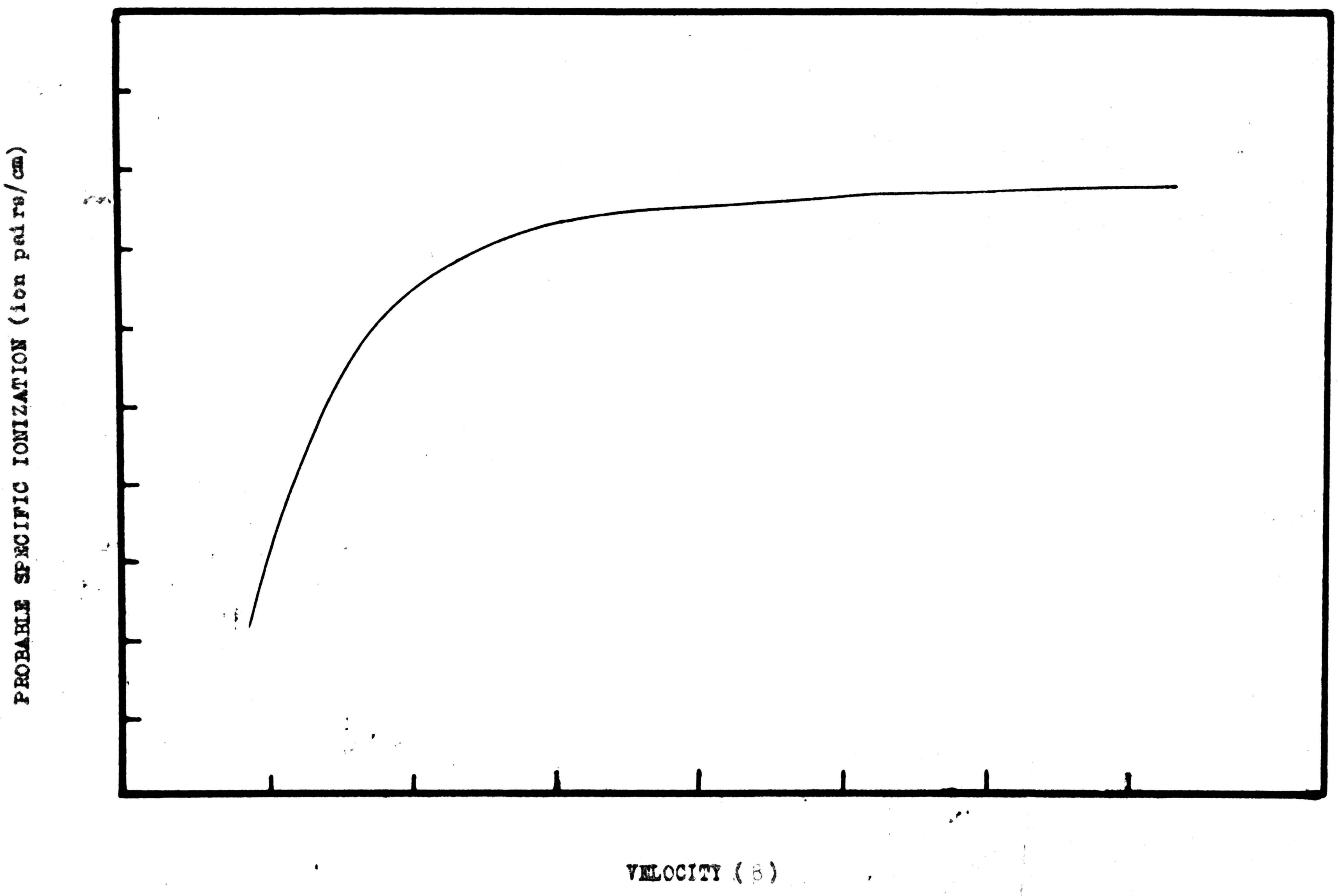

Fig. 3 Probable Specific Ionization of a Magnetic Monopole in Air as a Function of Velocity.

One would expect that, as the velocity falls off, the ionization would remain about the same, because of the compensating effect of the increased impulse time, until the decrease of the electric field causes the ionization to fall off very rapidly. The effect of variation of pole strength is shown in Figure 4. The effect of a variation of mass is the same as for a charged particle, a decrease in mass merely displaces the graph to the right.

Droplet Coalescence

The possibility arose that the ion count may be reduced by the coalescence of droplets in the heavier clumps along the track since the diffusion time is small. If this were so, it would put an upper limit on the ionization rate of a subionizer track which would be distinguishable from an electron track.

Hazen[4] found experimentally that the drop radius varied as the square root of the time.

$$R_o = C\sqrt{t} \qquad \text{where} \qquad C \approx 2 \times 10^{-4}$$

The root mean squared drift distance due to the Brownian motion of the droplet is:

$$x \approx 5 \times 10^{-6}\sqrt{\frac{t}{a}} \, ,$$

where a is the particle diameter. (The drift would actually be somewhat greater than this due to the initial kinetic energy of the ions.) The order of magnitude of the initial ion diameter is 10^{-8}cm, giving a drift of $5 \times 10^{-2}\sqrt{t}$. Thus the ions are initially diffusing apart at a rate two orders of magnitude higher than the droplet radii

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[4] Hazen, W. E., "Operating Characteristics of the Wilson Cloud Chamber," Review of Scientific Instruments, 13, 247, (1942).

WHERE: G IS THE POLE STRENGTH PREDICTED BY DIRAC

═ INDICATES THE CONTOUR CORRESPONDING TO THE MINIMUM IONIZATION RATE OF THE ELECTRON

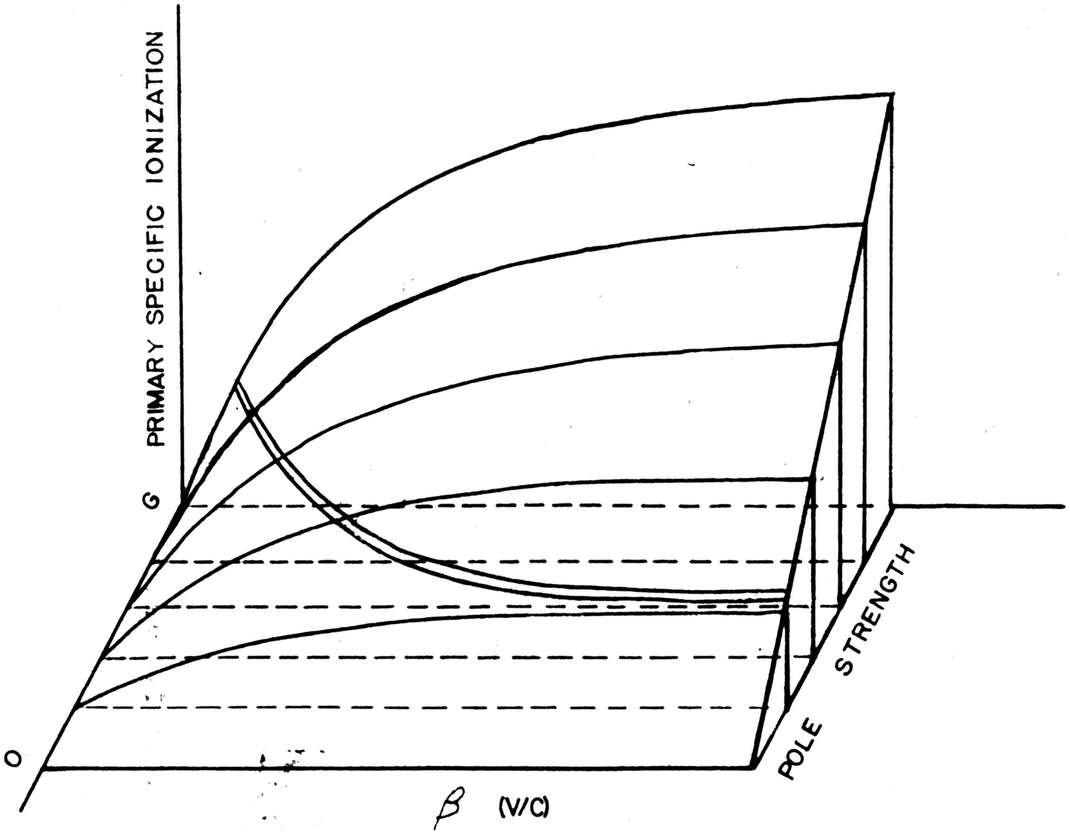


FIGURE 4 IONIZATION OF A MAGNETIC MONOPOLE AS A FUNCTION OF POLE STRENGTH AND VELOCITY

are growing. The diffusion rate does not decrease to the same order of magnitude as the drop growth rate, until the drop diameter is 10^{-4}cm, which is approximately the size the droplets reach before falling into the liquid. Therefore, the chance of droplet coalescence due to chance collisions is rather unlikely, even in the heavier tracks.

Now, treating the subject without diffusion, we will take the very nondiffuse case, of a line of ions uniformly distributed along the path length. The droplets in our chamber have been observed to grow to a size of about twenty microns diameter. Placed in a line, it would take an ionization rate of about 500 ions per cm to cause coalescence. An electron moving at about ninety-five percent of the speed of light gives about 100 drops per cm of path length. This investigation will be concerned with these tracks.

The latter effect coupled with that of diffusion would lead one to believe that coalescence can be neglected when computing the ionization rates of all but the most heavily ionizing particles.

Misleading Experimental Evidence

It is possible, under certain conditions, to get a low droplet count per unit path length for ordinary electron tracks. In order to ascertain when we have a definite subionizer track, we must be able to discount all possible explanations for the tracks shown in our photographs except the basic properties of the ionizing particle itself. The results of poor experimental technique, or misleading evidence must be eliminated.

First of all, let us consider vapor poverty. If there is insufficient vapor, the droplets will not all grow to visible size, giving an indication of low ionization. There are several instances when this effect is encountered. Near the boundaries of the chamber, which are at a higher temperature than the expanded chamber gas, there will be a localized region of lower supersaturation. Since the chamber is viewed through the top plate, and the side walls are not seen, it is only tracks parallel, and very close to the top plate, or the liquid in the bottom, that will exhibit this type of vapor poverty. By use of stereoscopy, tracks in these regions can be disregarded. When a track falls through a region that another track has fallen through previously, it will encounter a localized depletion of the vapor, and will not develop completely. This effect can be discounted by using multiple photography and noting the relative positions of tracks in time. After about three seconds of expansion, the warmer air near the walls will have set up turbulence currents to the extent that it would be impossible to keep up with the regions of lower supersaturation. This effect merely sets a limit on the useful sensitive time of the chamber.

There are a number of different types of tracks that can be seen when the chamber first expands that would appear to have low ionization. There is the possibility of a light track appearing which is actually made up of re-evaporation nuclei from droplets in the previous expansion that were neutralized and not swept away by the clearing field. There are cases where half of a field-separated track can be caught in the chamber when it expands. This might give a track with an apparently low ionization rate. There is another possible effect that has been suggested by Ruark that might well merit further investigation. It is possible that in the passage of an ionizing particle through the chamber not only ionization of the atoms and molecules in the medium might occur, but it could also excite some of them so that they would fall into metastable states; or, possibly, the ions themselves may form metastables upon recombination. The ions would be swept out of the chamber by the clearing field, and the metastables would remain. It is known that metastables can sometimes form molecules where stables cannot. If these molecules are of sufficient size, they might act as droplet nuclei. These droplets would appear in the beginning of an expansion as a very low ionization rate track. All three of these effects can be eliminated by disregarding any tracks that appear as the chamber initially expands.

Newly forming tracks would appear to have a low ionization rate before the droplets have all grown to visible size. These will be readily detected by multiple photography.

One last effect that could lower the sensitivity of the chamber and produce subionizer-like tracks is the excessive background caused by a large number of re-evaporation nuclei. This can be avoided by allowing the chamber to expand at such a rate that toward the end of the expansion, the supersaturation gets low enough that no new droplets will form, but it is still high enough that the droplets already in the chamber can grow until they fall into the liquid. The method of accomplishing this will be discussed in detail in Chapter IV.

It has been shown, then, that the tracks of interest to us are those entering the chamber in the middle of an expansion, passing through the center portion of the chamber, and having an ionization sufficiently low that they can be distinguished from the straight or minimum ionization electron tracks. Tracks meeting these criteria would be the tracks of subionizing particles.

IV. EXPERIMENTAL CONSIDERATIONS

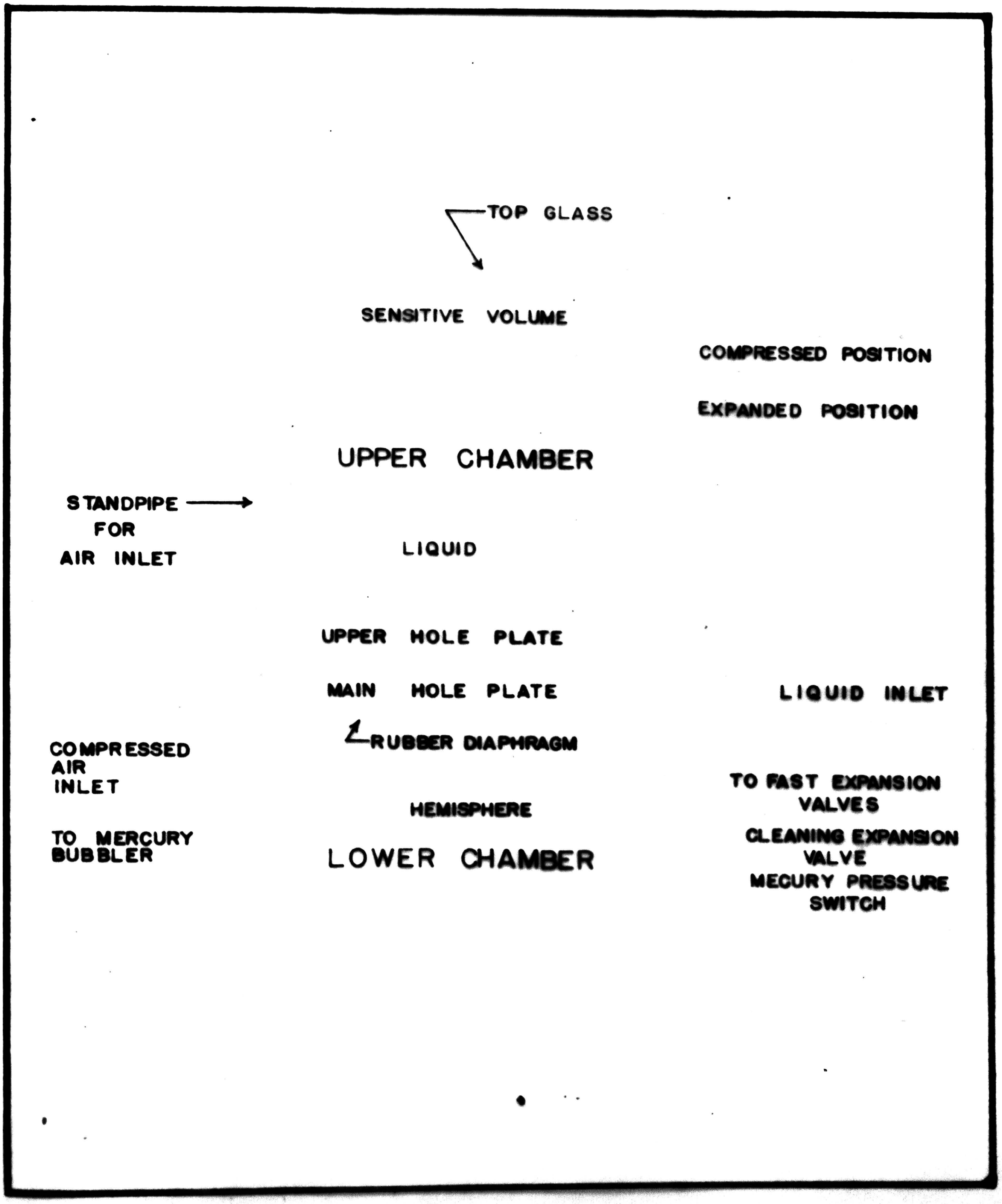
General

In searching for lightly ionizing particles, it is desirable to consider only those tracks which enter the chamber during the central portion of the sensitive period. This may be achieved by using a long sensitive time chamber and taking a series of stereoscopic pictures of each expansion. Xenon flash-tube illumination is capable of providing high intensity illumination and short exposures for the greatest possible photographic resolution. Many problems arose in setting up a reliable and workable experimental apparatus. Many of these problems are discussed in earlier theses and will not be mentioned here. Only those particular developments taking place during this investigation will be discussed in detail.

The Chamber

The apparatus used is a simple Wilson cloud chamber which is compressed and expanded by the motion of a liquid piston. This motion is accomplished by varying the pressure in the lower chamber (See Figure 5). This causes the rubber diaphragm to move, and raises and lowers the liquid piston, thus compressing and expanding the sensitive volume.

The primary disadvantages of the Wilson chambers in common use have been their short sensitive time and their long recovery time. Before, it has been necessary to operate a chamber at very high pressures to appreciably increase the sensitive time; however, with this chamber,


TOP GLASS
SENSITIVE VOLUME
COMPRESSED POSITION
EXPANDED POSITION
UPPER CHAMBER
STANDPIPE FOR AIR INLET
LIQUID
UPPER HOLE PLATE
MAIN HOLE PLATE
LIQUID INLET
RUBBER DIAPHRAGM
COMPRESSED AIR INLET
TO FAST EXPANSION VALVES
HEMISPHERE
CLEANING EXPANSION VALVE
TO MERCURY BUBBLER
LOWER CHAMBER
MECURY PRESSURE SWITCH

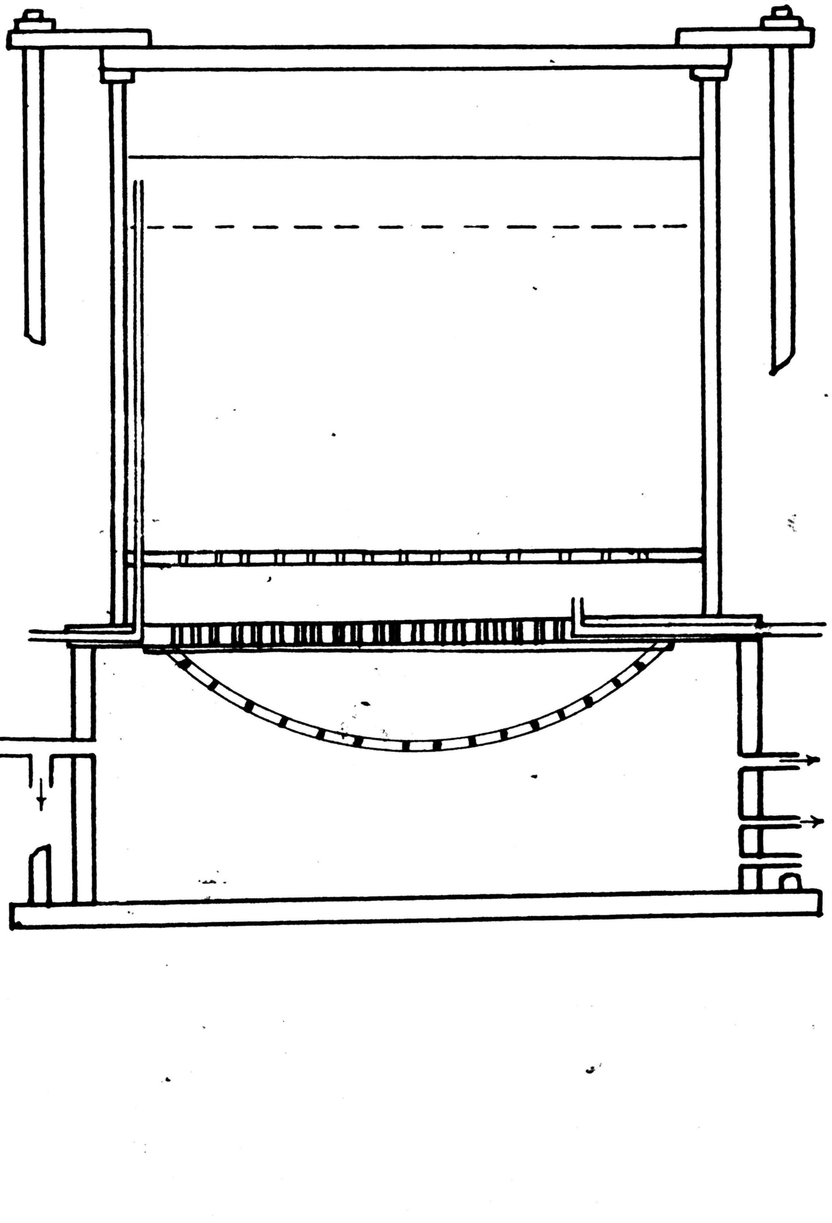


FIG 5 THE CLOUD CHAMBER

a system of valves with different orifices provides a means of holding the chamber in the sensitive region up to three or four seconds. Most previous chambers were sensitive for times of the order of one-tenth second.

The problem of the long recovery time is primarily one of vapor redistribution. It has been found beneficial to employ a rapid re-compression which over-compresses the chamber. After the chamber has remained in the over-compressed state long enough for vapor saturation to become reasonably complete, a slow expansion brings the chamber to the desired pressure one minute prior to the succeeding main expansion. This fast re-compression and slow expansion tend to introduce turbulences in the chamber which greatly speed the vapor redistribution. The slow expansion serves as a cleaning expansion to remove those nuclei formed by re-evaporation and to insure the complete redistribution of saturated vapor. The one minute waiting interval prior to the next main expansion allows the establishment of quiescence and the accurate establishment of 100 percent vapor saturation throughout the sensitive volume.

It is seen from Figure 6, that the chamber is brought quickly to the sensitive region, then held there for the desired sensitive time. The expansion is interrupted momentarily, at which time the chamber becomes insensitive, and is then continued so that the chamber remains just below the sensitive region for several seconds. Thus, without causing any new droplets to form, one can cause the droplets already in the chamber to grow to full size and fall into the liquid. Some of these droplets are caught in the turbulent up-draft

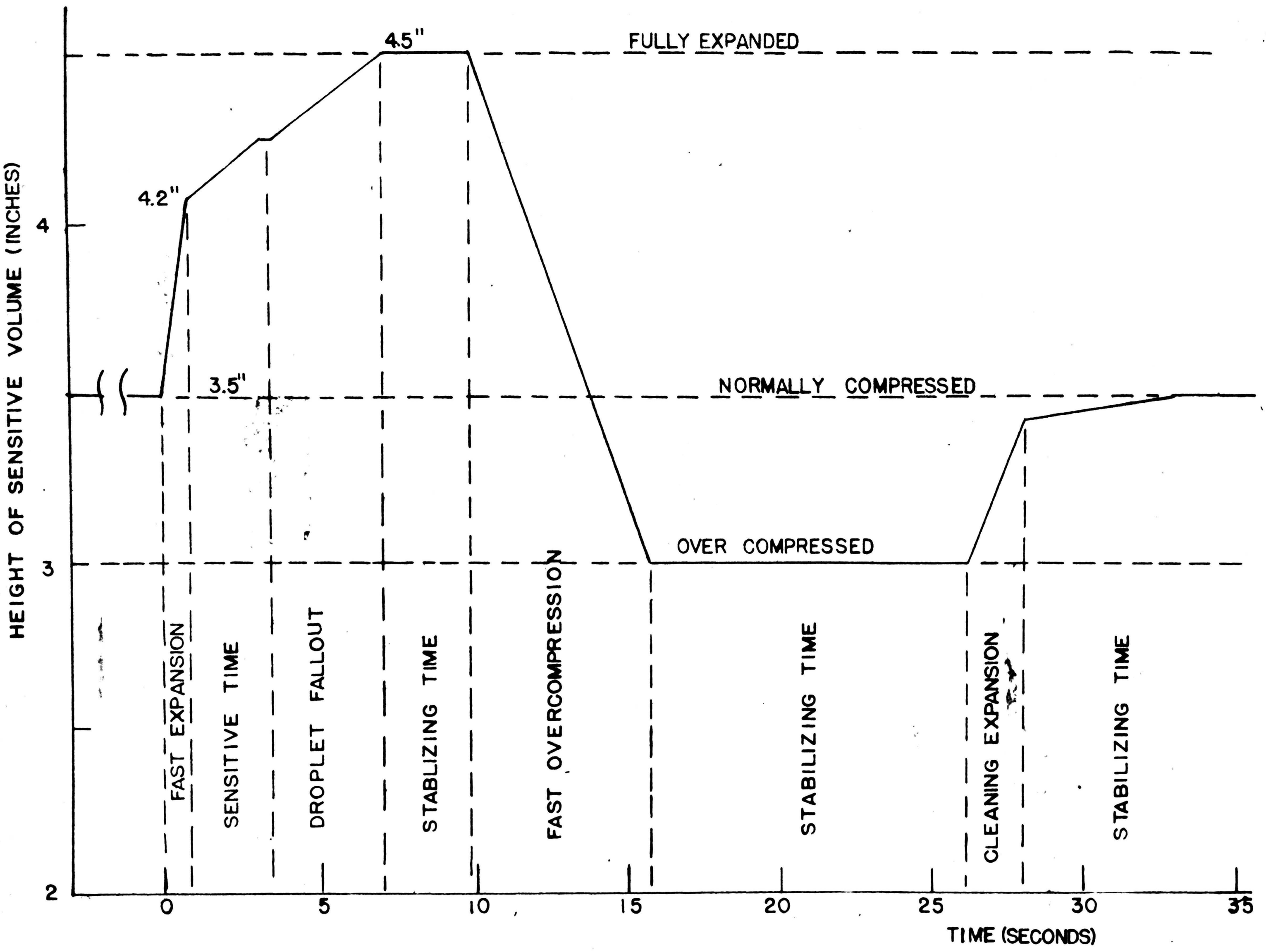


FIGURE 6 COMPRESSION CYCLE

in the chamber toward the end of the expansion, and are then trapped in the re-compression cycle in spite of our precautions. Droplets caught in the re-compression will evaporate leaving nuclei which may be condensed upon during the succeeding expansion causing background. The cleaning expansion will bring down most of these remaining re-evaporation nuclei.

The timing circuits which control the cycle are essentially as shown by Rinker except for the over-compression and cleaning expansion systems. The fast re-compression is started by a timer as before; but, now, instead of compressing for a fixed time and cutting off with a timer, which introduces errors with slight fluctuations of tank pressure or plate voltage, the compression is cut off at a fixed pressure (78cm) by a mercury manometer pressure switch (See Figure 7). The timer which previously stopped the re-compression, now starts the cleaning expansion which is also stopped (at 43 cm) by the manometer pressure switch.

Changes in the air and liquid systems were minor. Even so, it was felt that a complete and current schematic drawing of these systems would be useful and appropriate (See Figure 8). A few precautions on their use are also in order. To expand the chamber fully, the diaphragm must be stretched against the hemisphere. This necessitates 20 cm of pressure in the sensitive volume and atmospheric pressure in the lower chamber. In pressurizing the sensitive volume, care must be taken not to splatter liquid from the stand pipe onto the top glass. Drops which dry on the top glass will leave spots which show up in the photography. If the stand pipe is not refilled, a group of particles ionized by friction will squirt out of the pipe and form a small cloud. Thus, the

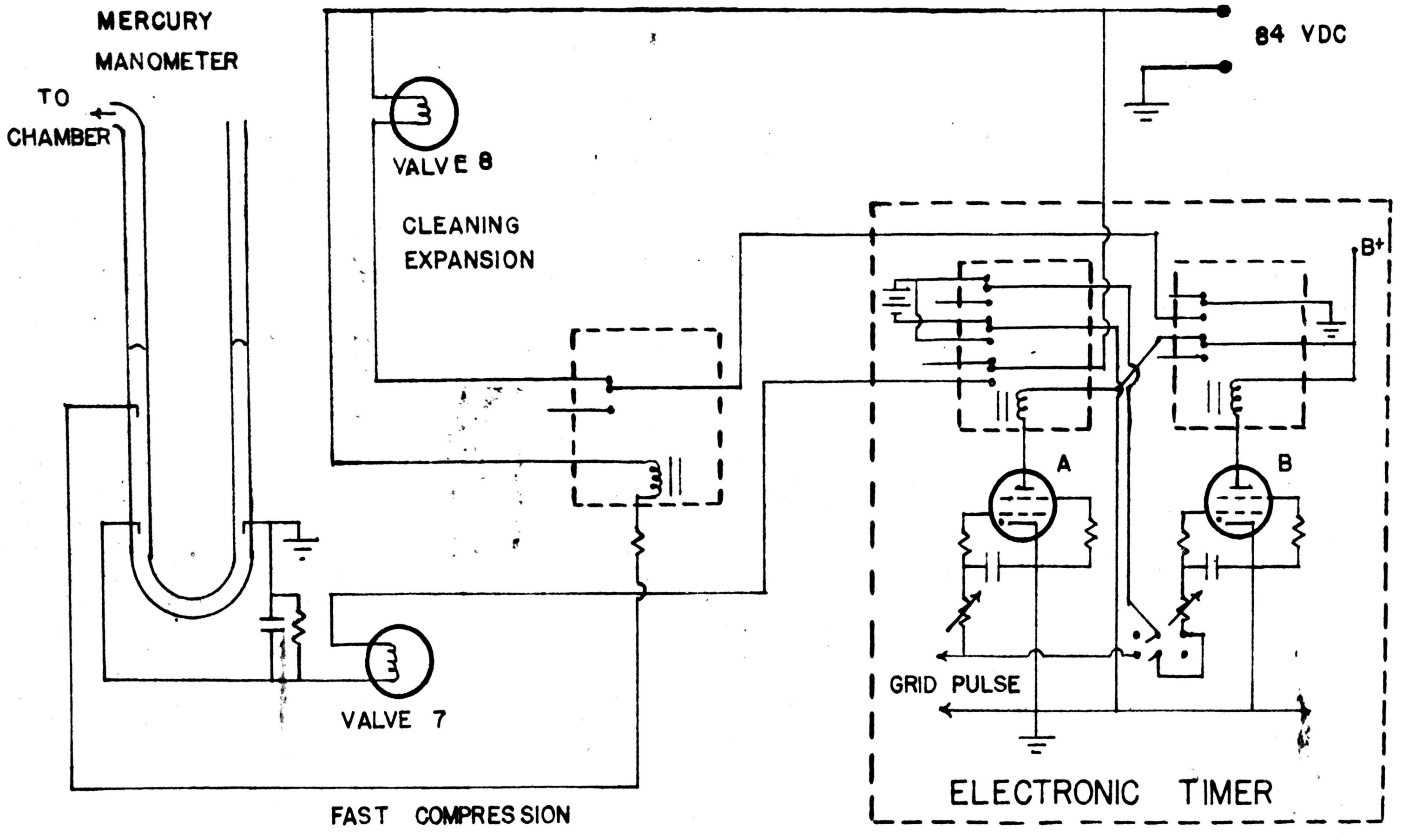


FIGURE 7 FAST COMPRESSION AND CLEANING EXPANSION CIRCUIT

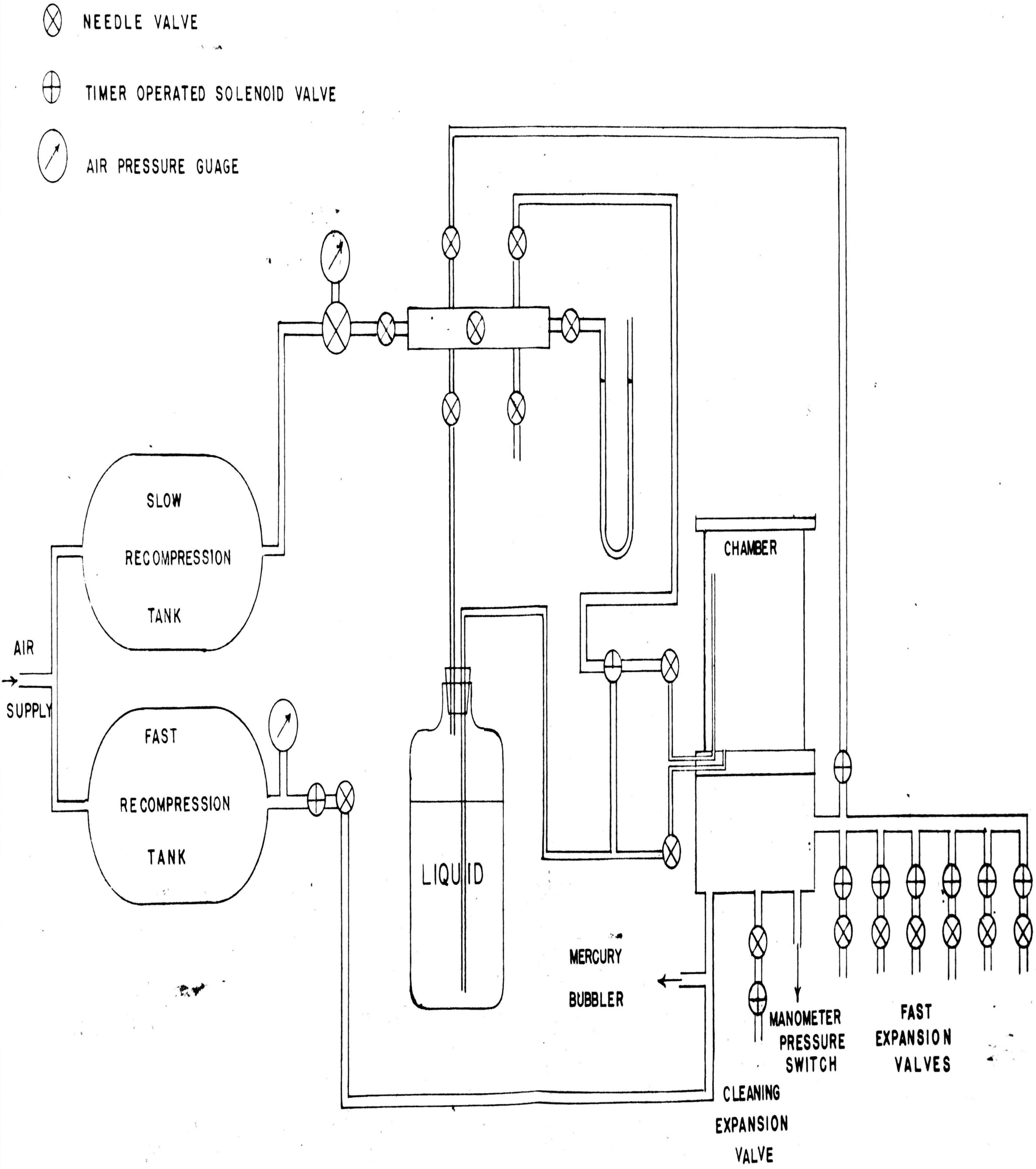


FIGURE 8. SCHEMATIC OF AIR AND LIQUID SYSTEMS

stand pipe must be refilled with liquid and extreme caution must be taken, once again, to keep the liquid off of the top glass.

Photography

A special camera has been designed and built for this chamber. It is a very precise and rugged instrument of photography, capable of taking one to twenty stereo-pictures per second with either 35 mm or 70 mm film. Normally twenty-two stereo pairs are taken of a single expansion during the sensitive time. The camera uses about 4 feet of 35 mm film per expansion, and about half this much 70 mm film. By varying the gear ratio between the motor and the clutch, different speed ranges can be obtained; and, by varying the voltage on the motor, we can adjust the speed within these ranges. The film gate consists of four optically flat pieces of glass, mounted two in a fixed metal plate, and two in a spring-loaded metal frame. The film is moved by two constant motion sprockets, and one intermittent motion sprocket. The film moves about 2 1/4 inches each time the intermittent motion sprocket moves. The intermittent motion is achieved by use of a geneva drive assembly. Since the light from our flash tubes only lasts for about one millisecond, a shutter is unnecessary. See Figure 9 for the film threading diagram.

The camera is mounted above the chamber and views the sensitive volume through the top glass. Stereoscopy is achieved by taking two separate frames through two separate lenses at the same time. The lenses are 3 inches apart center to center with parallel axes, and the frames 3 3/8 inches center to center. The 5 inch focal length lenses are focused on a plane 19 1/2 inches from the base plate of the camera,

TABLE I: OPERATING CONDITIONS

1. Chamber Constituents
   Liquid: 2 parts pure ethyl alcohol to 1 part distilled water by volume.
   Solution blackened with Putnam black dye.
   pH adjusted to 6 by addition of ordinary aspirin.
   Gas: Natural Air

2. Sensitive Volume Pressures at 72° F

Over Compressed	68 cm Hg.
Normally Compressed	61.7 cm Hg.
Fully Expanded	20 cm Hg.

3. Clearing Field (applied between ring and metal base)
   Voltage, 708 volts DC; current, 0.7 microamperes.

4. Cycle Time 2 minutes

5. Expansion Valve Settings (Seconds)

Valve	Start	Stop
1	0.00	0.25
2	0.00	0.50
3	0.50	2.00
4	2.00	3.50
5	3.80	5.80
6	5.80	10.00
7	10.00	(78 cm Hg in Lower Chamber)
8	17.50	(43 cm Hg in Lower Chamber)

6. Room Temperature 72° F

7. Illumination
   Incandescent: 4 G.E. 200W clear lamps
   Operating voltage, 200 volts AC
   Ultraviolet Filter, Kodak 2B
   Flash: 3 xenon flash tubes, 3/8 inch diameter
   Operating voltage, 2000 volts DC
   Ultraviolet filter, Kodak 2B

8. Camera
   Stereo-movie camera, 35 or 70 mm.
   lens opening, f/11
   base plate to chamber distance, 49.5 cm.
   depth of focus, 8.9 cm.
   framing rate, 16 per second (variable 1 to 20)
   magnification, 1/9

9. Film and Processing (72° F)
   Kodak 35 mm Tri-X
   Developer, Kodak D-19, 7 minutes
   Stop bath, Kodak SB-5, 1 minute
   Fixer, Kodak F-5, 15 minutes

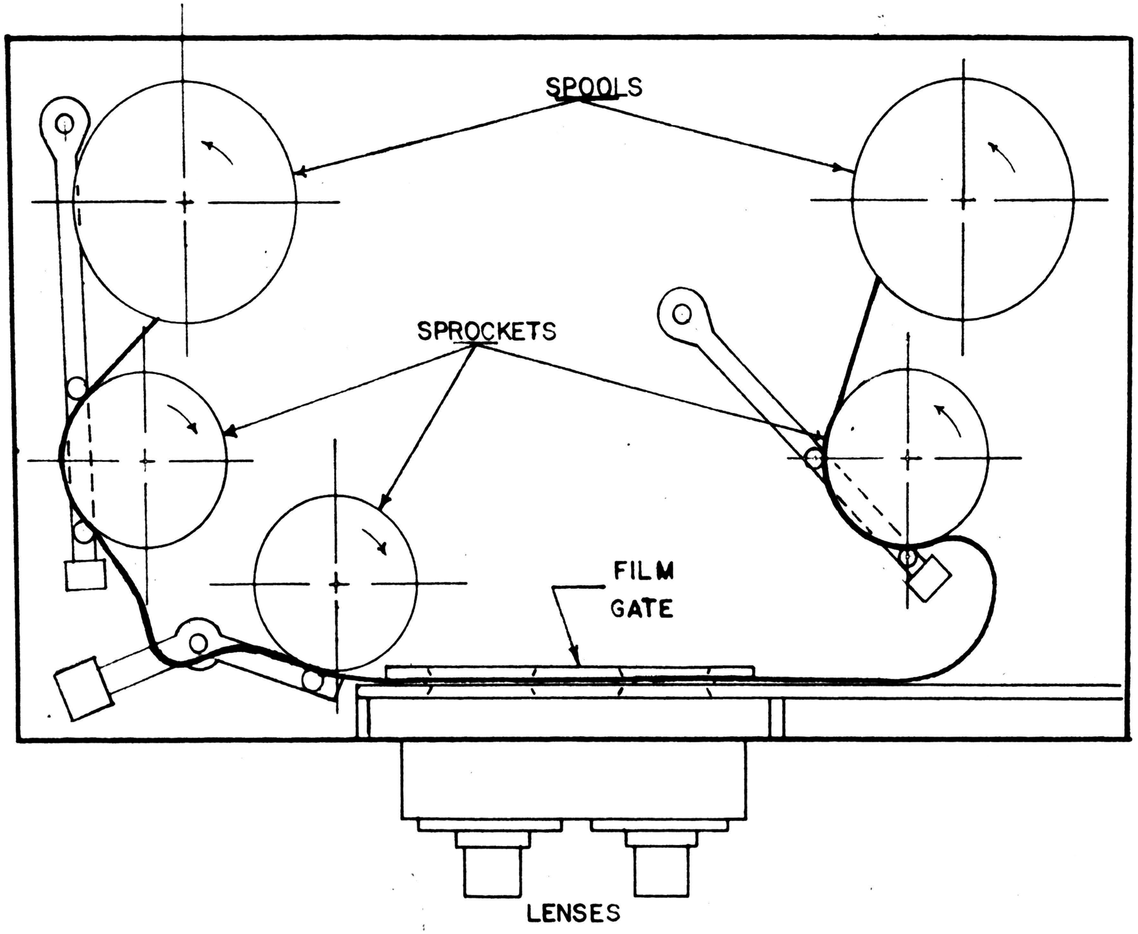


FIGURE 9 FILM THREADING DIAGRAM FOR STEREO-CAMERA

which is the distance to the center of the sensitive volume. With lens aperture f/11, the depth of field is about 6 inches. This includes all of the sensitive volume. For reprojection, the same lens and film gate system is used, with two lamp, lens, and blower assemblies set in place as shown in Figure 10. The lenses are covered with sheets of polaroid material in such a way that light from one lens is polarized at 90° to that from the other lens. This light will focus on a plane 19 1/2 inches from the base plate. A viewing screen of Bruning No. 390 frosted acetate is used as a screen. Fortunately, this screen does not depolarize the light to any appreciable extent. One views the screen on the opposite side from the camera, through polarized plastic spectacles. If the polaroid sheets in the spectacles are properly oriented, the image from one lens will be viewed by one eye and that from the other lens will be viewed by the other eye. The proper viewing distance is 19 1/2 inches. Thus one seems to be looking into a white chamber and viewing black tracks. The depth of perception is quite good. A good discussion of orthostereoscopy is found in Kurtz.[1]

In viewing the chamber for the purpose of making adjustments, the incandescent lighting system described by Mettenburg is used. For photography, however, more light is needed. It is supplied by a system of three xenon flash tubes, firing in cyclic order. The tubes, manufactured by Amglo, Inc., are 3/8 inches in diameter, have an effective length of 10 inches, and are half aluminized. The reflector system is still as described by Mettenburg and Rinker. To provide power for these tubes,

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[1] Kurtz, H. J., "Orthostereoscopy," Journal of the Optical Society of America 27, 323, (1937).

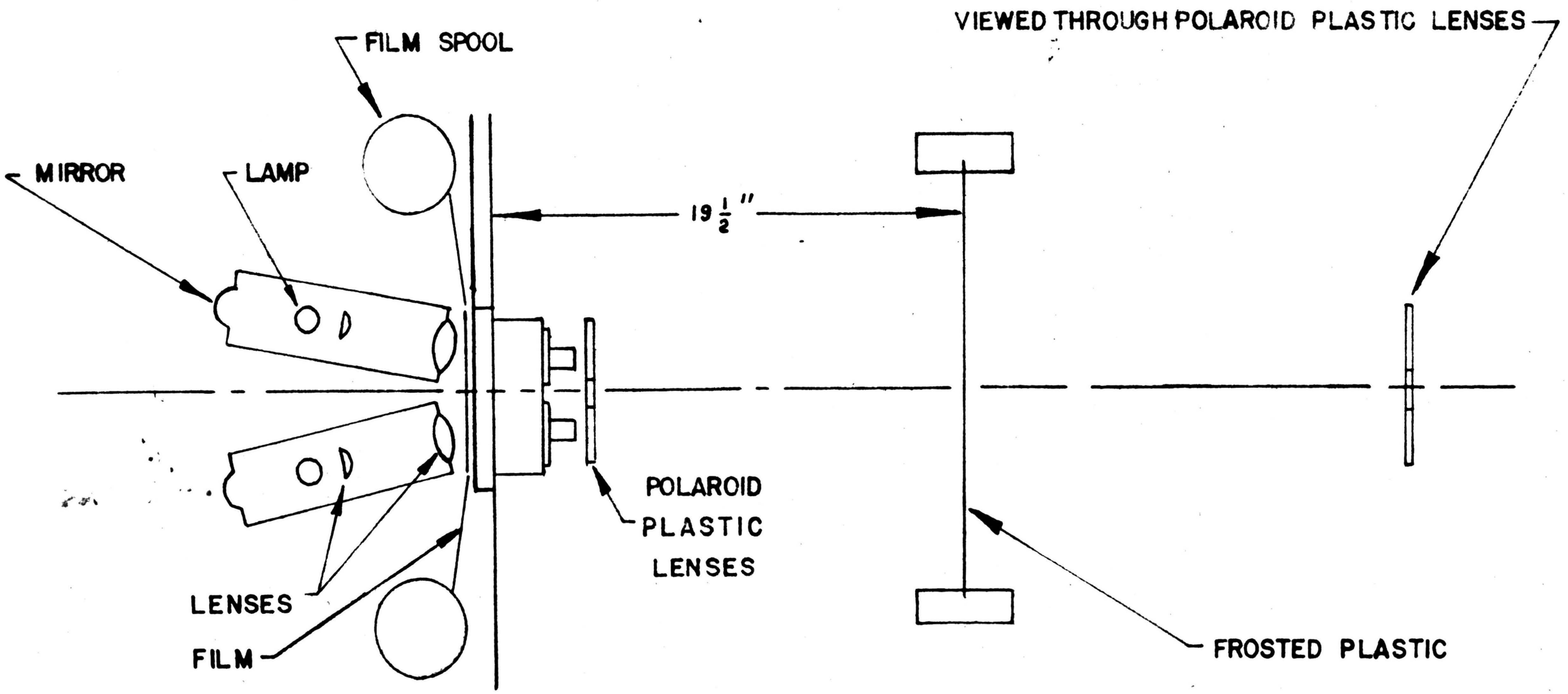

FIGURE 10 STEREOSCOPIC REPROJECTION APPARATUS

twenty-two 120 μf capacitors are charged to 2000 volts. Previously, these capacitors were discharged individually by closing a relay to one of them, then triggering the flash tube with a separate coil and capacitor circuit which was activated by a microswitch in the camera. The currents through the flash tube, however, reach peaks of nearly 400 amps and the relays would weld closed occasionally. Heavier relays could not be employed because their operating times became excessively large. Thyratrons were tried as switching devices, but none were found that could stand the current load. A circuit was suggested by Mr. R. T. Reed of General Electric Company using type GL-5550, size A ignitrons in the switching (See Figure 11). They seemed to be the most economical switches consistent with long life and reliability. The circuit operates as follows: The stepping switch closes a relay, choosing which ignitron will fire. A pulse from the power supply is triggered by the microswitch in the camera. This pulse initiates the cathode spot in the ignitron, allowing the 2000 volts from the large capacitor to hit the flash tube assembly. The primary of the trigger coil conducts until the small capacitor is charged, producing a high voltage RF pulse in the secondary, and thus ionizing the flash tube. This allows the 120 μf capacitor to discharge through the flash tube. Two hundred forty joules are input to the tube on each flash. The light from both the viewing lights and the xenon flash tubes must be filtered to avoid the formation of photonuclei. Rinker has shown that the unfiltered radiation from the flash tubes passing through the 1/4 inch thick ordinary glass walls of the chamber will produce innumerable droplets in the chamber. An attempt was made to filter the light from both the

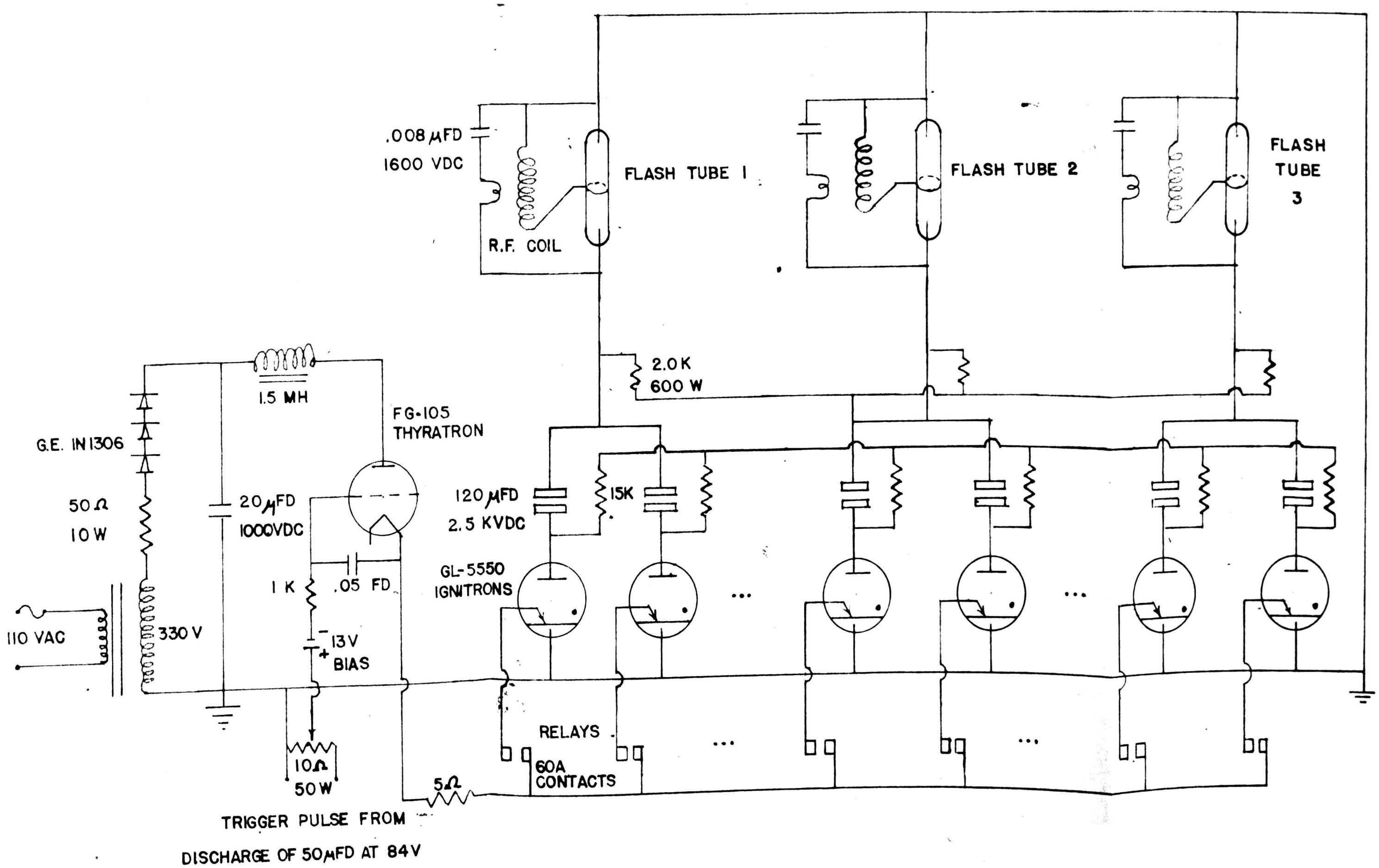

FIGURE 11 IGNITRON SWITCHING CIRCUIT

viewing lights and the flash system by use of Kodak Wratten Filters, type 2B, which transmit less than 0.1% of the light below 3900A°. The intensity of the flash lighting was such, however, that the chamber became filled with photonuclei as the expansion progressed, even through the filters and a quarter of an inch of glass. This did not occur when only the incondescent viewing lights were employed. Rinker studied this effect, but he apparently never took multiple photographs with the filter in place.

The Search

The primary objective of this work has been to surmount the remaining obstacles in the experimental equipment. It was necessary that these problems be solved before an actual search for subionizers could begin. A brief search for subionizers was conducted. The primary aim of this search was to check the operation of the equipment and furnish guiding remarks for succeeding investigators.

The chamber was set in operation and adjusted for the most favorable conditions obtainable. Two hundred feet of film were exposed. Normally the examination of the film would be divided into two parts. First, the film would be projected with a film strip projector to a magnification such that one cnetimeter in the chamber corresponds to five centimeters on the screen. It is then examined non-stereoscopically for any obvious subionizer suspects. It is felt that tracks with as few as three or four droplets per centimeter of length should be recognized in this examination. Wherever suspects were observed the film was then viewed stereoscopically to determine its position and orientation in the chamber. Only those tracks which appeared in the central portion of the sensitive time and which were initially not closer than two centimeters from one of the chamber surfaces were classified as true suspects.

The second portion of the search can only be undertaken after the track load is appreciably diminished. Here a thorough examination is made for particles ionizing more lightly than three or four droplets per centimeter of path. This would be accomplished by projecting the film stereoscopically with the camera lens and gate system. Each background droplet in the chamber will be plotted throughout the expansion disregarding all obvious tracks and staying away from the regions in which tracks are rapidly disintegrating as they fall into the liquid. Care will be taken to look for any new droplets which were not present at the onset of chamber sensitivity. Droplets appearing nearly simultaneously, that is in the same photograph or two consecutive photographs, will be examined carefully to see if they might have been produced by the trajectory of a particle. Such examination of the film will be very painstaking and can only be accomplished under the most favorable chamber conditions. The large number of tracks in our chamber obscures many background droplets and leaves little room in which to observe lightly ionizing tracks. The background density is also primarily controlled by the track load of the chamber, other factors remaining constant. Thus, a thorough search for tracks of very low ionization is impractical and must wait until the heavy track load is reduced.

Sources of chamber contamination have been considered. Any activity localized on the chamber itself was unobservable above the cosmic ray background with a scintillation counter. It does not appear that the tracks originate in the chamber. Almost no alpha tracks are observed in the chamber so that natural radioactivity is almost eliminated unless it is located outside the chamber. It has been reported that the background radiation due to fall out has increased considerably over the past year. It is possible that this is the source of the activity encountered in this work.

V. RESULTS AND CONCLUSIONS

Apparatus

The background in the chamber has been reduced by the addition of an over-compression and cleaning expansion to the cycle. These also increase the stability of the chamber by insuring that the redistribution of vapor is more nearly complete before the succeeding expansion. Although the initial background is reduced, the track load is so great that the minimum detectable ionization in the first few frames is about the same as for Mettenburg and Rinker. An effort was made to reduce this track load by replacing all of the chamber parts which could have caused it if they had been contaminated, and by surrounding the chamber by about an inch of lead. Both attempts failed to reduce the track load. In fact, the track load increased slightly when the components were changed. It is possible, however, that some unsuspected contaminant is being introduced into the chamber despite our precautions.

Since Mettenburg and Rinker were unable to operate the apparatus with a full set of flashes, it was previously unnoticed that the photonucleation is so profuse even when the light is filtered. Some means must be found of reducing the number of photonuclei. At present, these droplets start appearing in the second frame, and by the seventh frame, form a background fog of about 210 drops per cubic centimeter. It is possible that the organic material in the filter has decomposed under the intense radiation, allowing the cutoff wavelength to change. In this case, it would be better to employ an inorganic filter. As an additional precaution, one could eliminate nitrogen and oxygen from the chamber.[1]

It was noted on some of Rinker's films that the majority of the tracks were nearly vertical and exhibited little scattering; whereas, the present track population consists largely of low energy electron tracks. Any radioactive contamination is of such a nature that it is not readily detectable with geiger or scintillation techniques.

Certain modifications need to be made on the camera to avoid jamming of the film on the sprockets, and to indicate when the film has broken or run out. Also, the system of modifying the camera for reprojection is rather unwieldy and should be simplified.

If properly filtered, the lighting system is adequate as such; however, the flash tubes are somewhat expensive and their lifetimes are rather short. It is estimated that by increasing the voltage as the tube is used, a tube can be used successfully for approximately 100 expansions or 700 flashes. The deterioration of the tubes can possibly be attributed to one of two processes. If the pressure in the tube increases, it requires more voltage for a flash; and, if the pressure decreases, the same effect occurs. An increase from the optimum pressure could be caused by erosion of the glass by the discharge as the tube is flashed. A decrease in gas pressure could be attributed to the carrying down of gas molecules by the flash of

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[1] Farley, F. J. M., "Clouds Produced in an Expansion Chamber by Ultra-violet Light," Proceedings of the Royal Society of London 207, 527, (1951).

evaporated metal leaving the anode upon each flash. A thorough study needs to be undertaken to find a means of producing a similar tube with a longer life.

The Search

In this preliminary search, approximately 200 feet of film were exposed. Due to the excessive background density caused by photonucleation and the large track load, it was impossible to make a search for subionizers under the conditions set forth. However, even if we had not encountered these difficulties, there would still not have been time after the equipment was perfected to have obtained a reasonable amount of data for a search. Should these particles occur only rarely in nature, many hundred feet of film must be expended in order to obtain reasonable cross-sections for their production.

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VITA

Joseph Bernard Hughes was born June 23, 1932, in St. James, Missouri, the son of Bernard and Frances Hughes. He received his elementary education in the Springfield, Lebanon, Forest Grove, and St. James, Missouri, Public Schools; and was graduated from the John F. Hodge High School, St. James, Missouri, in May, 1950.

In September, 1950, he enrolled at the University of Missouri School of Mines and Metallurgy, Rolla, Missouri, and received a B. S. Degree in Physics in May, 1954.

In June, 1954, he was married to Miss Narine Pettus of Butler, Missouri. He has two sons, ages four and two.

He entered the United States Army in July, 1954, and was discharged in November, 1957. In September, 1957, while still in the Army, he enrolled as a half-time student at the University of Missouri School of Mines and Metallurgy. In January, 1958, he enrolled as a full-time student as a candidate for the degree of Master of Science, Physics Major.

A PRELIMINARY SEARCH FOR SUBIONIZERS

BY

JOSEPH B. HUGHES

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AN

ABSTRACT

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THE UNIVERSITY OF MISSOURI SCHOOL OF MINES AND METALLURGY

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MASTER OF SCIENCE, PHYSICS MAJOR

Rolla, Missouri

1959

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A PRELIMINARY SEARCH FOR SUBIONIZERS

A long sensitive time cloud chamber has been developed for the primary purpose of detecting subionizing particles. An improved expansion and compression cycle has been employed, with material reductions in background and cycle time. A system of multiple solenoid operated valves with adjustable orifices is employed to obtain the desired expansion versus time curve. In the first three seconds of expansion, the chamber is sensitive to ions; and, in the final portion of the expansion, it is held just below the region of sensitivity to allow the droplets to grow to full size and fall to the floor of the chamber. The chamber is then over-compressed in about six seconds and expanded slowly to the normally compressed position. This provides a final cleaning expansion before the chamber is made sensitive again. Average background densities as low as one drop in forty cubic centimeters are easily obtainable.

A high energy multiple flash lighting system has been introduced for the purpose of taking a short series of moving pictures of each expansion. GL-5550 ignitrons were employed for switching large capacitors to a set of three flash tubes. The system is reliable, limited only by the lifetimes of the flash tubes themselves which have been appreciably diminished by the high energy input.

A stereoscopic movie camera has been designed and built for photographing the chamber. This camera will take stereo-photographs at rates of from one to twenty frames per second on either 35 mm or 70 mm film. The system is arranged to take twenty-two stereo-pairs of each expansion.

A preliminary search for subionizers was attempted but was handicapped by the presence of numerous background droplets produced by photonucleation processes. Kodak 2B filters were found inadequate for filtering out the radiation producing these photonuclei.