Continuous X-Ray Spectrum from 8A to 14A*

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The continuous x-ray spectrum has been studied at voltages from 1.1 kv to 2 kv and at wave-lengths from 8A to 14A using a vacuum single crystal Geiger counter spectrometer. The measurements were corrected for window absorption and counter efficiency but were not corrected for absorption in the target or for the reflecting power of the crystal. The total intensity in the continuous spectrum, as measured and partially corrected, is found to be proportional to the atomic number of the target, a result similar to results obtained for shorter wave-lengths, but the total intensity is not proportional to the square of the voltage applied to the tube. The shapes of the curves approach the shape to be expected from a thin target.

INTRODUCTION

AMONG the earlier experimental investigations of the energy distribution in the continuous x-ray spectra of various elements were those made by Ulrey,[1] whose curves have been reprinted many times in textbooks on x-rays, and those of Behnken,[2] Dauvillier,[3] Wagner,[4] Wagner and Kulenkampff,[5] Kulenkampff,[6] and Kirkpatrick.[7] The curves given by Ulrey were presented without correction although the data were sufficiently complete to allow Pike[8] to compute some pertinent corrections at a later date. Kirkpatrick's work covered the region from 0.4A to 1A and included corrections for: superposition of higher orders, incomplete absorption by the ionization chamber, absorption by the tube wall and ion chamber window, and variation of the reflecting power of the crystal. Kulenkampff carried out a thorough study in the range 1A to 2.8A making correction for absorption in the target in addition to the corrections made by Kirkpatrick. A survey of all the literature cited indicates that the total energy in the continuous spectrum is approximately proportional to the atomic number of the target and to the square of the voltage applied to the x-ray tube. There seems to be little general agreement as to the specific nature of the shape of the curve or the position of the maximum. Kulenkampff found empirically that the expression

$$I_\lambda = \frac{CZ}{\lambda^2}\left(\frac{1}{\lambda_0}-\frac{1}{\lambda}\right)+\frac{BZ^2}{\lambda^2} \qquad (1)$$

represented his experimental data fairly well, where I_λ is the intensity at any wave-length λ, Z is atomic number, λ_0 is the minimum wave-length present, and C and B are constants, with B so small that the last term is much smaller than the first. Differentiating the equation for I_λ in order to find the wave-length of maximum intensity we find

$$\lambda_{max} = \frac{3\lambda_0}{2(1+BZ\lambda_0/C)} \qquad (2)$$

in agreement again with Kulenkampff's data. If B is small, $\lambda_{max}=3\lambda_0/2$ which is the empirical formula proposed by Dauvillier. Kirkpatrick, however, found $\lambda_{max}=k+k'\lambda_0$ where k and k' are two different constants.

The most successful of the earlier theoretical attempts to arrive at an expression for the intensity as a function of the wave-length was made by Kramers[9] using an application of the ideas underlying Bohr's correspondence principle. Kramers obtained

$$I_\lambda = \frac{CZ}{\lambda^2}(1/\lambda_0 - 1/\lambda) \qquad (3)$$

for the intensity from a thick target where C could be determined from fundamental constants and the tube current. This expression leads directly to $\lambda_{max}=3\lambda_0/2$. The total intensity should be proportional to the atomic number of the target and the square of the applied voltage, according to Kramers. An application of quantum mechanics to the problem was made by Sommerfeld.[10] The results of the quantum-mechanical calculations have been made available by Kirkpatrick and Wiedmann[11] in a form more suitable for comparison with experiment. They show that the total intensity should be roughly proportional to the atomic number of the target and the square of the applied voltage.

It should be emphasized that most of the experimental work has been carried out at voltages of

* This work was carried out under contract with the U. S. Navy, ONR.
[1] C. T. Ulrey, Phys. Rev. **11**, 401 (1918).
[2] H. Behnken, Zeits. f. Physik **3**, 48 (1920).
[3] A. Dauvillier, Ann. de physique **13**, 49 (1920).
[4] E. Wagner, Physik. Zeits. **21**, 621 (1920).
[5] E. Wagner and H. Kulenkampff, Ann. d. Physik **68**, 369 (1922).
[6] H. Kulenkampff, Ann. d. Physik. **69**, 548 (1922).
[7] P. Kirkpatrick, Phys. Rev. **22**, 37 (1923).
[8] Eugene W. Pike, J. App. Phys. **12**, 206 (1941).
[9] H. A. Kramers, Phil. Mag. **46**, 836 (1923).
[10] A. Sommerfeld, Ann. d. Physik **11**, 257 (1931).
[11] P. Kirkpatrick and L. Wiedmann, Phys. Rev. **67**, 321 (1945).

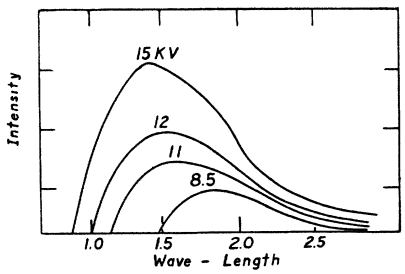

FIG. 1. Intensity in arbitrary units as a function of wave-length in Angstroms (8.5 to 15 kv in air uncorrected).

20 kv to 70 kv and at wave-lengths extending out to 1A as an upper limit. The lowest voltages, 7–12 kv, and longest wave-lengths were used by Kulenkampff but the upper wave-length limit was only 2.8A. The present paper is based upon data taken with a vacuum x-ray spectrometer at voltages from 1.1 kv to 2 kv and at wave-lengths extending out as far as 14A. The reason for the present study was to see whether the intensity in the continuous x-ray spectrum depends upon atomic number, voltage, and wave-length, in the same fashion as outlined earlier in this introduction when the wave-length is extended by a factor of five and the voltage is reduced by a factor of five. The vacuum x-ray spectrometer described in this paper was designed for x-ray spectroscopy of the solid state, and it is important to know the nature of the continuous radiation at the long wave-lengths used in such a study. This is especially true for absorption measurements where one wishes to choose the target which will give the strongest radiation in the region being studied. The experiments and theories already outlined, if extrapolated to long wave-lengths, predict the use of targets with large atomic number for obtaining maximum intensity. One cannot be sure of this extrapolation, especially when one considers the observation of Munier, Bearden, and Shaw[12] that, at the isolated wave-length of 10A, the radiation from an Al target was 30 percent stronger than the radiation from a W target. Further doubt is cast on the extrapolation because some of Kulenkampff's curves for different atomic numbers actually cross over one another in the region 2.5A to 2.8A, and the question arises as to whether this behavior is real or is entirely caused by characteristic absorption in the target.

EXPERIMENTAL

A vacuum x-ray spectrometer[13] was constructed for the purpose of making either single or double crystal measurements in the region out to 15A. The double crystal arrangement is of the Ross[14] type with the x-ray tube target and the axis of crystal B stationary. Crystal A, on a table halfway between, is moveable on ways perpendicular to a line joining the target to the axis of crystal B. A Geiger counter rotates around the axis of crystal B. This arrangement is laid out on a steel base plate $23\frac{1}{2}$ inches in diameter and $\frac{7}{8}$ inch thick. A large Pyrex bell jar with inner diameter 18″ fits over the spectrometer assembly and rests on the base plate compressing a lightly greased Koroseal gasket.

For the experiments herein described, crystal A was replaced by a slit system on the line joining the target and the axis of crystal B. Thus the vacuum spectrometer becomes a single crystal spectrometer of the simple Bragg type working under an evacuated bell jar. Two slits of 0.4-mm width were used with a distance between slits of 8 cm. The first slit was 6 cm from the target and the second slit was 6 cm from the axis of crystal B. The mica crystal was mounted so that the reflecting planes were the cleavage planes with a grating space of 9.9A. The slit for the Geiger counter was 6 cm from the crystal and was 1 mm wide. The crystal and Geiger counter can be turned independently from outside the spectrometer or they can be locked together in such a manner that the counter sweeps through twice the angle of the crystal.

The Geiger counter presents peculiar difficulties in a vacuum spectrometer because the window must be very thin and yet must be capable of withstanding an excess pressure from outside when there is air in the spectrometer and an excess pressure from inside when the spectrometer is evacuated. The metal counter described below has been found to be satisfactory. The window of 0.008-mm Al foil was sandwiched between two brass pieces which had been drilled with a series of $\frac{1}{32}$-inch holes forming a grid 2 mm×10 mm. The window was sealed with Picein wax and squeezed tightly in its sandwich by six screws. A window so supported has withstood over one hundred evacuations of the spectrometer without rupture. The Geiger tube was evacuated and torched mildly. The counter was designed to permit flashing of the central wire although this procedure seemed to make but little difference in the final performance. The counter was filled with 9 cm (Hg pressure) of argon and 1 cm of absolute alcohol vapor, and then sealed off. The threshold was 765 volts and a reasonably good plateau extended to 900 volts. The counter was operated at 840 volts using a commercial Cyclotron Specialties Company preamplifier, scaler, and mechanical counter. Automatic recording could be used when the intensity was sufficiently great by feeding the scaler output through a frequency meter to a pen and ink recorder. During automatic registration the crystal and the Geiger counter were locked together in

[12] Munier, Bearden, and Shaw, Phys. Rev. **58**, 537 (1940).
[13] S. T. Stephenson and F. D. Mason, Phys. Rev. **72**, 744 (1947).
[14] P. A. Ross, Rev. Sci. Inst. **3**, 253 (1932).

angular ratio of 1 to 2 and were driven slowly by a synchronous motor through a worm gear. Actually, because of low intensities, all the data collected in this study in the range 1.1 kv to 2.0 kv were taken by counting at least one thousand counts for each point and running each curve several times.

The water-cooled post which supports the x-ray tube target fits into the steel base plate through a ground cone and can be removed readily. Target blocks of Cu and Al were machined and threaded to match threads cut on the top of the target post. The target of W was prepared by sinking a W button into a copper block which was threaded to fit the target post. All target blocks were of identical geometry so that there would not be any variations in the electric field between different targets and the filament to cause variation in the focal spot and spurious intensity changes. As an added precaution the target faces were viewed edge on so that the entire 3-mm×8-mm focal spot, which lay in a vertical plane, would always see the crystal through the slits. The filament was of W partly enclosed in a hemi-cylindrical shield of Ni suspended from a ground glass seal at the top of the x-ray tube. The x-ray tube envelope was a bell jar within the main bell jar and consisted of a four-inch diameter Pyrex cylinder resting around the target post on the base plate. A hole 6 mm in diameter in the Pyrex cylinder opposite the focal spot permitted passage of the x-rays into the rest of the spectrometer. This hole could be covered with a foil for vacuum testing but, for the runs described herein, the hole was left uncovered. The x-rays emerged at right angles to the direction of the electrons striking the target.

The main bell jar and the x-ray tube were pumped by two separate pumping systems. An oil diffusion pump of 250 liters per second capacity was fastened directly beneath the bell jar and was backed by a Hypervac fore pump. The x-ray tube was pumped through a cold trap by another oil diffusion pump of similar capacity backed by a Duoseal pump #1405.

In the course of normal operation the x-ray target became fouled with a blackish deposit which appeared in a matter of minutes after the high voltage was turned on. Most of the runs made to determine the general shape of the continuous spectrum and its dependence upon the voltage across the tube were taken with well-coated targets. A target was considered to be well-coated after further running showed no change in the intensity of the x-rays produced. However, it was obviously impossible to obtain the dependence of the continuous spectrum upon atomic number with coated targets. Many schemes were tried in order to eliminate the coating for a period long enough to obtain readings on Al, Cu, and W targets at a few wave-lengths in this region. At first the oil in the diffusion pumps was suspected as the source of the deposit, but the introduction of a cooling trap in dry ice and acetone did not reduce the coating. A separate mercury pumping system for the x-ray tube failed to eliminate the deposit. The scheme described below reduced the deposit to such an extent that it was barely perceptible at the end of the first hour of running, which was sufficient time to make readings at several wave-lengths. Hillier[15] has suggested that deposits of this kind come: (*a*) from organic material diffusing out to the surface of the target being bombarded by the electrons; and (*b*) from vapors of the organic material present in the vacuum chamber, i.e., greases, pump oils, greasy surfaces of metal parts, etc. Accordingly, the target blocks were pre-heated for an hour in a quartz furnace at about 600°C and at a pressure of less than 0.1 micron before introduction into the spectrometer. This treatment removed organic impurities from the target. The target post was turned through 180°, thus placing the back side of the target opposite the filament, and the tube was run at regular voltage for about 20 minutes. A small deposit immediately formed on the back of the target but did not grow in magnitude. This treatment temporarily cleaned up the organic vapors from the vacuum chamber. The x-ray target was then turned back into proper position and remained free of coating for about an hour.

Power was supplied by an army radar power supply, Model RA 38, capable of furnishing up to 500 milliamperes current at voltages ranging from 300 volts to 15,000 volts. The output of the four rectifying tubes was smoothed by condensers and by an inductance so that the ripple was about one-half percent. All electrical power was supplied through a commercial voltage regulator capable of holding fluctuations to about one percent. Measurement of the potential applied to the x-ray tube was made to one percent using a meter in series with a high resistance. Currents from 5 to 80 milliamperes were used depending upon intensity requirements.

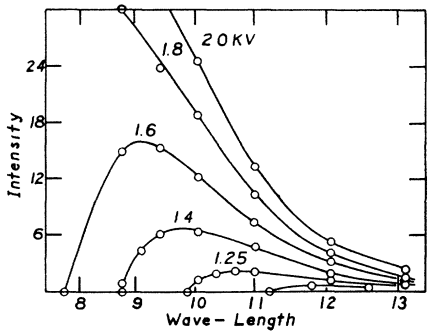

FIG. 2. Intensity in arbitrary units as a function of wave-length in Angstroms (1.11 to 2 kv in vacuum uncorrected).

[15] J. Hillier, J. App. Phys. 19, 226 (1948).

TABLE I. Intensities observed for clean targets at 1.6 kv and 40 ma.

Element	Atomic number	Intensity in counts/sec. at 9.1A	12A
Al	13	7.5	1.5
Cu	29	14.0	
W	74	30.0	8.0

RESULTS

The spectrometer assembly was tested by replacing the x-ray tube with a commercial, tungsten target tube and by running some curves in air at voltages ranging from 8.5 kv to 15 kv. These curves are reproduced without correction in Fig. 1 and are similar to curves shown by Kulenkampff for this region. The point of maximum intensity is close to $1.5\lambda_0$ and the areas under the curves are proportional to V^2. These curves constitute a test of the proper functioning of the spectrometer parts but contribute no new information.

Following this test the vacuum spectrometer was used for many runs on the continuous spectra from well-coated targets at voltages from 1.11 kv to 2.0 kv. The K edge of the Al window in the Geiger counter appears at 7.94A and at voltages above 1.55 kv and renders a determination of the shape of curves above 1.6 kv practically impossible. Fortunately the M series lines for tungsten are not excited at voltages below 1.9 kv and the L series lines for copper are at too long a wave-length to disturb the measurements. A typical set of curves is shown in Fig. 2. These curves are uncorrected except for counter and x-ray background and cover the range 8A to 13A. Occasionally points were taken to 14A. All experimental points are not shown but those presented are typical. The tube current was kept constant in all cases. A similar set of curves partially corrected as described below is shown in Fig. 3. It was not considered that correction factors were known accurately enough to correct beyond 13A. Corrections were applied as follows: (1) The amount of absorption in the Al window of the counter and in the dead gas space between the window and the counting region was calculated using absorption coefficients taken from Appendix IX of Compton and Allison.[16] (2) The efficiency of the counter was calculated from the percent of radiation absorbed by the known amounts of argon and alcohol vapor in the counter. Since all measurements were made with wave-lengths too long to excite the characteristic argon radiations, this calculation of the efficiency should be accurate. (3) A multiplying factor involving the frequency was used since a quantum causes a count independent of the energy of that quantum. An order correction was not necessary since the runs were cut off before any second-order radiation entered the counter. The curves were not corrected for any variations in the reflection coefficient of mica because no data were available on the reflection coefficient of mica in this region. The curves were not corrected for absorption in the target itself.

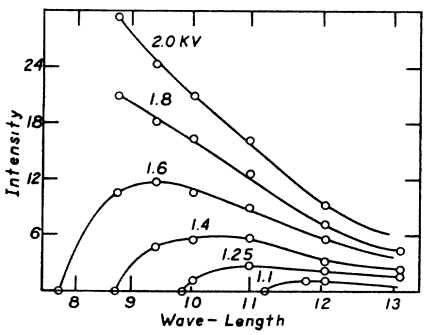

FIG. 3. Same as Fig. 2 but partially corrected.

In order to obtain accurate data on uncoated targets of W, Cu, and Al, the target blocks were vacuum fired as described above and the spectrometer was set at either 9.1A or 12A and readings taken at 1.6 kv and 40 ma (except that 12A for Cu was not done). The readings were made as soon as possible after turning up the high voltage and were continued for several minutes to note any trend caused by a coating. The intensity for the target of W gradually decreased while Al and Cu gradually increased. These curves were extrapolated to zero time to obtain a value characteristic of the pure metal. This extrapolation was quite accurate, since the coating caused a very slow change with time. The extrapolated values are presented in Table I. The coating did not become even faintly visible to the eye until after an hour had elapsed. Enough points were obtained with clean targets at wave-lengths other than 9.1A and 12A to indicate that the general shape of the curves for the pure metals was the same as is shown in Figs. 2 and 3 for a coated target.

DISCUSSION

A comparison of the curves of Fig. 1 with those of Fig. 2 reveals a very definite shift in the shapes of the curves if due cognizance is taken of the position of the point of zero wave-length. Whereas the high voltage curves of Fig. 1 and those of other investigators[1–7] reach a maximum at approximately $1.5\ \lambda_0$, the low voltage curves in the region 1.1 kv to 2 kv reach a maximum at approximately $1.05\ \lambda_0$ to $1.2\ \lambda_0$ (see Table II) and are evidently approaching the shape often assumed to be representative of a thin target in which the intensity rises immediately to a maximum at λ_0 and falls off thereafter as

[16] A. H. Compton and S. K. Allison, *X-Rays in Theory and Experiment* (D. Van Nostrand Company, New York, 1935).

TABLE II. The ratio of the wave-length of maximum intensity to the cut-off wave-length, λ_{max}/λ_0.

Kilovolts	Uncorrected Fig. 2	Partially corrected Fig. 3
1.11	1.05	1.05
1.25	1.1	1.1
1.4	1.1	1.2
1.6	1.15	1.2

$1/\lambda^2$. This general behavior might be expected if one considers the continuous spectrum from a thick target to be made up of a summation of the contributions of a number of thin targets. The contribution from each succeeding layer will decrease because of absorption of the electrons as they go in, and of the x-rays as they come out. At the low voltages used here the electrons do not penetrate far, and at these long wave-lengths the x-rays are strongly absorbed; thus the thick target spectrum is the sum of relatively few thin target contributions, each largely attenuated by electron and x-ray absorption. Consequently, at the lower voltages the thick target spectrum should approach the thin target spectrum[17] and this is observed.

The formula (2) given by Kulenkampff predicts that λ_{max} should shift toward λ_0 as λ_0 is increased; but in order to achieve the shift observed here, the constant B would have to be made so large that Eq. (1) would predict large quantities of radiation right at λ_0 which is contrary to experimental fact. Consequently, Kulenkampff's formulas do not adequately express the continuous spectrum in the region 8A to 14A as measured and partially corrected in the present work. One can determine empirically that the curves of Fig. 3 fit an expression of the type

$$I_\lambda = \frac{CZ}{\lambda^5}(1/\lambda_0 - 1/\lambda)$$

from 8A to 12A but not out to 14A.

The curves of Fig. 1 and of Figs. 2 and 3 cover approximately similar voltage ranges of almost two to one. Inspection of the curves reveals the fact that the dependence of the total integrated intensity upon voltage is decidedly different in the two wave-length regions. The region 8.5 kv to 15 kv yields curves whose integrated intensities are proportional to V^2. However, in the region covered by 1.1 kv to 2.0 kv the integrated intensity is proportional to a higher power of V. Part, at least, of the excessive drop in total intensity with decreasing voltage can be attributed to increasing absorption in the target itself with increasing wave-length. Fundamentally, one is here concerned with the question of what one means by total integrated intensity. In previous investigations the integration has been carried out to two or three times the cut-off wave-length. It is not possible to follow this procedure for the wave-lengths used in the present experiment. Actually one should obtain the equation of the curves and integrate from cut-off to very long wave-lengths in order to obtain a true integrated intensity, but it is not possible to obtain a simple equation that fits all the present data. In any event, if one studies the intensities obtained at one particular crystal setting well beyond the maximum (at 11 or 12 or 13A, see Table III) as a function of voltage, one should obtain a picture independent of all factors involving target absorption or crystal reflectivity since these factors would be the same at the different voltages for the one wave-length. Reference to Table III for three isochromats shows that the intensity at a given crystal setting varies as the square of the voltage from 2 kv to 1.6 kv and about as the cube to 1.25 kv. It is probable, therefore, that the total integrated intensity at the voltages used in this work is dependent upon a higher power of the voltage than the square. Whether this is a true effect or an apparent effect caused by the increasing importance of electrons reflected from the target face before losing all of their energy cannot be decided. Presumably x-rays produced by these electrons subsequent to reflection, as they impinge on other parts of the apparatus, would not enter the slit system nor contribute appreciably to measured x-ray intensities. If one assumes that there is an effective loss of 0.5 kv energy by the electrons, one finds fairly good agreement between the intensity at one wave-length and $(V-0.5)^2$. (See Table III.) Such an assumption would allow one to retain the dependence upon the square of the voltage.

TABLE III. The ratios of intensities at several wave-lengths and of the second and third powers of the voltage using 2 kv as standard.

	Intensity ratios			Voltage ratios		
Kilovolts	11A	12A	13.1A	V^2	V^3	$(V-0.5)^2$
2.0	1.0	1.0	1.0	1.0	1.0	1.0
1.8	1.3	1.3	1.5	1.23	1.4	1.3
1.6	1.8	1.6	1.7	1.57	1.9	1.9
1.4	2.8	2.8	3.0	2.04	2.9	2.8
1.25	6.0	4.0	4.0	2.56	4.1	4.0
1.11		7.0		3.25	5.9	6.1

The total intensity of radiation from a target has been regarded as proportional to the atomic number for high voltages and short wave-lengths. The data illustrated by Table I indicate that at 9.1A and at 12A the measured intensity is proportional to the atomic number within experimental error. The largest source of error comes from difficulty in positioning the targets in exactly similar fashion. If one assumes that all ordinates are proportional to atomic number, the total intensity of

[17] Jesse W. M. DuMond, Phys. Rev. 72, 276 (1947).

radiation will likewise be proportional to the atomic number.

CONCLUSION

The present work indicates that the total intensity in the continuous radiation of x-rays at 1.1 kv to 2.0 kv, as measured and partially corrected, is proportional to the atomic number and to some power of the voltage higher than the second. The shape of the curve resembles that to be expected from a thin target.

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The Mass of Cosmic-Ray Mesotrons*

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By cloud-chamber observations of the curvature of mesotrons in a magnetic field of 4750 gauss and the subsequent range of these same particles in a second cloud chamber containing fifteen lead plates each 0.67 cm in thickness, the mass of 43 cosmic-ray particles has been determined. 37 of these particles appear to give a set of observations that are consistent with a unique mass of 215±4 times the mass of an electron. Of the 6 remaining observations 4 indicate a mass much too large (474, 538, 588, and 717) to be reasonably considered as statistical fluctuations in the observations of normal mesotrons. The remaining 2 observations (114 and 120) also appear to be inconsistent with the normal mass of the mesotron and the observed probable errors in individual measurements in this experiment.

A NUMBER of experimental studies of the mass of cosmic-ray mesotrons have been made. Some of the earlier data have been discussed by Wheeler and Ladenburg,[1] and by Hughes.[2] More recent studies have been reported by Fretter,[3] Lattes, Muirhead, Occhialini, and Powell,[4] LePrince-Ringuet and M. Lheritier,[5] and by Alichanian, Alichanow, and Weissenberg.[6] Since the work on which this report is based was completed, the detection and identification of mesotrons produced artificially by the 184-inch cyclotron has been accomplished by Lattes and Gardner.[7] The purpose of the work reported here was to add to the data on the mass of the mesotron and to try to improve the accuracy of the measurement.

THE EXPERIMENTAL APPARATUS

The experimental arrangement is illustrated in Fig. 1. The upper cloud chamber, CH_1, was placed in a magnetic field of 4750 gauss. The chamber was 12 inches in diameter and 3 inches deep. B represents a baffle system which consisted of two perforated brass sheets and a drilled plate 0.25 inch thick, which were separated by 0.25-inch spacers. Velvet was fastened to the front of the first perforated sheet to provide a black background for photography. The baffle was intended to smooth out irregularities in the expansion caused by uneven motion of the rubber diaphragm, R. An asymmetrical arrangement of two expansion ports, E, resulted in a detectable distortion of the tracks. This distortion was reduced but not eliminated by installing a symmetrical arrangement of three expansion ports (see the discussion of errors). The upper cloud chamber was filled with air and a 3:1 mixture of ethyl alcohol and water to a total pressure of 1.13 atmospheres in the expanded position. The chamber was not saturated with liquid but the amount of vapor was adjusted to keep the expansion ratio in the range of 14 percent to 16 percent. A clearing field of 100 volts between the metal back plate and an aquadag ring on the front glass was reduced to zero as soon as possible after the passage of the tripping particle through the Geiger counters, C. Illumination was provided by two GE FT 422 flash lamps each of which was excited by the discharge of a condenser of 160-μf capacity charged to 2000 volts. The illuminated region was 1 inch deep and the full height of the cloud chamber. The tracks were photographed on Ansco Ultra-Speed 35-mm film in a single frame camera using a Summar lens of focal length 5 cm at an aperture of f:9.

To reduce the effects of temperature variations a copper heat shield was built around the upper

* Assisted by the Joint Program of the ONR and the AEC.
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[1] J. A. Wheeler and R. Ladenburg, Phys. Rev. 60, 754 (1941).
[2] Donald J. Hughes, Phys. Rev. 69, 371 (1946).
[3] William B. Fretter, Phys. Rev. 70, 625 (1946).
[4] Lattes, Muirhead, Occhialini, and Powell, Nature 159, 694 (1947).
[5] L. LePrince-Ringuet and M. Lheritier, J. de Phys. et Rad. 7, 65 (1946).
[6] Alichanian, Alichanow, and Weissenberg, J. Phys. U.S.S.R. 11, 97 (1947).
[7] C. M. G. Lattes and E. Gardner, Science 107, 270 (1948).