Ionization Chamber Bursts at High Altitudes*†

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A thin-walled, low pressure ionization chamber has been sent into the upper atmosphere by means of balloons to study bursts of ionization. Pulse size, barometric pressure, and temperature were telemetered to the ground by means of a FM audio subcarrier system with a 75-Mc radio link. Measurements have been made of the size and frequency of bursts of ionization greater than that produced by 0.8 polonium alpha-particles ($0.8\times 5.1=4.1$ Mev) at altitudes up to that corresponding to an air mass of 17 g/cm^2 remaining overhead.

I. INTRODUCTION

THE ionization chamber has taken on a new importance for elementary particle investigations as a result of recent technical improvements in the removal of electron-capturing impurities from chamber gases, in rapid collection of electrons from such gases, and in associated fast amplifiers. In contrast with the Geiger-Müller counter, which determines only the number of particles, and the integrating ionization chamber, which yields only total ionization, the modern ionization chamber determines the ionization produced by individual particles. Such an instrument can be used in two quite different ways for the study of the cosmic radiation. (a) The chamber can be used purely as an indicator for events which produce sufficient ionization to be detected, events which we hereafter call "bursts" without any implications as to their nature or source. In this case we can measure the frequency of the bursts at several altitudes and determine the rate of change with air mass overhead of the burst producing radiation. Likewise, we can measure the *absorption* of the burst producing radiation in other substances. (b) Alternatively, we can study the size-frequency distribution of events observed in an ionization chamber at a single altitude and thus investigate the *nature* of the events which cause the bursts. The present investigation is an attempt to study nuclear processes in the upper atmosphere by means of both the above methods.

At the time when these investigations were commenced, June, 1946, burst studies in modern ionization chambers had never been carried out at altitudes above mountain-top levels. Also, the experimental picture was confused by lack of agreement between different observers,[1] largely owing to the wide variety of equipment and conditions used by the various experimenters and to the inability to distinguish between bursts due to electron showers and those due to fragments from nuclear explosions.

Euler[2] has shown that both types of events contribute to ion chamber bursts and succeeded in giving a satisfactory explanation of the observed size-frequency distribution of bursts in an ion chamber. Using the data of Stetter and Wambacher[3] for the energy distribution of star particles, he calculated the burst distribution expected from this cause. He showed that the expected distribution was in qualitative agreement with that found by Carmichael and Chou[4] if one assumed a mixture of bursts due to electron showers and nuclear disintegrations.

About 98 percent of the pulses in an ionization chamber at 3500 meters are produced by heavy particles, according to an analysis of the shapes of the pulses made by Rossi and Williams.[5] In view of this large percentage of heavy particles at this altitude and in view of the fact that this proportion should become even greater at higher altitudes, it is evident that the ionization chamber is a very useful device for studying nuclear explosion phenomena. Bridge and Rossi[6] have measured the burst rate in a cylindrical ionization chamber at altitudes up to 35,000 feet in a B-29 aircraft. They find that the rate of pulses increases rapidly with altitude and state that the increase corresponds to an exponential absorption in the atmosphere with a mean free path of 150 g/cm^2, assuming vertical radiation. Also, Tatel and Van Allen[7] have sent an identical chamber to the top of the atmosphere by means of a V-2 rocket. From their results, together with the results of Bridge and Rossi, they conclude that the bursts are nuclear explosions induced by the primary cosmic radiation with a mean free path of 200 to 225 g/cm^2, assuming isotropic incidence of the burst producing radiation. Rossi,[8] on the other hand, interprets the data as indicating a maximum and states that bursts are produced by a secondary radiation, probably neutrons.

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[1] H. Carmichael, Phys. Rev. 74, 1667 (1948).

[2] H. Euler, Z. Physik **116**, 73 (1940).

[3] G. Stetter and H. Wambacher, Physik. Z. **40**, 702 (1939).

[4] H. Carmichael and C. N. Chou, Proc. Roy. Soc. (London) **A154**, 223 (1936); Nature **144**, 325 (1939).

[5] B. Rossi and R. W. Williams, Phys. Rev. **72**, 172 (1947).

[6] H. Bridge and B. Rossi, Phys. Rev. **71**, 379 (1947).

[7] H. E. Tatel and J. A. Van Allen, Phys. Rev. **73**, 87 (1948).

[8] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).

Hulsizer[9] has reported results obtained from an ionization chamber sent into the upper atmosphere to look for shower-producing electrons. He observed bursts which he interprets as being due to heavy particles from stars and concludes that the frequency of the star-produced bursts does not reach a maximum below the top of the atmosphere at a geomagnetic latitude of about 54°N.

This paper reports the results of an experiment which has been carried out in order to study the variation of ion chamber bursts as a function of altitude and of burst size at 52°N geomagnetic.

II. EXPERIMENTAL APPARATUS

In our experiments, a thin copper ion chamber filled with pure argon was sent into the upper atmosphere by means of free balloons. Burst amplitude, barometric pressure, and equipment temperature were simultaneously telemetered to the ground by means of a FM radio link.[10] The balloon signals were received at a fixed ground station and the telemetered data recorded permanently by photographic means.

In this technique the balloon equipment is built into a light wooden gondola and designed to have as little weight as possible without sacrificing stability and reliability. Labile equipment, such as batteries and high voltage leads, are protected from harmful effects of the extremes of temperature and pressure encountered via dielectric sheaths and sun shields. A clock-driven standardizing system is incorporated to check periodically the entire burst measuring system with polonium alpha-particles.

The ionization chamber used in the balloon flights consists of a 30.5-cm diameter copper sphere fabricated from two spun hemispherical shells soldered together with pure tin. The wall thickness is 0.54 mm, but is not absolutely uniform, varying by about 10 percent.

The collecting electrode is a 5-cm diameter copper sphere suspended by a radial rod $\frac{1}{8}$ in. in diameter. This rod is supported by an assembly of insulating material that is force-fitted into the neck of the chamber. Figure 1 shows the construction of the chamber. The first stage of the pulse amplifier is contained within the chamber neck. It is a cathode follower providing a low output impedance for the chamber.

A special feature of the chamber is the cylindrical guard ring that surrounds the collecting electrode support and grid blocking condenser. This guard ring is connected to the output of the cathode follower through a high voltage blocking condenser and is thus fed with a pulse of approximately the same size as appears on the collecting electrode. This cancels a large fraction of the stray capacity to ground of the input circuit. With this arrangement the effective input capacity of the chamber and amplifier is only 6.5 $\mu\mu$f.

[9] R. I. Hulsizer, Phys. Rev. **73**, 1252 (1948).

[10] The apparatus is described in detail in a separate article by Coor, Darago, and Snow, to be submitted to Rev. Sci. Instr.

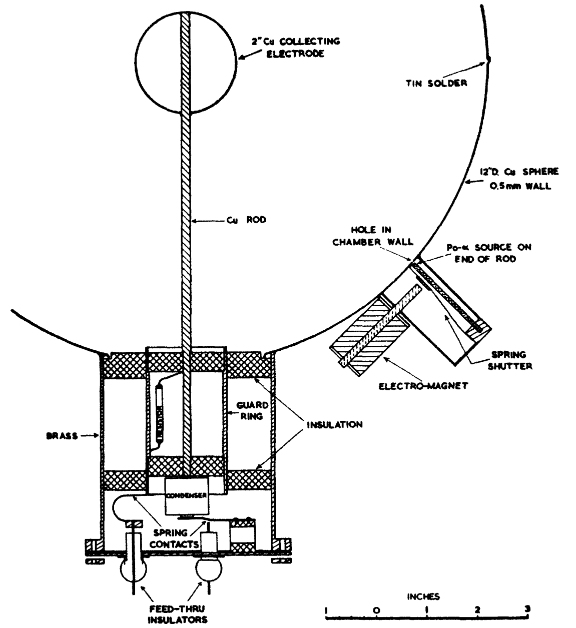

FIG. 1. The construction of the ionization chamber used in the balloon flights. The first stage of the amplifier (not shown) is located in the chamber neck just below the bronze spring contact for the central electrode. The polonium alpha-particle source for periodic calibration is shown on the side of the chamber. The chamber was filled with pure argon to a pressure of 1.3 atmos, and electron collection achieved.

The guard ring rides at the collecting potential and hence acts also in the conventional manner to protect the central electrode from leakage currents.

In order to collect electrons before they combine to form heavier negative ions, pure argon is used as the chamber gas. It is found that the amplitudes of pulses from polonium alphas originating at the wall remain essentially unchanged for chamber voltages above 550. This result applies to pure argon at 1.3 atmospheres (of 76 cm Hg, 21°C), the pressure adopted for the experiments. With 600 volts as the collecting potential, the value used in the experiments, it is found that the chamber pressure may be doubled with a consequent drop of less than 10 percent in pulse height if the gas is pure. This small drop is adopted as the criterion for gas purity and consequently for saturation. Polonium alpha-particles originating at the wall of the chamber give a pulse with a rise time of roughly 3 μsec when observed with a fast scope.

A permanent alpha-source is incorporated in the chamber for clock controlled standardization. The arrangement of the source and shutter mechanism is shown in Fig. 1. A small hole drilled into the chamber wall allows alphas from a thick source on the end of a nickel rod to enter the collection field when a thin shutter is pulled aside. The source is 2 mm from the inside wall; thus, $(37.5/39.5)^{\frac{2}{3}}\times 5.25=5.1$ Mev of ionization is formed in the chamber by each alpha-particle.

A moderately fast lightweight amplifier was developed for use with the chamber. It is a three-stage, resistance-coupled type employing inverse feedback to improve stability and linearity. A gain of about 500 with a rise time of about 3 μsec and a decay

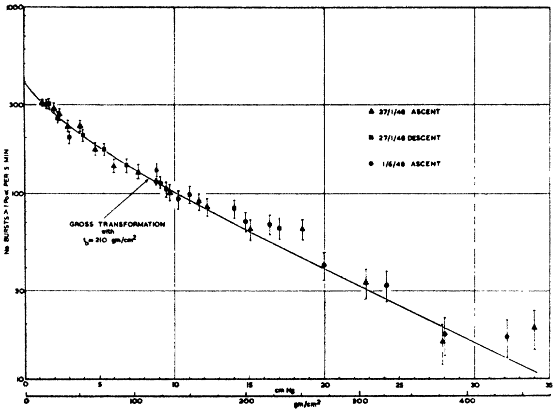

FIG. 2. The number of bursts per 5 min greater than 1 polonium alpha as a function of atmospheric thickness at 52°N magnetic latitude. Two flights were used to obtain the data represented in the figure, those of January 27, 1948 and May 1, 1948. The points at 8.9 and 1.27 cm Hg represent data obtained while the equipment floated for 45 minutes at almost constant level. The flags indicate the statistical errors. The curve drawn in is the Gross curve fitted to the points at 1.27 and 8.9 cm Hg.

time of roughly 50 μsec is obtained. The signal to noise ratio is 30:1 for a 5.1-Mev alpha-particle in the chamber.

The amplified chamber pulse is converted into a pulse whose duration is a function of the ionization produced in the chamber. This pulse is then transmitted to the ground station by means of one channel of an FM audio subcarrier—75 MC, FM radio link, system. Temperature and pressure are telemetered on another channel. The pressure sensing element is a baroswitch unit used in meterological work. It is calibrated in a bell jar before each flight. Its readings are good to about 0.5 mm Hg.

On the ground, the radio signal from the balloon is received and the telemetered information unscrambled and recorded. The recorder is of the moving mirror galvanometer type and employs photographic recording. The height of the trace on the photographic record is directly proportional to the logarithm of the size of the bursts in the chamber.

The ionization chamber, telemetering equipment, and transmitter are contained in a light wooden gondola. The ion chamber is located at the top of the gondola and is supported at five points by means of sponge rubber pads. This arrangement effectively shockmounts the chamber and the pulse amplifier, which is suspended from the chamber neck. The transmitter and its batteries are located in the lower section of the gondola. The antenna is suspended around the bottom of the gondola by four supports that project from the corners.

Before launching, the top half of the gondola is covered with aluminum foil and the lower half with several layers of cellophane. This arrangement keeps the ion-chamber from being heated by the sun's rays and prevents the batteries in the lower part of the gondola from freezing. Scotch tape is used to seal the cellophane and foil as nearly airtight as possible. The gondola is attached to the balloons by means of four Nylon ropes, fastened to the four main gondola posts. The total weight of the complete apparatus is 30 lb.

For one flight, clusters of Dewey and Almy type J-2000 balloons were used. This flight reached 1.2-cm Hg pressure. The other flight was carried out with a 20-foot General Mills polyethylene constant volume balloon. This flight reached 8.8 cm Hg, where it floated for some time.

III. EXPERIMENTAL RESULTS

The experimental results discussed in this section were obtained in two flights, January 27 and May 1, 1948. The January flight went to 1.2 cm Hg, while the May flight ascended to 8.8 cm. Data yielded by two previous flights (without periodic standardization) will not be considered, because of discrepancies and inconsistencies caused by equipment failure and drift.

A. Burst Frequency *vs* Atmospheric Depth

The dependence of burst frequency upon mass of air remaining overhead is shown in Fig. 2. The results shown are from the ascent and descent of the January 25 flight and from the ascent of the May 1 experiment. (The balloons were out of radio range during descent.) The rates given for the bursts at 1.27 cm (January 27 flight) and at 8.9 cm (May 1 flight) are each the average of nine 5-min periods, obtained while the balloons floated at an almost constant level. These two values are used to calculate the "absorption thickness," or mean free path t_0, of the burst-producing radiation in the atmosphere.

It is general practice at low altitudes to express the decrease with atmospheric depth in the intensity of a radiation as a simple exponential of the form

$$N(t)=N_0\exp(-t/t_0). \quad (1)$$

For some cosmic-ray phenomena a satisfactory fit may be obtained with this law, even at high altitudes; but it is clear that the t_0 is not the true absorption thickness for the radiation, because it is not correct to assume vertical incidence. Even at atmospheric depths of the order of three mean free paths, the error introduced in the effective mean free path by the assumption of vertical incidence is about 15 percent. The true absorption law is given by the Gross expression[11]

$$N(t)=2\pi N_0\left[\exp(-t/t_0)-(t/t_0)\int_{t/t_0}^{\infty}x^{-1}\exp(-x)dx\right], \quad (2)$$

where N_0 is the number of incident particles $cm^{-2}\,sec^{-1}\,steradian^{-1}$.

For bursts of ionization greater than 1 Po-α, the absorption thickness for the burst-producing radiation, assuming isotropic incidence, is found to be $t_0=210\pm7$ g/cm² [as defined in Eq. (2)]. This constant was evaluated graphically. A plot was made of the calculated ratio of the burst rates for 1.27 cm (17 g/cm²) and 8.9 cm (121 g/cm²) as a function of t_0. From this plot was determined that value of t_0 which would reproduce the experimentally observed ratio of burst frequencies. The Gross curve drawn in Fig. 2 for burst frequency as a function of altitude is determined entirely by the data at 1.27 cm and 8.9 cm. It reproduces satisfactorily the observations for all values of the air mass overhead less than 300 g/cm². It may be noted that at atmospheric depths in the region of 300 g/cm² the observed curve would correspond to an effective absorption thickness of 160 g/cm², if one assumed a simple exponential law and vertical incidence.

[11] B. Rossi, Revs. Modern Phys. 20, 564 (1948), Eq. (11).

The value 210 g/cm² obtained near the top of the atmosphere in this experiment is somewhat larger than the figure obtained by observers lower in the atmosphere. Rossi,[11a] for example, finds that bursts in an ionization chamber from 35,000 ft down fit a Gross curve for a mean free path of 165 g/cm². However, this is not unexpected as the primary radiation is complex and the various components will show differing behavior as they pass down through the atmosphere.

B. Size-Frequency Distribution

It is of interest to observe the nature of the size-frequency distribution of bursts at different altitudes. The integral and differential distributions are shown in Figs. 3 and 4, respectively. The integral distribution curve gives the number of bursts per five minutes greater than a size E as a function of E at three atmospheric depths. The curves shown for 1.27 and 8.9 cm Hg were obtained while the gondolas floated at an almost constant altitude. The points of the curve shown for the region 15 to 40 cm Hg were obtained in the two flights as they rapidly ascended through the lower atmosphere. The good agreement between the two experiments in this region demonstrates the reproducibility of the apparatus and validates a comparison between them when there is less air mass overhead.

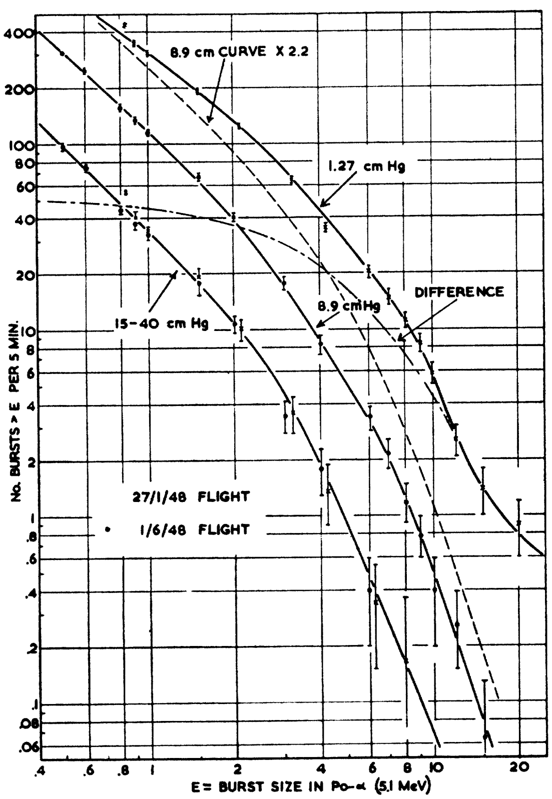

FIG. 3. The integral burst-size distribution obtained at three points in the atmosphere. The distributions at 1.27 and 8.9 cm Hg were obtained in 45 minutes while the apparatus floated at almost constant level. The data given for 15–40 cm Hg was obtained as the balloons rose through this region of the atmosphere. Best-fit curves are drawn through the points. The dashed line in the figure is calculated by multiplying all readings at 8.9 cm Hg by the constant factor 2.2. Note how different this curve is at large burst sizes from the experimental curve found for 1.27 cm Hg. The difference between the two curves is indicated by the dot-dash line. It is quantitatively in accord, as regards magnitude and shape, with what one would expect from the known flux of heavy particle primaries (see discussion in text).

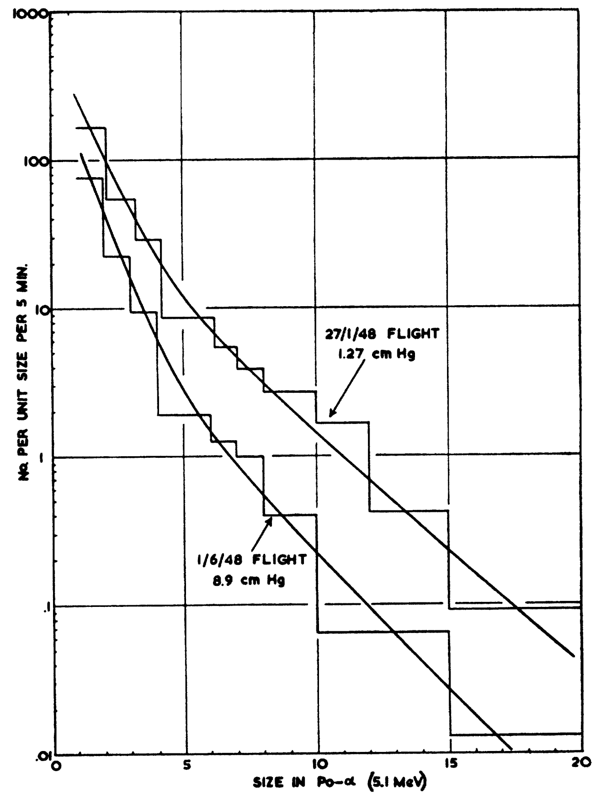

FIG. 4. The differential burst-size distributions obtained while the balloons floated at 1.27 and 8.9 cm Hg for 45 minutes. Best-fit curves are drawn in.

The differential distribution was obtained by constructing histograms of the counts obtained at the two regions of good statistics.

It is seen that the integral distributions of pulse sizes at 8.9 cm and at 1.27 cm differ appreciably, especially in the region of larger bursts. The differential distribution, however, does not show such a marked difference. A quantitative way to describe this difference is to give the ratio of burst frequencies as a function of burst-size at the two pressures. These results are presented in graphical form in Fig. 5. The curve for the ratio of the differential distributions was obtained by taking the ratio of the "best-fit" curves for the histograms in Fig. 4. The absorption thickness corresponding to the ratio between the rates at 1.27 and 8.9 cm Hg (17 and 121 g/cm²), is given on the left-hand side of the figure. The mean free path, t_0, for the radiation responsible for bursts of each size was so

[11a] Private communication.

chosen as to give, in each case, the experimental value for the ratio of burst frequencies at the two altitudes

$$R=N(17)/N(121),$$

as calculated from Eq. (2). It is evident from the curves that a large part of the difference between the size distributions at the two altitudes results from the eight bursts greater than 20 polonium alpha that occurred in 45 min at the 1.27-cm level. Of these eight bursts, six are in reality larger than 30 alpha, driving the system to its limit. These very large bursts show up in the upper right-hand point in Fig. 3. For lower values of the bias, these bursts affect the *integral* curves of Fig. 3, but not the *differential* curves of Fig. 4.

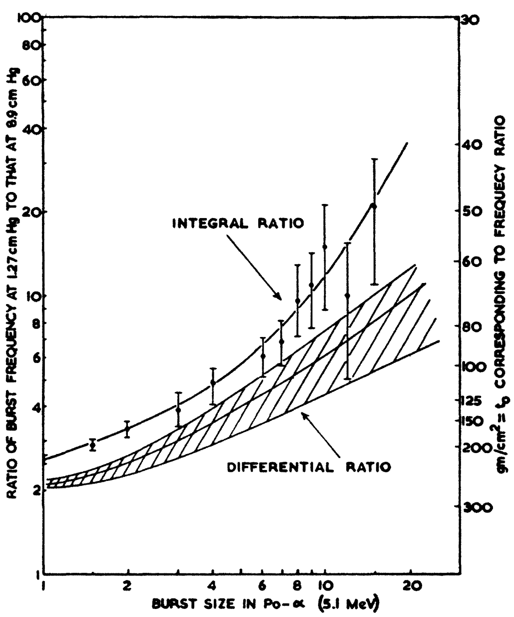

FIG. 5. Ratio of the burst-size distributions at 1.27 cm Hg to those at 8.9 cm Hg. The ratio of the integral distributions was plotted point by point and the best-fit curve drawn in. The curve for ratio of differential distributions was drawn by taking the ratio of the best-fit curves in Fig. 4. A scale of mean free path in g/cm² is drawn on the right. This mean free path, when inserted in the Gross formula for isotropic incidence, reproduces the ratio of rates at 1.27 and 8.9 cm Hg.

IV. DISCUSSION OF RESULTS

Experimentally, a burst represents the production of some few Mev of ionization in the active volume of a chamber within an extremely short period of time. Two explanations for this effect immediately offer themselves: that the bursts are produced by showers of electrons impinging upon the chamber, or that they are produced by one or more heavier particles. The frequency of air showers of a given density should, according to cascade theory, increase rapidly up to a certain altitude, then fall off again. Also, as was first known from the work of Stetter and Wambacher,[12] the frequency of stars, a possible source of heavy particles, increases rapidly with altitude. In addition, bursts may originate from the heavy nuclei in the primary cosmic radiation.[13] These three types of events will now be analyzed to see whether they can account for the observations. An attempt will be made to infer as much as possible about the nature of the observed events and their relation to the over-all cosmic-ray picture.

A. Negligible Frequency of Bursts Due to Electron Showers

The average path length in the spherical ionization chamber used in the experiments is $\frac{2}{3}\times 30$ cm, which is equivalent to 0.047 g/cm² of argon. An electron at minimum ionization loses energy at the rate of about 2 Mev per g/cm², so that each electron will lose, on the average, 0.094 Mev in the chamber gas. Therefore, about 55 electrons passing through the chamber in coincidence will be required to produce a burst equivalent to 1 Po-α. This number corresponds to a density of 800 particles/m². Electron showers of much greater density than this have been observed at moderate altitudes,[14] but little is known about them experimentally in the upper atmosphere. Theoretically, it is to be expected that dense cascade showers are almost nonexistent in about the top 9 cm Hg of the atmosphere, as a cascade unit for air is 3.3 cm Hg. Also, as the chamber wall is very thin, less than 0.1 cascade unit, little multiplication will take place there. It can be calculated that not more than one shower induced burst occurs per hour at 3.9 cm Hg, a number negligible in the present experiments.

As has been mentioned, there is also good experimental evidence that the large majority of bursts observed in thin-walled ion-chambers at 25,000 ft (24 cm Hg)[15] and at 11,500 ft (45 cm Hg)[5] are actually due to nuclear fragments. Consequently, it will be assumed that at *all* altitudes for which data were obtained in the balloon flights, the large majority of observed bursts were due to heavy particles, either singly or as stars.

There is some evidence that electron showers may be produced in nuclear processes,[16,17] but little is known about the nature or frequency of such events. However, it would seem quite probable that a transformation as energetic as this would release at the same time several nucleons. Then the ionization due to the protons and alpha-particles would dominate in these processes over that due to the electrons produced at the same time. Thus, such events are to be considered as normal stars for the purpose of the present experiment. Consequently, it will be legitimate to disregard the effects of electrons in the following considerations.

[12] G. Stetter and H. Wambacher, Physik. Z. **40**, 702 (1939).

[13] Freier, Lofgren, Ney, Oppenheimer, Bradt, and Peters, Phys. Rev. **74**, 213 (1948); Freier, Lofgren, Ney, and Oppenheimer, Phys. Rev. **74**, 1818 (1948).

[14] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **50**, 263 (1936).

[15] H. Bridge, Phys. Rev. **72**, 172 (1947).

[16] J. Daudin, Compt. rend. **218**, 275 (1944).

[17] F. Oppenheimer and E. P. Ney, Phys. Rev. **76**, 1418 (1949).

B. Heavy Particles from Nuclear Explosions

One or more heavy particles (alphas or protons) entering the chamber can produce a large burst. A proton near the end of its range can produce a maximum pulse equivalent to 1.1 Po-α if it traverses the diameter of the chamber. An alpha-particle can produce four times as much ionization under the same circumstances. These heavy particles are known to exist in the atmosphere, and Bagge[18] has shown that the proton intensity observed in the lower atmosphere can be accounted for in terms of nuclear explosions. Stetter and Wambacher[12] found that the rate of these nuclear explosions increases by a factor of 60 in going from sea level to 11,000 ft, which is the order of increase found for the ionization chamber bursts. We must therefore explain some of the bursts in the chamber at high altitudes as single and multiple heavy particles from stars which occur in the chamber gas and wall, and in the surrounding atmosphere.

This star picture of nuclear explosions is looked into in detail in a paper to appear later. It will be shown there that (1) the observed burst size distribution is explainable qualitatively, except at the highest altitudes, in terms of protons and alpha-particles from nuclear explosions, and (2) that the absolute number of bursts is in reasonable agreement with the rate of proton production observed in photographic emulsions.

The change in the relative frequency of bursts which occurs near the top of the atmosphere may be taken to indicate that the absorption coefficient for the radiation producing the larger bursts is greater than the coefficient governing the smaller bursts, but that the nature of the event is basically unchanged. Insofar as large bursts are due to stars, the observed change of distribution with altitude is qualitatively reasonable. It is known from photographic plate data that the frequency of large stars increases more rapidly with altitude than that of small ones.[19,20] However, it is difficult to give a quantitative estimate of this effect on the burst distribution. Since large bursts can result from the passage through the chamber of two or more particles from the same nuclear explosion, it is expected that on the average larger stars will give larger bursts. As far as statistics allow, it can be seen from Fig. 3 that there is an indication of a change in the pulse size distribution between 15–40 cm Hg and 8.9 cm Hg. However, statistical difficulties prevent any accurate estimate of the magnitude of the effect. It is difficult to explain the alteration in distribution at these depths in terms of any mechanism other than the change in the relative frequency of large and small stars produced in the wall of the chamber. The heavy particles that have recently been found in the primary radiation should not penetrate to these depths in significant number to account for the effect.

C. Heavy Nuclei from Outer Space

The heavy nuclei in the primary radiation, which were recently discovered by the Minnesota and Rochester groups,[13] have atomic numbers up to 40 and are very energetic, some penetrating more than 30 g/cm^2 of the atmosphere. The authors estimate that the majority of these particles are largely absorbed after traversing about 30 g/cm^2 (2.2 cm Hg) of atmosphere, and that the flux averaged over a hemisphere is 0.4 $\times 10^{-4}$ cm^{-2} sec^{-1} steradian^{-1} ($z>10$) at a depth of 14 g/cm^2 (1 cm Hg). This flux corresponds to about 50 heavy particles ($z>10$) per 5 min passing through the chamber used in the present experiments.[21] A particle at minimum ionization having $z=10$ should ionize 100 times more heavily than a proton at minimum, or about 200 Mev/(g/cm^2). In our chamber, this particle would produce an average burst of 9 Mev or about 1.8 polonium alpha; therefore, almost all heavy particles with $z>10$ should produce detectable pulses in the chamber.

The rate of 50 per 5 min calculated for 1.27 cm Hg from the Minnesota-Rochester data is an appreciable fraction (about one-third) of the total rate of bursts >9 Mev (1.8 Po-α) found at this elevation in the present experiments (about 160 per 5 min). Thus, heavy nuclei produce a significant fraction of all ionization chamber bursts in the upper 30 g/cm^2 of the atmosphere. Their effect comes more clearly into evidence when we examine (1) the abnormally high absorption coefficient of large ionization chamber bursts, (2) the large change with altitude in the burst-size distribution, and (3) the number of bursts greater than 100 Mev found at 1.27 cm Hg.

(1) The observed rapid absorption of the bursts of abnormal origin is consistent with the idea that heavy nuclei are responsible for these events. Figure 5 shows the effective mean free path of the burst-producing radiation, the normal and abnormal radiation being lumped together, as a function of the size of the burst produced by this radiation. It is seen that there is a systematic trend to higher absorption coefficients with increasing burst size. This effect is just what is to be expected on the assumption that many of the bursts are due to the traversal of the chamber by heavy nuclei. Thus, it is reasonable to consider the burst-producing radiation as a mixture of protons with a mean free path certainly no less than 60 g/cm^2, and perhaps much greater, and heavy nuclei with mean free paths of the order of 30 g/cm^2, according to Bradt and Peters.[22] As the large bursts are produced in larger and larger pro-

[18] E. Bagge, article in *Kosmische Strahlung*, edited by W. Heisenberg (Berlin, 1943), p. 119.

[19] Kaplon, Peters, and Bradt, Phys. Rev. **75**, 1329 (1949).

[20] Salant, Hornbostel, and Dollman, Phys. Rev. **74**, 694 (1948).

[21] This is in substantial agreement with the rate calculated from more recent data of H. L. Bradt and B. Peters, Phys. Rev. **76**, 156 (1949), by extrapolating their flux given for the top of the atmosphere down to 17 g/cm^2 using the Gross equation with $t_0=23.5$ g/cm^2.

[22] H. L. Bradt and B. Peters, Phys. Rev. **75**, 1779 (1949).

portion by heavy particles, the mean free path tends systematically to a lower and lower figure. Of course, a part of the observed effect may also be due to a possible decrease of protonic mean free path with increasing energy. Only a discrimination between proton- and heavy-nucleus-induced events, say, by the emulsion technique, would allow one to say how much of the observed shortening of the mean free path for big bursts is a proton effect and how much is due to heavy nuclei.

(2) A related effect attributable to heavy nuclei is the large change with altitude in the burst size distribution, as shown in Fig. 3. The dashed curve in the figure allows one to compare more easily the observations at 1.27 cm Hg and at 8.9 cm Hg. It is clear from the figure that it is possible to consider the burst size distribution curve at 1.27 cm Hg to be made up of two parts: (a) a component (indicated by the dashed line) which is absorbed with the same mean free path which is found for small bursts; and (b) a heavy-nucleus-induced effect, which has become negligible at a depth of 8.9 cm Hg=120 g/cm^2 (dot-dash curve in figure). Obviously, this interpretation is not the only possible one (conceivably there may be a decrease of proton mean free path with energy). But the dot-dash curve corresponds to an intensity of the heavy particle component ($\sim$60 per 5 min) of just the order ($\sim$50 per 5 min) calculated from the data of Bradt and Peters. Also the shape of the dot-dash difference curve is qualitatively in agreement with this interpretation. It is difficult, therefore, to escape the conclusion that this difference curve gives a reasonable order of magnitude representation of the effect of heavy particle primaries.

(3) Eight very large bursts ($>$20 Po-α or 100 Mev) were observed in 45 min at 1.27 cm Hg, but none at any lower altitude. It would be a very unusual explosion in the wall or gas of the chamber which could release in the gas so much energy, for a proton can at best lose only 5 Mev in a traversal ending just short of the far wall of the chamber (densest portion of the Bragg curve). A heavy particle with a charge of $Z=33$ suffices, however, to produce a pulse of this size even at minimum ionization; and near the end of its range, a much smaller charge is enough to produce the observed effects.

We conclude from absolute intensity, from absorption coefficient, and from maximum pulse magnitude that a substantial proportion of the large bursts observed at 1.27 cm Hg are produced by heavy nuclei.

It is true, of course, that many observations have been made of heavy nuclei producing stars in a photographic plate. However, the probability for production of an event of this kind in the wall of our chamber, of thickness 0.45 g/cm^2, by a heavy nucleus of mean free path[23] 25 g/cm^2, will amount to only two chances in 100. Consequently, practically all the *bursts produced by heavy nuclei are due to the direct ionization* which they produce in the argon of the ion-chamber.

D. Ionization in Bursts Compared with Total Ionization

The ionization in bursts is an important quantity in problems dealing with the energy balance in the over-all cosmic-ray picture.

Assume that the number of bursts per unit time larger than a given size E is given by $F(E)$. The total amount of ionization in units of E per unit time will then be given by

$$I=-\int_0^\infty EdF(E). \tag{3}$$

If we extended the integration literally to zero on the lower end, we would naturally include in Eq. (3) the ionization due to electrons as well as to nuclear particles. An electron at minimum ionization, however, produces a pulse equivalent only to (1/55) Po-α, and, in any case, a pulse no greater than about (1/25) Po-α. Also, a pile-up of small pulses from many independent electrons passing through the chamber has a negligible probability of accidentally producing a pulse as great as 0.5 Po-α, while no pulses smaller than 0.5 Po-α were counted in the present experiments. Finally, showers of electrons have already been excluded as a cause of any significant number of the observed bursts. Consequently, we shall obtain from Eq. (1) an amount of ionization due almost exclusively to nuclear particles if we extend the integration only down as far as 0.5 Po-α.

The procedure just described will not give the *total* ionization due to nuclear particles, of course, as many of these entities will produce pulses smaller than 0.5 Po-α. The ionization from evaporation fragments can, however, be estimated with sufficient accuracy for our purpose. We have only to compute the distribution of pulses of size less than 0.5 Po-α due to evaporation protons. Using the computed curve to extrapolate the observed curves, we find, for example, that pulses between 0.1 Po-α and 0.5 Po-α contribute less than a third of the ionization due to all nuclear bursts greater than 0.1 Po-α. Thus, the uncertainty introduced by this extrapolation will constitute only a small fraction of the total ionization. We conclude that the *integral* (3), extended down to 0.1 Po-α, *gives very nearly the whole contribution of nuclear evaporation fragments to the cosmic-ray ionization.*

The actual integrations were carried out numerically at 1.27 and 8.9 cm Hg. Figure 6 shows the observed ionization rates at these two levels joined by a smooth curve based on the observed rate of increase of bursts with altitude. The total ionization curve is taken from the work of Millikan, Neher, and Pickering[24] at 50°N magnetic latitude. Their curve refers to air in a metallic

[23] H. L. Bradt and B. Peters, Phys. Rev. **75**, 1179 (1949) find a value 23.5 g/cm^2 for nuclei $10 \leqslant z \leqslant 18$.

[24] Millikan, Neher, and Pickering, Phys. Rev. **61**, 397 (1942).

chamber of volume comparable to ours, so that the two results are comparable.[25]

It is seen that an appreciable fraction of the total ionization is due to heavy particles. About 18 percent of the total at 3 cm Hg (40 g/cm^2), the point of maximum, can be ascribed to nuclear fragments. It is to be emphasized that the value given for the ionization due to bursts is not for heavy particles produced in air, but essentially for heavy particles produced in an air-copper mixture. For this reason it would be interesting to repeat the experiment with an ionization chamber having a light-element wall.

V. CONCLUSIONS

(1) The majority of bursts occurring in a thin-walled ionization chamber near the top of the atmosphere is produced by heavy particles, and the contribution of electron showers is negligible. (2) The abnormally large bursts observed at the highest altitudes receive a reasonable explanation in terms of the heavy-nucleus component of the primary radiation. This explanation accounts, in order of magnitude, for the size of these events, their absolute number, and their very strong variation in number with altitude. (3) The heavy nuclei which are responsible for the anomalous distribution of pulse sizes near the top of the atmosphere produce roughly 12 percent of the observed bursts. (4) It is shown that pulses due to heavy-nucleus-induced nuclear explosions in the chamber are negligible in number compared to pulses due to direct ionization by the passage of these nuclei through the chamber. (5) The total ionization due to nuclear fragments is determined as a function of altitude and extrapolates to 3200 ev per cm^3 of argon (0°C, 76 cm Hg) per sec at zero pressure. When the air mass overhead is 40 g/cm^2, the ionization due to nuclear fragments is 1800 ev per cm^3 of argon per sec, about 18 percent of the total cosmic-ray ionization.

[25] The results of Millikan, Neher, and Pickering are obtained directly in ion-pairs/cm^3-sec-atmos in air. In order to compare their values with the results of this work which yields values in Mev of ionization the factor 32 electron volts per ion pair was used.

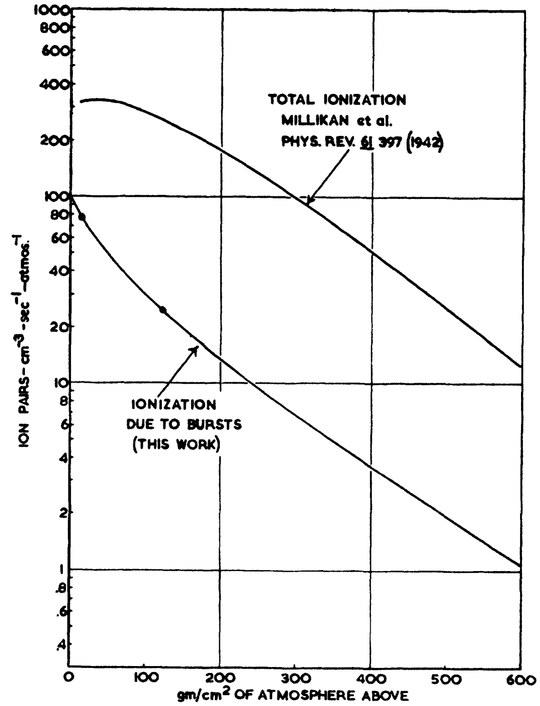

FIG. 6. Ionization of bursts of size greater than that produced by 0.1 polonium alpha compared with the total ionization (Millikan, Neher, and Pickering) produced by the cosmic radiation as a function of depth below the top of the atmosphere. Points for the burst-produced ionization were obtained at 1.27 and 8.9 cm Hg and a curve drawn through them based on the altitude dependence of bursts as measured in the present experiments.

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