Measurement of Multiply Charged Cosmic Rays by a New Technique*

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The Čerenkov effect has been applied to the problem of determining the charge of cosmic rays. Cloud chamber photographs have been obtained of the events that caused large signals from a thin Čerenkov counter during a balloon flight which carried the apparatus above most of the atmosphere. They show that the Čerenkov counter was notably effective at discriminating against the background effects that plague counter measurements on the charge spectrum of cosmic rays, for a relatively large proportion of the signals were caused by single heavily ionizing particles. The theory of the Čerenkov effect associates a lower velocity limit with the signal amplitude requirement that those particles met. Their ionization was determined well enough to classify particles of such velocity as having $Z=2$ or $Z>2$ with considerable certainty. The vertical flux of doubly charged particles with kinetic energy $>(610\pm100)$ Mev/nucleon beneath 17 g/cm² of atmosphere and 13 g/cm² of local matter is found to be (79 ± 11)/m² sec steradian. That result and currently accepted assumptions concerning absorption imply the value (135 ± 20)/m² sec steradian for the extrapolated vertical flux of primary alpha particles with energy above (670 ± 100) Mev/nucleon. Some of the alpha particles were seen to interact in copper plates within the cloud chamber. The observations indicate that the collision mean free path is (100 ± 25) g/cm². The problem of counter measurements on components heavier than helium is scrutinized.

I. INTRODUCTION

WHEN it was discovered that the primary cosmic-ray particles are nuclei not only of hydrogen but of many heavier elements it became plain that the cosmic radiation is a much richer source of information than there was reason to hope previously.

The fields that we suppose accelerate cosmic-ray particles act on the first power of their charge, while energy loss by ionization varies as the charge squared. Heavy nuclei that attain the energies observed can be degraded rapidly in mass if they suffer nuclear collisions, and the collision cross section varies somewhat more slowly than the charge. Therefore, the facts that heavy nuclei get accelerated in spite of competition from ionization loss and that they are delivered to the earth in spite of competition from nuclear collisions are very pertinent information concerning the processes that account for the phenomena. And the fact that they reach the earth at all means that the relation between the elemental composition of the cosmic radiation and that of the matter where its particles begin to acquire energy is not trivial, even though intervening processes may be supposed to affect it. Such matters have been discussed in some detail by Morrison, Olbert, and Rossi.[1]

The heavy nuclei were discovered simultaneously by means of two of the earliest techniques for detection of penetrating charged particles, the Wilson cloud chamber and the photographic emulsion.[2] Since then nearly all quantitative information that has been obtained about the relative abundances of the various nuclei heavier than helium has come from use of emulsions. Cloud chambers and counters of various types have been used mostly for measuring the abundance of helium and the total flux.

The experimental problem is to determine the charge of individual fast particles. A number of effects related to energy loss by ionization and proportional to Z^2 are available for that purpose. The dependence of the same effects on particle velocity presents a difficulty, for a sufficiently slow particle can lose energy by ionization at the same rate as a faster one with a greater charge, so commonly it is necessary to measure range or rate of change of ionization loss in order to establish with much accuracy the charge of individual particles. That difficulty is particularly troublesome in measuring the relative abundance of hydrogen and helium, for secondary protons that ionize the same as primary alpha-particles are as abundant as the latter in any attainable experimental environment, and such protons still have very appreciable range. The difficulty applies to the emulsion technique as well as to methods that exploit ionization counters.[3]

Charge-measuring counters suffer for their part from an inherent inability to distinguish the effect of an individual particle from that of a group of secondaries from a multiple event. The facts that multiple events are generated copiously by primary cosmic-ray particles and their immediate secondaries and that a nuclear interaction even at relatively low cosmic-ray energies is characterized by production of intense local ionization from evaporated secondaries mean that multiple events can be expected to compete effectively with primary heavy nuclei at producing large signals from ionization counters. Use of absorbers to impose a range requirement that will eliminate slow particle background tends to increase background from local interactions.

The Čerenkov effect provides an alternative principle

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[1] Morrison, Olbert, and Rossi, Phys. Rev. **94**, 440 (1954).
[2] Frier, Lofgren, Ney, Oppenheimer, Bradt, and Peters, Phys. Rev. **74**, 213 (1948).
[3] The term "ionization counter" is used here to designate any device that gives an electrical pulse proportional to ionization produced by an event within a certain volume; e.g., gas proportional counters, pulse ionization chambers, and scintillation counters.

for charge measurement, for the amount of Čerenkov radiation that is emitted by a fast particle in traversing a transparent medium varies with its charge as the square. The way in which the energy radiated varies with particle velocity indicates that the various events that go to make up background in an ionization counter will produce, in a Čerenkov counter, either no response whatever or a far smaller response, in terms of that produced by a single fast particle with unit charge.

II. ČERENKOV COUNTER MEASUREMENT OF CHARGE

According to classical electromagnetic theory the Čerenkov light is emitted in a forward cone of angle ϑ, where $\cos\vartheta = 1/\beta n$, about the direction of motion of a sufficiently fast ($v > v_c \equiv c/n$) charged particle traversing a medium with refractive index n. The energy emitted (integrated over frequency, neglecting dispersion) is given by

$$E(Z,\gamma) = E_0 Z^2 \left[1 - \frac{1}{(n^2-1)(\gamma^2-1)}\right] = E_0 Z^2 f_c(\gamma), \quad (1)$$

where $E_0 \equiv E(1,\infty)$, Z is the charge in units of that of the electron, and $\gamma \equiv (1-\beta^2)^{-\frac{1}{2}}$, $\beta \equiv v/c$. The velocity dependence expressed by $f_c(\gamma)$ (Fig. 6) is distinctly unlike that of ionization loss.

Consider a detector consisting of a Lucite radiator viewed by a photomultiplier. Since the critical velocity in Lucite ($n=1.5$) corresponds to an ionization 1.6 times minimum the slow protons that are difficult to distinguish from fast alpha particles by use of emulsion or ionization counters will be completely ignored by the Čerenkov counter, and its response to an individual proton of any speed will be limited to one-fourth its response to a fast alpha particle. It is true that a Čerenkov counter can respond equally to a fast alpha particle and a slower heavier nucleus, but the heavier nuclei that can compete are rare and will not disturb a measurement of the flux of fast alpha particles.

As for background from multiple events, prediction again favors a Čerenkov counter over one that measures ionization. Studies with emulsion[4] show that most charged secondaries from multiple events at high altitude are low-energy evaporations (black tracks) or "knock-on" protons (gray tracks) with less than the critical velocity in Lucite, and that the great majority of nuclear interactions have less than two secondaries that are faster (thin tracks). Thus, only the less frequent interactions and only the least abundant of their secondaries can give Čerenkov light, whereas all the interactions give ionizing secondaries, and for ionization counters the most abundant secondaries are heavily weighted because ionization increases with diminishing velocity.

Bibliographies on experimental and theoretical investigations of the Čerenkov effect have been published elsewhere,[5,6] so only applications of the effect to detection and measurement of cosmic radiation will be referred to in this paper. Quantitative detection of cosmic rays by their Čerenkov radiation was first accomplished by Jelley.[7] In later experiments he and Galbraith[8] have succeeded in detecting the Čerenkov light produced in air by soft showers at sea level. Duerden and Hyams[9] have detected sea level cosmic-ray protons efficiently by using a Čerenkov counter in anticoincidence to set a velocity limit and an absorber to require penetration.

The possibility of using a Čerenkov detector for investigating the charge spectrum of primary cosmic rays was pointed out by Winckler and Anderson[10] in a letter describing the Čerenkov counters they have developed and used in a study of directional and albedo effects at high altitude.[11] In their design the directional properties of the Čerenkov radiation permit collection of light from 20 cm of path length in Lucite for traversals with one sense of direction and result in practically complete absorption of the light for traversals in the opposite sense. The pulse-height distribution they obtained at 25 g/cm^2 atmospheric depth (Fig. 10 of reference 11) has a tail toward large pulse heights which they attribute to nuclear interactions with relativistic secondaries, many of which must have originated in the relatively thick (29 g/cm^2) Lucite radiator of their detector. The amplitude of their distribution near four and nine times the sea level meson pulse height seems to exceed significantly the background from collisions in those regions. They attribute the excess to individual fast doubly and triply charged nuclei.

It was decided to investigate the charge resolving capability of Čerenkov counters with "thin" radiators; that is, radiators of thickness a small fraction of an interaction mean free path. Promising results were obtained using a thickness of one inch. The radiator, a polished Lucite cylinder $1\frac{1}{2}$ in. in diameter, was coupled with Canada balsam to an EMI 6260 phototube ($1\frac{3}{4}$ in. diameter photosurface). Bright aluminum foil was sealed to the remaining Lucite surfaces with the same material. Figure 1(A) shows the distribution of pulse heights (multiplier gated by a Geiger counter telescope) from sea-level cosmic rays obtained with counter axis vertical and radiator uppermost. The smooth curve is the Poisson distribution for $\bar{n}=18$.

The differential expression corresponding to (1), integrated over the absolute spectral sensitivity characteristic of an S-9 photosurface, indicates that a very fast singly charged particle might give 40 photoelectrons per inch of path length in Lucite for a selected photo-

[4] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950).

[5] R. L. Mather, Phys. Rev. **84**, 181 (1951).
[6] J. V. Jelley, Atomics **4**, 81 (1953).
[7] J. V. Jelley, Proc. Phys. Soc. (London) **A64**, 82 (1951).
[8] J. V. Jelley and W. Galbraith, Phil. Mag. **44**, 619 (1953).
[9] T. Duerden and B. D. Hyams, Phil. Mag. **43**, 717 (1952).
[10] J. Winckler and K. Anderson, Rev. Sci. Instr. **23**, 765 (1952).
[11] J. R. Winckler and K. Anderson, Phys. Rev. **93**, 596 (1954).

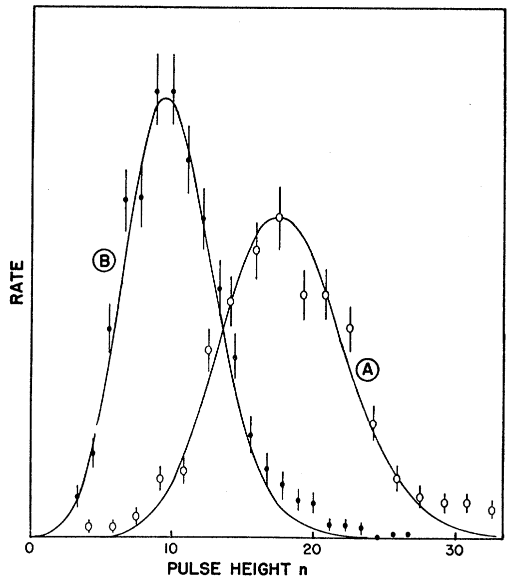


FIG. 1. Čerenkov counter pulse height distributions. The curves are Poisson distributions $P(18,n)$ (A) and $P(10,n)$ (B). Open circles are measured for normal counter sense; full circles for counter inverted. Total rate for each has been normalized to the area under the curve. The gain was the same during the two runs. Errors are statistical.

tube, with perfect light collection.[12] We think the assumption that the mean number of photoelectrons was about 18 in our case, i.e., that nearly all the spread in Fig. 1(A) comes from fluctuations in that number, is consistent with the prediction in view of its idealized hypotheses. More recent work at this laboratory shows that a width at half-maximum as small as 35 percent can be obtained for the sea-level flux with a similar radiator of the same thickness and a better phototube.

III. THE EXPERIMENT

It seemed then that by combining the counter with a cloud chamber in a high altitude experiment two results could be accomplished: the flux of fast alpha particles could be measured, and at the same time an insight into the general problem could be gained which might point out how to make more extensive and precise abundance measurements with simpler equipment.

The chamber was of the type that has been developed at the University of Minnesota for use in high altitude research.[13]

The particular model that was used had a sensitive region about 4 by 8 in. in plan and 8 in. in height. It was filled to a pressure of about 85 cm with argon and water-alcohol vapor and contained five transverse copper plates $\frac{1}{4}$ in. thick. The chamber walls were of $\frac{5}{16}$ in. Lucite. The control circuit imposed a dead time of about one minute following an expansion. Stereoscopic cameras photographed the events and an instrument panel showing time and temperature.

The Čerenkov counter was inverted so that the radiator could be directly above the top of the chamber (Fig. 2). The resultant change in sea-level pulse height distribution (to B, Fig. 1) is explained by imperfect reflection from the foil coating of the radiator. From symmetry it was believed that the 'inherent' resolution (the limit $Z\rightarrow\infty$) was not much changed.

The placing of the phototube coaxial with the Geiger counter telescope had obvious disadvantages: proton induced interactions in the phototube would add to the background, and the alpha particle flux would be attenuated. However, we have not been able to design a Čerenkov counter with good inherent resolution for particles that pass at right angles to the phototube axis. We chose for this experiment to accept the disadvantages of the coaxial arrangement for the sake of the better resolution it gives.

The beam defined by the telescope traversed the cloud chamber entirely within the chamber's illuminated region.

Figure 3 is a block diagram of the electronics. A Geiger counter tray of effective area 2 by 4 in. and a single counter of diameter 1 in. and nominal length 1 in. made up the telescope.

Usually the "geometric factor" of a counter telescope (the constant of proportionality between counting rate and flux of particles) is calculated from measured dimensions. In our case, however, the effective lengths of the counters were not known very precisely, so the

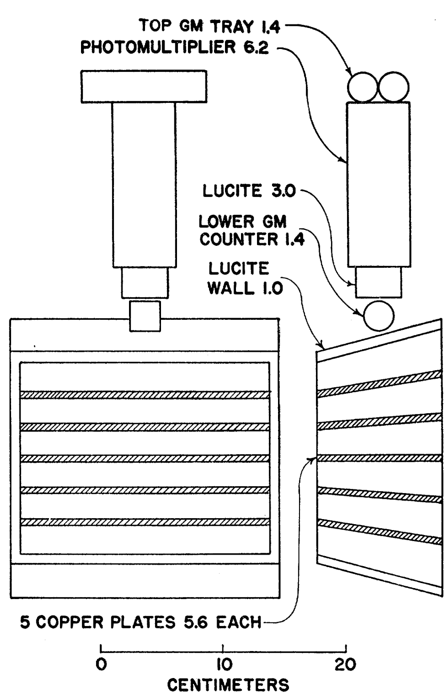


FIG. 2. Arrangement of apparatus. Numbers shown are thicknesses in g/cm².

[12] J. Marshall, Phys. Rev. **86**, 685 (1952).

[13] Lofgren, Ney, and Oppenheimer, Rev. Sci. Instr. **20**, 48 (1949). Extensive changes in design have been made since that article appeared.

geometric factor K was found by a substitution method. A second telescope of roughly similar size and shape was constructed using crossed counters to define its apertures so that its geometric factor could be calculated accurately. Counting rates of both telescopes were measured in the laboratory. The ratio of those rates times the calculated geometric factor gave, for the telescope to be used with the Čerenkov counter, $K=(0.78\pm0.04)$ cm^2 steradian. A small correction (3 percent) for difference in angular distribution between the flux used in calibration and that at high altitude was taken into account.

The position of the discriminator edge was adjustable and could be measured by counting trigger pulses delivered to the cloud chamber and referring to the absolute pulse height distribution at sea level. For the high altitude experiment it was set at about twice the mean pulse height for a fast singly charged particle.

It was necessary to stage the flight at 55° geomagnetic latitude, where the momentum cutoff for nuclei other than protons corresponds to a velocity less than v_c in Lucite. That fact influenced the results in two ways which will be mentioned now and discussed later: (1) the energy threshold for detection of particles was determined by a property of the detector and the discriminator bias rather than by geomagnetic effects, and (2) particles could trigger the cloud chamber and not be at their minimum ionization.

The equipment, housed in a pressurized insulated gondola with walls of thirty-mil aluminum, was flown October 12, 1953. The complete apparatus weighed 120 lb. The pressure-altitude was recorded by a separate unit in which a Wallace and Tiernan aneroid gauge, a clock and a thermometer were photographed at five minute intervals. Gauge calibrations before and after the flight showed no change. The flight reached 16.4 millibars and remained level within limits ±0.3 millibar for 345 minutes until the load was released. The gauge temperature did not leave the region in which tests at this laboratory have shown that the gauge is fully temperature compensated.

The temperature in the main gondola fell during the ascent, reaching its lowest value of 71°F slightly after the flight reached ceiling. Thereafter it rose slowly to an equilibrium value of 78°F. The cooling during ascent caused some condensation of vapor on the glass chamber-front, but that condition was never severe enough to cause uncertainty in interpreting events, and within less than an hour as the temperature rose the front had cleared.

The mean dead-time of the cloud chamber was determined from the set of trigger times recorded during the flight by photographing a sweep-second clock beside the cloud chamber. The total sensitive time during the 345 minutes at ceiling was $(1.013\pm0.017)\times10^4$ sec. One hundred fifty-seven events were photographed in that time, and tracks of good quality were produced at every expansion. The photographs show that the chamber condition stayed constant and that no change took place affecting its control cycle.

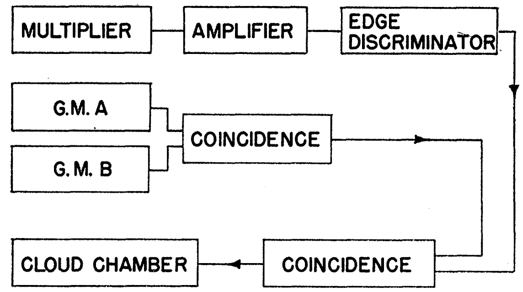


FIG. 3. Trigger circuit block diagram.

IV. ANALYSIS OF THE PHOTOGRAPHS

Classification of Events

Two kinds of event would be capable of triggering the cloud chamber: (I) an individual fast multiply charged particle could traverse the telescope and enter the chamber, or (II) the trigger requirements (Geiger counter coincidence plus a large enough Čerenkov counter signal) could be met by cooperation between secondaries from a multiplicative interaction or a primary and its fast secondaries. Which type of event triggered the chamber had to be determined in each case by examining the photographs. The events of type I measure the flux of multiply charged particles while those of type II provide information that may help in interpreting results of other experiments or in developing improved techniques for cosmic-ray measurement. It will be shown that although it was not always possible to establish the nature of the multiplicative events still there was hardly ever any doubt whether the chamber had been triggered by such an event or by one of the type described first. In most cases the decision could be made without ever estimating the ionization along a track.

The photographs were searched for counter-age tracks that projected through the telescope apertures in both stereoscopic views, penetrated the plates without scattering or else interacted, and—if they did not interact—remained visible in all spaces between plates except possibly the lowest one. The cases in which such a track was found include all events of type I; that is, in which a fast multiply charged particle traversed the telescope and entered the cloud chamber. (A track as dense as four times minimum is conspicuous and could not be overlooked.)

The events that satisfied the preceding necessary condition (criterion A) were subdivided in two ways: according to the density of the track (criterion B) and according to the number of other tracks in the photograph that appeared to be related to it (criterion C). Table I shows the result.

If more than one track satisfied criterion A, criterion B was applied to the densest of such tracks. Track

TABLE I. Breakdown of cases in which the photographs showed an "allowed" track (one that satisfied criterion A).

Density of allowed track	Number of additional related tracks 0	1	$\geqslant 2$
1	6	1	19
2	1	0	2
$\geqslant 4$	75	0	1

density in units of that corresponding to a fast singly charged particle was estimated visually by comparing the given track to others of the same age selected for some significant characteristic (for example, the electron tracks in a typical soft shower). We believe that relative ionization was estimated correctly within limits ± 50 percent.

Tracks of obvious knock-on electrons were not counted in applying criterion C, which was aimed at separating nuclear interactions from events in which a particle triggered the chamber all by itself. Tracks were considered related if they were of the same age and projection of the stereoscopic photographs showed that they came from a common point. The time resolution was good enough so that the background of counter-age tracks was small, about five reasonably long tracks per photograph.

In the following discussion of Table I a group of events will be designated by its coordinates in the table; for example, there were 75 "$(\geqslant 4, 0)$" events.

The $(j, \geqslant 2)$ events (all those in the third column) were surely multiplicative, nearly all of them nuclear interactions. However, they include only part of the multiple events that were photographed: only those that had an "allowed" track. In very few cases did an allowed track that was known to be secondary have greater than minimum density. The one event entered at $(\geqslant 4, \geqslant 2)$ showed two nearly parallel tracks of density four times minimum and a number of other related tracks. One of the heavily ionizing particles made a sizeable interaction in the fourth copper plate. The primary event was probably breakup of a heavy nucleus with production of two fast secondary alpha particles.

The small number of $(j, 1)$ events is understandable on two counts. In the first place only the more energetic nuclear interactions could satisfy the trigger requirement, so most of those that were detected show tracks of three or more secondaries. Second, there is less chance that a smaller interaction would happen to have a secondary whose track would be allowed.

The preceding observations permit a strong inference that none of the $(\geqslant 4, 0)$ events were local nuclear interactions which had a slow proton secondary whose track happened to satisfy criterion A and have 4 times minimum density but which had no other secondaries that made visible tracks. The argument follows: If we keep in mind that only rather large nuclear interactions could trigger the equipment, it is apparent that the condition $(j,0)$, "there shall be but one visible secondary, and it shall be allowed" is more restrictive than the condition $(j,1)$, "there shall be two visible secondaries, one of which shall be allowed." Consequently there should be fewer nuclear interactions of type $(j,0)$ than of type $(j,1)$, of which we find only one example. The clinching argument is that nuclear interactions of type $(\geqslant 4, 0)$ are a subset, and must be a rather small subset, of interactions with the properties $(j,0)$.

The (1,0) entry needs special comment. A singly charged particle can give a signal twice the average size for a fast mu meson by making a relativistic knock-on electron (see the 'tail' of the pulse height distribution, Fig. 1) though only with a small probability and only if the particle itself is at minimum ionization. It seems likely that the (1,0) events were not nuclear interactions but were multiplicative in the sense that a fast secondary electron provided part of the Čerenkov signal. It would be expected that in many cases the electron be absorbed or scattered so as not to produce a related track.

The only case in which doubt could not be resolved is entered at (2,0). The particle interacted in the topmost copper plate. Either it was a proton at minimum ionization whose track was abnormally bright in the one section where it was seen, or it was an alpha particle whose track was unusually faint.

This completes the argument for classifying the $(\geqslant 4, 0)$ events as type I and all others as type II. In what follows the latter will usually be called background events.

Tracks of Heavy Nuclei

Although the great majority of individual particles that triggered the chamber were helium nuclei, the term multiply charged particle has been used throughout the preceding discussion because in a number of type I events (13 of them in fact) the track of the particle that triggered the chamber was conspicuously denser than that of an alpha particle fast enough to generate a trigger. Moreover, several of the background events show a very dense counter-age track that penetrates a number of the quarter-inch copper plates. In such cases the particle that made the track must have been a nucleus heavier than an alpha particle.

Figure 5 shows examples of very heavy tracks, tracks of alpha particles and tracks of fast singly charged particles. In order to express quantitatively the difference in density between tracks of those different types the photographs were measured with an integrating photometer constructed for that purpose.

The tracks were projected full size on a slit 2.5 mm wide (the width of alpha-particle tracks being about 1 mm) and as long as the separation between cloud chamber plates. The light that fell on the slit was focused on the cathode of a vacuum phototube. The phototube current was measured for each section of a track, corrected for local background in the photograph, and averaged. Figure 4 (ordinate) shows results for each track denser than that of an alpha particle, the average for the alpha particles, and the average for a selection of penetrating-shower secondaries. (The $Z=1$ tracks were necessarily favorable, not representative, examples. The photometer could not distinguish the faintest of such tracks from the background.)

The phototube measurements reflect the fact that a cloud chamber "saturates" for heavily ionizing particles. Fast alpha-particle tracks are not opaque and show occasional gaps. However, even the lightest of the very dense tracks has an opaque core and no gaps. Apparently, as the ionization increases the diameter of the completely opaque core increases, but it does so slowly.

Delta rays were counted for all tracks of multiply charged particles. The delta-ray range requirement, which cannot be considered precise, was about 1.5 mm (measured perpendicular to the track in projection). For the alpha particles, the mean count was $(0.038 \pm 0.008)/\text{cm}$; for mesons (photographed in the laboratory, but with no other difference in conditions) it was $(0.012\pm 0.002)/\text{cm}$. Results for each heavier nucleus are shown in Fig. 4, where the quantity $(N/0.0105)^{\frac{1}{2}}$ is plotted as abscissa (N being the number of delta rays per cm).

It will be shown that the pulse height requirement implies that nearly all the alpha particles traversed the chamber with ionization within 20 percent of their minimum (Fig. 6). The same is not true for the heavier nuclei; they could enter the chamber with ionization up to 1.5 times their minimum and could be slowed down very appreciably (or even stopped, for $Z>6$) by the plates. Hence the "apparent charge" (Fig. 4, abscissa) is an upper limit to the real charge. Assuming that the heavy nuclei were primary and taking into account their energy spectrum, one would expect about half of the heavy nuclei to have traversed the chamber at minimum ionization and the remainder to have ionized more heavily.

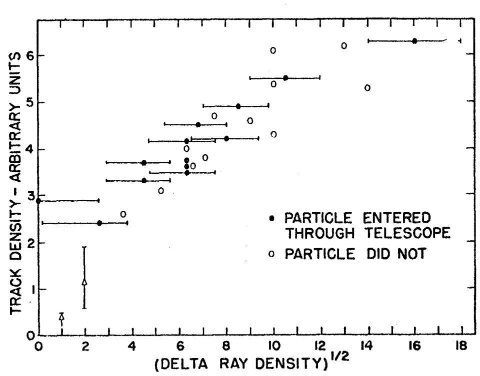


FIG. 4. Ionization measurements. Track densities were measured with a photometer. Delta-ray counts have been converted to a Z scale after being normalized to the mean density for alpha particles. Points represent individual tracks, and errors are statistical standard deviations, except for the triangles. The coordinates of the upper triangle are averages for alpha-particle tracks. The ordinate of the lower triangle is an average for selected tracks of singly charged particles. For those two cases limits of variation in density are shown.

TABLE II. Classification of all events that triggered the cloud chamber.

Description	Number
Type I. Chamber triggered by passage of an individual fast multiply charged particle through the telescope	
(A) Track density corresponds to $Z=2$	62
(B) Track density corresponds to $Z>2$	13
Type II. More than one fast particle contributed to triggering the chamber	
(A) Nature of multiplicative event is evident	
Hard shower above Čerenkov radiator	22
Hard shower in radiator	8
Hard shower below radiator	4
Soft shower	8
(B) Photographs show a single counter-age track, that of a particle at minimum ionization that traversed the telescope and penetrates or interacts	7
(C) The track of a penetrating particle with $Z=2$ (one instance) or $Z>2$ enters the chamber from above but does not project through both Geiger counter trays	11
(D) Photographs show little or nothing that would indicate what kind of event triggered the chamber	22
Total	157

Background

The many side-effects that commonly are lumped under the term "background" cause difficulty in most cosmic-ray experiments, but they depend to such an extent on details of method which may vary widely from one experiment to the next that an analysis of background in any particular case may have quite limited usefulness. Nevertheless in this instance there is perhaps more reason than usual for reporting what was learned about the unwanted events.

Only recently has the Čerenkov effect been put to use, and so far as the writer knows it was first deliberately employed to measure charge in this experiment. The reason for that step and for using a radiator many times thinner than has been used in a Čerenkov counter for cosmic-ray applications heretofore was to achieve the drastic reduction in background that it seemed might follow. Moreover, because a cloud chamber was used and because the photographs were of uniformly good quality it was possible to establish definitely the nature of a greater proportion of the unwanted events than in previous comparable experiments.

Contributions to the background would be expected from both of the mechanisms by which fast secondary charged particles can be generated, nuclear interaction and electromagnetic interaction. The latter could be either radiative (pair creation by a π^0 decay photon or by bremsstrahlung) or nonradiative (production of knock-on electrons). A phenomenological classification of the background events, which we will try to fit to the preceding framework, is given in Table II.

An event was called a hard shower if there were three or more counter-age tracks that extrapolate to a common point and there was evidence that some track was not that of an electron. If the event was clearly multiple but all the tracks seemed to be those of electrons it was called a soft shower. It must be substantially correct to equate "hard shower" to nuclear interaction and "soft shower" to radiative electromagnetic interaction.

The hard showers had definite origins whose location is interesting from an experimental design standpoint. The importance of reducing the radiator thickness and the amount of material above the radiator to the absolute minimum is evident. At the same time it is encouraging to learn that the counter was almost completely indifferent to interactions in matter beneath it. At most two of the multiple events that triggered the chamber occurred in the 6 kilograms of copper in the illuminated region of the cloud chamber (where they could be identified with nearly perfect efficiency) while at least 30 were contributed by the few hundred grams of material above or included in the radiator. Since the counter actually favored upward particles, that observation has to be explained by the counter's velocity bias and the tendency for the fast secondaries from nuclear interactions to preserve the primary direction.

Obviously any change in design that would reduce the hard shower background would do the same for soft showers.

It may be of interest that no event showed evidence of more than one charged particle incident from outside the gondola; that is, multiplication in the atmosphere had no effect, except of course to increase the total flux of background-producing particles.

The background events in group (II-B) show only one counter-age track, that of a fast singly charged particle which apparently went through both of the Geiger counter trays and the Čerenkov radiator before entering the chamber. Though the evidence is not conclusive we will assume that the mechanism was nonradiative electromagnetic interaction, that an unseen knock-on electron contributed enough additional Čerenkov light to satisfy the pulse height requirement.

The same mechanism, knock-on production, can operate in a different manner to cause background when the primary particle is multiply charged, for then the primary needs no help in satisfying the pulse-height requirement. The primary itself can miss either or both of the Geiger counter trays, so long as it goes through the radiator, and still satisfy the coincidence requirement by means of knock-on electrons. We use this model to account for the (II-C) events.

As for group (II-D), presumably the events were nuclear interactions whose secondaries all missed the illuminated region of the chamber or were similarly extreme manifestations of the other types of multiplicative interaction.

The number of events in each background group relative to the number of wanted events is of some interest, but the relative size of background pulses is probably more important from a design standpoint. Judging from the number of fast secondaries that seem to have passed through the Čerenkov radiator, the largest nuclear interaction might have produced as large a pulse as a fast boron nucleus, but it was exceptional. The next largest could have produced no larger a pulse than a beryllium nucleus, and most of the background pulses must have been much smaller than that.

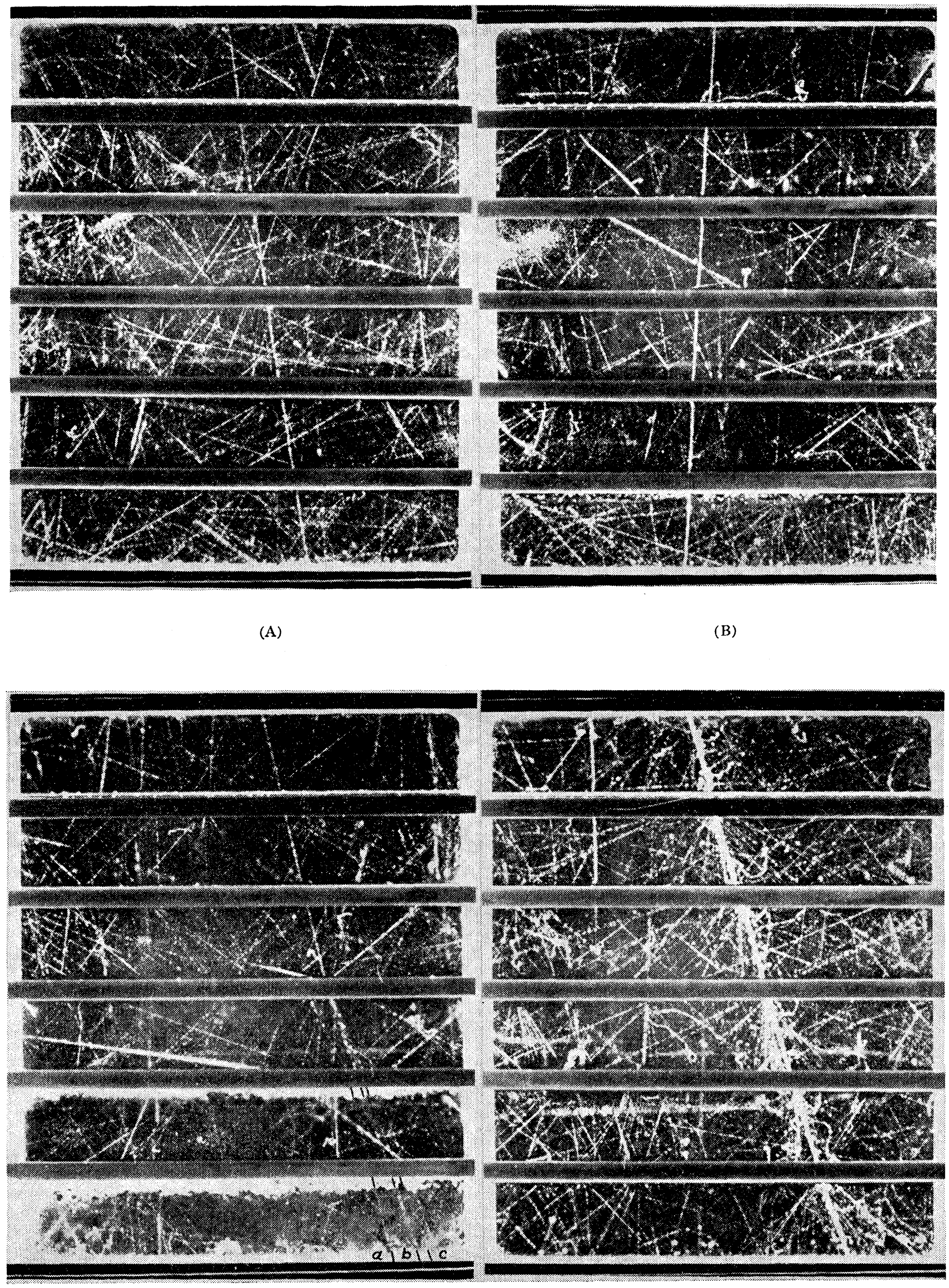
However, one group is exceptional: the events in which a heavy nucleus went through the radiator, did not itself go through the telescope, but satisfied the trigger requirement with the aid of one or more long range delta rays. Background pulses produced in that way could be as large as any "legitimate" pulse. The numbers in Table II, which show that "background" heavies are practically as frequent as the legitimate events they compete with, are not surprising if one bears in mind that knock-on production increases as the square of the primary particle's charge. Figure 5 (D), which illustrates the abundant fast knock-on electrons associated with passage of a fast heavy nucleus through matter, may add emphasis to this discussion.

We think emphasis is justified, for those events point out potentially serious sources of uncertainty in measurements of the flux of heavy nuclei by means of counters alone. In the first place, one might rely solely on Geiger counters to define the trajectories of particles considered and thus underestimate the effective size of the telescope apertures. Or one might exclude events in which signals from guard counters resulted from knock-on electrons, mistaking the effect of the latter as indicating that the event in question was a nuclear interaction or an air shower rather than passage of a heavy nucleus. We will return to this matter again and suggest a method for solving the problem.

V. ENERGY THRESHOLDS

To meet the Čerenkov counter pulse-height requirement an individual particle not only had to be multiply charged but had to traverse the radiator with sufficient velocity. At the latitude of the experiment some multiply charged primaries would be too slow to meet that requirement; hence the measurements refer to primaries with energy above a threshold set by the counter and are to be compared with results obtained by conventional methods at certain latitudes lower than 55°.

Because the counter had limited resolution the effective threshold velocity for a given primary charge was a statistical average. We can assume as an approximation that the only significant fluctuation is in the number of photoelectrons that reach the first multiplier dynode. (Pulse heights will be expressed in units of the pulse from a single such electron.) Events for which the mean number of photoelectrons is $\bar{n}$ will give a normalized pulse height distribution $P(\bar{n},n)=\bar{n}^n$



(A) (B)

(C) (D)

FIG. 5. Cloud chamber photographs. (A) An alpha-particle track of average density. (B) The least dense track classified $Z>2$ (probably that of a fast Li nucleus). (C) An alpha particle which interacted in the central plate. Tracks a, b, c of penetrating secondaries show clearly in the original although it is plain that they are much less dense than that of the primary. Condensation on the chamber front is illustrated. (D) The track of a nucleus with $Z\sim 10$.

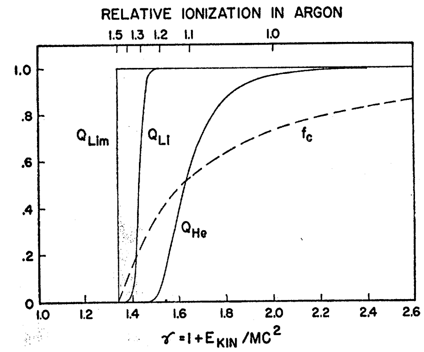


FIG. 6. Čerenkov radiation and detection characteristics. The solid curves give the probability of detection as a function of energy for helium and lithium, and the limiting curve for $Z\rightarrow\infty$. The dashed curve shows the energy dependence of Čerenkov radiation.

$\times\exp(-\bar{n})/n!$ (Poisson). If the pulses feed an edge discriminator set at n_1, the probability that such an event will trigger it is

$$R_{n_1}(\bar{n})=\sum_{n=n_1}^{\infty} P(\bar{n},n), \tag{2}$$

which is zero for $\bar{n}\ll n_1$, unity for $\bar{n}\gg n_1$, and assumes the value $\frac{1}{2}$ for $\bar{n}\sim n_1$. If the event is passage of a particle with charge Z and velocity parameter $\gamma=(1-v^2/c^2)^{-\frac{1}{2}}$ through a Čerenkov counter, $\bar{n}=Z^2\bar{n}_0 f_c(\gamma)$ where $\bar{n}_0$ is the mean pulse height for $Z=1$, $\gamma\rightarrow\infty$ (fast mu mesons) and $f_c(\gamma)$ expresses the velocity dependence of Čerenkov radiation [Eq. (1)]. Finally,

$$Q_{n_1}(Z,\gamma)=R_{n_1}[Z^2\bar{n}_0 f_c(\gamma)] \tag{3}$$

is the probability of detection (detection characteristic) for Z, γ (Fig. 6).

The differential energy spectrum of detected particles is the product of the detection characteristic and the energy spectrum of the incident particles, $D(E)dE$. The effective threshold energy E_b is defined so that the integral of the incident particles above that energy equals the integral of the detected particles over all energies. Since the detection characteristic is practically constant and equal to 1 for high energies ($>E_1$), the equation that defines E_b can be written

$$\int_0^{E_1} Q(E)D(E)dE=\int_{E_b}^{E_1} D(E)dE, \tag{4}$$

which shows that the form of the incident spectrum for $E>E_1$ does not influence the calculation. By assuming a reasonable analytical expression for $D(E)$ in the interval for which $Q(2,\gamma)$ is appreciably different from 0 or 1 and integrating (5) numerically the mean threshold γ for alpha particles was found to be $1.65_{-0.05}^{+0.07}$. Since not much of the total flux belongs to that energy interval, the result is relatively insensitive to what was assumed about the spectrum.

The quoted error arises instead from uncertainty in the measured parameters that determine $Q(2,\gamma)$. By substituting $\bar{n}_0 k$ for n_1 in (4) it can be seen that the mean threshold γ depends for its accuracy on the measurement of k. The threshold γ is essentially that for which the detection probability is $\frac{1}{2}$, and it has been pointed out that the detection probability attains that value when n_1 equals the argument of the function R, approximately; that is, when $f_c(\gamma)=k/Z^2$. $\bar{n}_0$ itself, which was obtained by fitting a Poisson distribution to the observed pulse-height distribution, plays a less important role in determining the energy threshold.

The value of k for the flight, 2.1 ± 0.2, was set by the ratio of over-all gain used for the flight to that needed in order to obtain the trigger rate from sea level cosmic rays that would correspond to $k=1$ according to the absolute pulse height distribution of Fig. 1. A calibrated linear attenuator was used to change the gain, and the value of k was found to be unchanged when checked after the flight. Detection characteristics for $k=2.1$ and $Z=2$, 3, ∞ are shown in Fig. 6, together with the function $f_c(\gamma)$.

For heavy enough nuclei the measured parameters k, $\bar{n}_0$ are unimportant; the threshold is determined by the critical velocity in Lucite. In this experiment $Q(Z,\gamma)$ could be considered a step function for $Z>2$, and error in the threshold is negligible for such nuclei. Results are shown in Table III, both for particles at the depth of the counter and primaries above the atmosphere. Taking into account the last column of that table, the fact that all of the 13 heavy nuclei that entered through the telescope penetrated all plates of the chamber (or else were seen to interact) confirms the ability of the Čerenkov counter to reject particles with less than critical velocity, regardless of their ionization.

VI. FLUX OF PRIMARY ALPHA PARTICLES

The flux of alpha particles that entered the cloud chamber was $(79\pm11)/\text{m}^2$ sec steradian. Both statistical and instrumental sources were taken into account in estimating the error.

The relation between the flux that entered the chamber and the cosmic radiation above the atmosphere

TABLE III. Energy thresholds.[a]

Nucleus	Z	E_b	E_a	E_a'
He	2	606	668	300
Li	3	442	519	370
Be	4	362	502	440
B	5	347	519	500
C	6	338	545	570
N	7	334	574	630
O	8	330	605	700
F	9	328	634	750
Ne	10	326	682	810

[a] E_b is the kinetic energy per nucleon in Mev corresponding to $2.1\bar{n}_0$ units of Čerenkov radiation in Lucite. E_a is the corresponding energy at entrance to the atmosphere. The depth of the center of the radiator was 26 g/cm² (16.9 g/cm² air, remainder telescope). E_a' is the kinetic energy per nucleon in Mev corresponding to range 60 g/cm². That figure is the thickness of material between the top of the atmosphere and the lowest space in the chamber.

depends on the effect of nuclear collisions, both in local matter and in the overlying atmosphere. Results published to date[14,15] agree with the following formula for collision cross sections:

$$\sigma=\pi R^2,$$
$$R=[1.45(A_1^{\frac{1}{3}}+A_2^{\frac{1}{3}})-2.0]\times 10^{-13}\text{ cm.} \quad (5)$$

(A_1, A_2 are mass numbers of incident and target nuclei, respectively), at least for incident nuclei with energy above 1 Bev/nucleon. There is evidence[14] that the cross section decreases somewhat for lower energies.

The experimental evidence is especially scanty for alpha particles. In the experiment we describe, traversal of 1.62×10^4 g/cm² of copper in the cloud chamber resulted in 16 interactions. The corresponding mean free path and the results of other investigators are shown in Table IV together with values given by Eq. (5).

From observing seven interactions of heavier nuclei in traversal of 560 g/cm² we obtain the mean free path (80±30) g/cm², which agrees within its considerable statistical error with the prediction 65 g/cm² of Eq. (5).

Attenuation in local matter was taken into account using calculated collision cross sections. According to Eq. (6) the collision mean free path for alpha particles in air is about 50 g/cm². That value was reported by Davis *et al.*[16] for the absorption mean free path. Using it to take into account attenuation in the atmosphere, we find the value (135±20)/m² sec steradian for the flux of primary alpha particles with energy above (670±100) Mev/nucleon.[17]

For comparison with that result we have collected and show in Fig. 7 values of the primary alpha-particle flux obtained elsewhere by methods that discriminate strongly against at least one of the two types of background event discussed in the introduction, local multiplicative interactions and slow singly charged particles.

Perlow *et al.*[18] and Davis *et al.*[19] measured ionization with proportional counters (2 and 3 of them, respectively) and eliminated individual slow particles by requiring penetration. Bradt and Peters[20] used photographic emulsions, so multiplicative events could not compete, and measured ionization of long tracks. The results we quote are a revision of those they reported originally,[21] and for the purpose of comparison we have adjusted them slightly to correspond to the absorption mean free path used in extrapolating other results shown. McDonald[22] used a scintillation counter to set upper and lower limits on ionization and a cloud chamber with absorber to eliminate both slow protons and interactions.

For protons our 670-Mev energy threshold would correspond to geomagnetic latitude 57°. Winckler and co-workers[23] found the value (0.23±0.01)/cm² sec sterad for the total vertical flux under 1.9 cm Pb at 56°. Van Allen and Singer[24] found the value 0.29±0.03 above the atmosphere at 58°. The relation between those measurements and the primary proton flux is still somewhat uncertain, however.

TABLE IV. Alpha-particle collision mean free paths.

Material	Collision mean free path (g/cm²) Observed	Calculated [Eq. (6)]
Copper	100±25	91
Brass	84±17[a]	91
Glass	50±11[a]	60

[a] See reference 15.

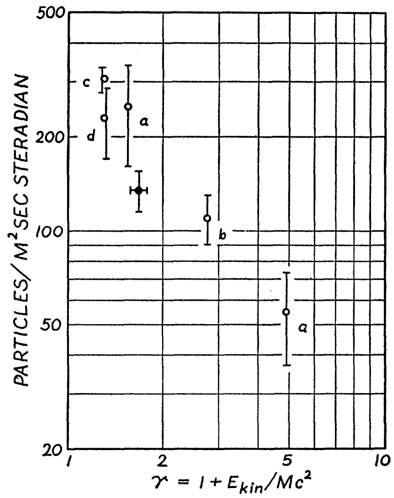


FIG. 7. Comparison of results. Filled circle is the result of this experiment. Open circles are previous measurements of the alpha-particle flux. Code: (a) Bradt and Peters (see reference 20), (b) Perlow *et al.* (see reference 18), (c) Davis *et al.* (see reference 19), (d) McDonald (see reference 22).

VII. PROBLEM OF FLUX MEASUREMENT BY MEANS OF COUNTERS IN THE REGION $Z>2$

The 13 heavy nuclei with allowed tracks observed in this experiment lead to the value (38±12)/m² sec sterad for the extrapolated flux of nuclei with $Z>2$ and energy above 500 Mev/nucleon. That may be compared to the result 18.6±2.0 reported by Kaplon *et al.*[15] for an insignificantly lower mean threshold, and the result 31±3 reported by Dainton *et al.*[25] for a threshold 330

[14] Freier, Anderson, Naugle, and Ney, Phys. Rev. **84**, 322 (1951).
[15] Kaplon, Peters, Reynolds, and Ritson, Phys. Rev. **85**, 295 (1952).
[16] Davis, Caulk, and Johnson, Phys. Rev. **91**, 431 (1953).
[17] The difference between this result and that we reported earlier, Phys. Rev. **93**, 899 (1954), comes partly from adopting a greater value for the absorption mean free path in the present case and partly from correcting errors in values given in that letter for the geometry factor and the energy that corresponds to v_c in Lucite.
[18] Perlow, Davis, Kissinger, and Shipman, Phys. Rev. **88**, 321 (1952).
[19] Davis, Caulk, and Johnson, Phys. Rev. **91**, 431 (1953). Flux value corrected in communication to E. P. Ney.
[20] H. L. Bradt and B. Peters, Phys. Rev. **77**, 54 (1950).
[21] G. Segrè, Nuovo cimento **9**, 116 (1952).
[22] F. B. McDonald (private communication to E. P. Ney).
[23] Winckler, Stroud, and Shanley, Phys. Rev. **76**, 1012 (1949).
[24] J. A. Van Allen and S. F. Singer, Phys. Rev. **78**, 819 (1950).
[25] Dainton, Fowler, and Kent, Phil. Mag. **43**, 729 (1952).

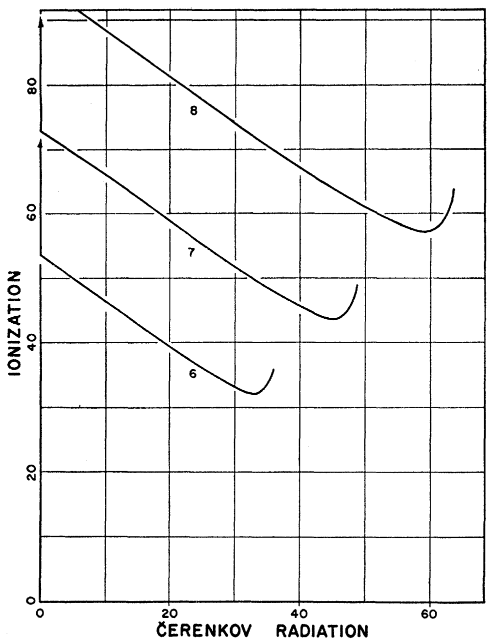


FIG. 8. Ionization *vs* Čerenkov radiation. Corresponding values of Čerenkov radiation and ionization for three values of charge: $Z=6$, 7, 8. Velocity is parameter for the curves. Scales have been normalized so that ionization plateau = Čerenkov plateau = 1 for $Z=1$.

Mev/nucleon. (For the purpose of comparison essentially the same value, 30 g/cm^2, was used for the air absorption mean free path in the present case as in the others.)

"Allowed" heavies and definite "background" heavies were observed in about equal numbers in this experiment. We believe that the measurements used in separating them were not capable of enough precision to avoid considerable uncertainty in the outcome. It is quite possible that in reality a third or even half of the allowed heavies narrowly missed one of the Geiger counter trays and triggered it by means of a knock-on electron. Consequently, the value 38 ± 12 we report above should not be considered a flux measurement but may be regarded as a measure of how far we have progressed toward solving the problem under discussion.

In a recent high-altitude experiment by Stix[26] a cloud chamber was triggered by sufficiently large pulses from each of three proportional counters in coincidence. He required that the cloud chamber show a single heavy track and that each of the pulses, which were recorded, be consistent with the density of the track. His result for the flux of heavy nuclei is in agreement with those obtained by use of emulsions. In the light of our observations, the fact that his geometry was defined entirely by proportional devices was important to that success. On the other hand the discrimination against background of the three proportional counters seems to have been poorer by orders of magnitude than might have been obtained using a single Čerenkov counter.

During the preparation of this report thin Čerenkov counters have been developed at this laboratory which have much better resolution and far greater useful area than the one we have described.[27] We suggest for consideration by others who are interested in this field that a Čerenkov counter might be combined with an ionization counter to great advantage, the geometry being defined by the two counter areas. There would be no knock-on electron problem as in the present experiment, and the Čerenkov counter would contribute its excellent discrimination against background. Furthermore, Fig. 8 shows that simultaneous measurements of Čerenkov radiation and ionization would serve to identify all primary nuclei as to charge up to the latitude at which the energy threshold determined by geomagnetic effects corresponds to the critical velocity in the material chosen for Čerenkov radiator.

VIII. ACKNOWLEDGMENTS

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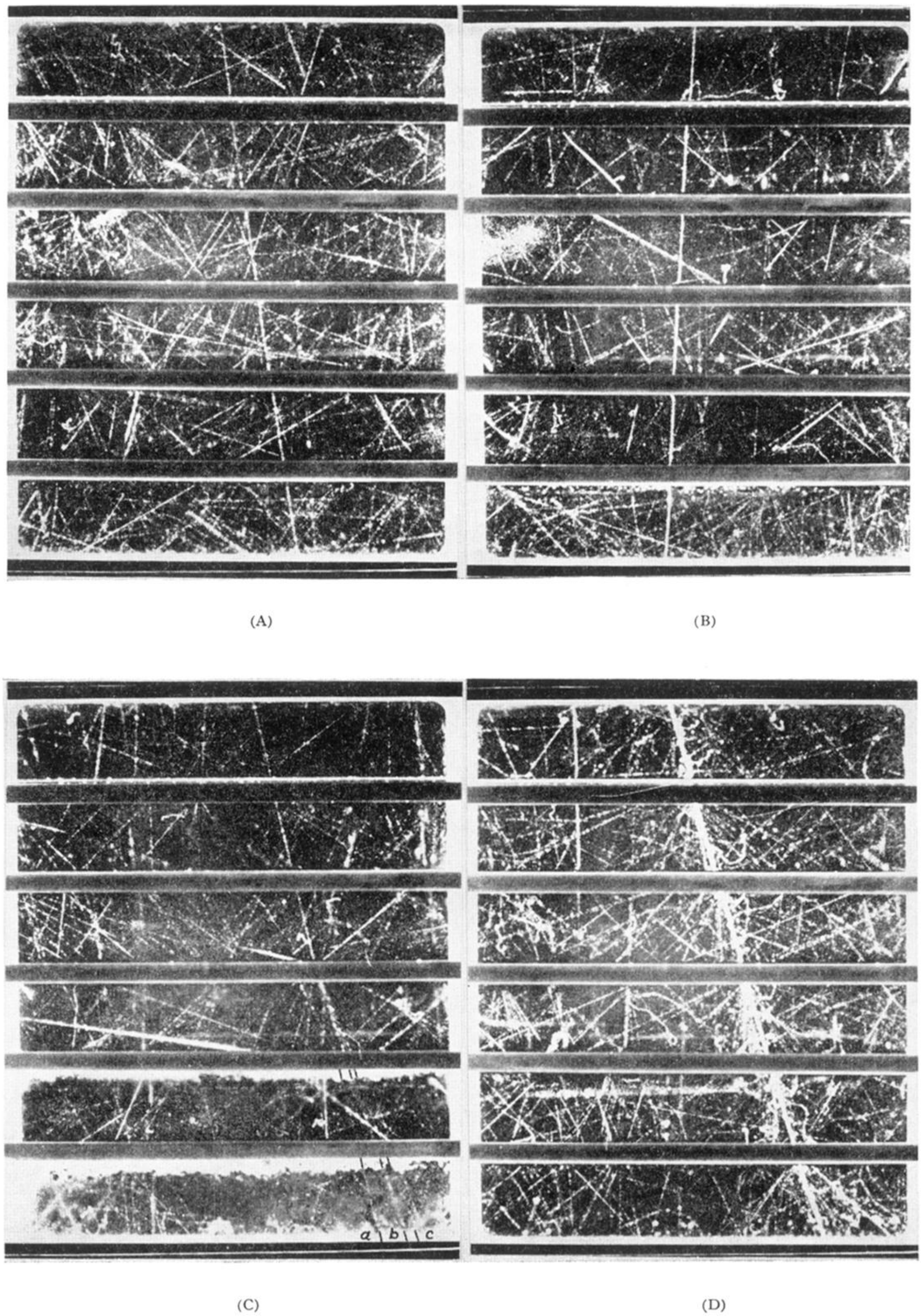
[26] T. H. Stix, Phys. Rev. **91**, 431 (1953); Phys. Rev. **95**, 782 (1954).

[27] J. Linsley and N. Horwitz, Rev. Sci. Instr. (to be published).



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