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Investigation of the Primary Cosmic Radiation with Nuclear Photographic Emulsions

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Several methods for determining the charge and energy of heavy nuclei found to be present in the primary cosmic radiation, are discussed. The application to a number of tracks of the heavy primary cosmic-ray component in Ilford C_2 emulsions shows the presence of nuclei from the neighborhood of carbon in the periodic system up to the neighborhood of iron ($Z\approx 20\div 30$).

A nuclear explosion caused by the collision of a $\gtrsim$3-Bev carbon or oxygen nucleus with a silver nucleus of the emulsion is discussed.

It is shown that both the magnitude of the flux and the distribution of ranges of the nuclei of the heavy primary cosmic-ray component may give valuable information regarding the origin of cosmic rays.

NUCLEAR photographic emulsions are particularly well suited for investigations at very high altitudes, because of their small weight, simplicity, large stopping power, and continuous sensitivity.

Recent developments in the technique of manufacturing emulsions sensitive to ionizing particles have greatly enhanced their value as a research tool.

The silver halide grains in the emulsion are made developable by the ionization produced by a charged particle. Since the same process is responsible for the energy loss of the particle in its passage through matter, the grain density, like the specific energy loss, will increase with increasing charge and decreasing velocity of the particle and will be independent of its mass.

In the Ilford C_2 boron-loaded emulsion, a proton track can be followed over a range of approximately 10,000 microns from its end until it is lost in the background. This determines the smallest observable specific energy loss K_0, from which the maximum observable energies and ranges for other particles can be obtained.

These are listed in Table I together with the quantity $K_0/K_{\min}$, which is the ratio of the smallest observable specific energy loss to the minimum value which the specific energy loss can assume.

The corresponding table (Table II) for the recently improved Eastman NTB emulsions is based on the fact that electron tracks can be observed of lengths up to 38μ. Thus the most sensitive photographic emulsions will record all multiply charged particles and singly charged particles up to a kinetic energy equal to 1/7 of their rest mass.

DETERMINATION OF CHARGE Z AND ENERGY E OF THE HEAVY PRIMARIES

The heavy primaries observed at 94,000 feet will be completely stripped by the passage through more than 14 g/cm² of air overhead and will remain stripped as long as their velocities are large compared to that of their inner shell electrons. This condition is certainly fulfilled for any particle capable of penetrating several g/cm² of material. We can therefore approximate the mass of the particles by the relation $M\approx 2Z$.

In general we can measure three quantities characteristic of the heavy particle tracks, or at least determine lower limits for them:

(1) the range R (in g/cm²);
(2) the track density D (the number of developed silver grains per unit length or, if the track consists of a solid column of developed silver, the width of this column);
(3) the number n of secondary electrons (δ-rays) ejected per unit length (the energy of the secondary electrons lying in a given arbitrary energy interval).

If some portion of the track consists of a series of resolved, developed silver grains on the trajectory, we can obtain the specific energy loss K of the particle by comparison with a track of equal grain density produced by a known particle of known energy or residual range (proton or α-particle). This is possible because the probability of making a certain fraction of the traversed grains developable depends only on the ionization and therefore on the specific energy

TABLE I. Ilford C_2 emulsions, boron loaded.

	max. energy E_{max}	Range in emulsion R	K_0/K_{min}	$\beta_{max} = V/C$
proton	50 Mev	10,250 microns	6.0	0.308
π-meson ($313m_e$)	8.5 Mev	1700 μ		
μ-meson ($200m_e$)	5.5 Mev	1100 μ		
electron	27 kev	6 μ		
α-particle	1.4 Bev	300,000 $\mu\mu$	1.5	0.677
heavier ions	all energies	all ranges	<1.0	

loss and not explicitly on the charge of the particle.

If, however, the particle is heavy or comparatively slow, the track no longer consists of a linear array of silver grains. The track then consists of a solid column of developed silver whose thickness can be many times larger than the diameter of the grains in the emulsion. The width of such tracks is far too large to be accounted for by the increased range of the effective electric field from multiply charged nuclei. The width is due to a great number of secondary electrons ejected with sufficient energy to make a few silver grains developable in the immediate neighborhood of the trajectory. Thus the width of such heavy tracks cannot be simply related to the specific energy loss and an estimate of charge based on such a relation which was made in the first communication[1] must be considered as misleading.

For heavy tracks we can only put a lower limit on the specific energy loss and hence obtain only a lower limit for charge and energy.

However, the large number of δ-rays ejected from these heavy tracks make it possible to determine the charge without knowing the specific energy loss. Some electrons will be ejected with sufficient energy to make recognizable δ-ray tracks of several microns length, and the number of such δ-rays per unit length (δ-ray density) in conjunction with the range can be used to determine charge and energy.

We shall therefore discuss separately the determination of charge and energy from range and specific energy loss which is applicable to lighter tracks and the determination from range and δ-ray density which is always applicable but more reliable for heavy tracks where the δ-ray density is high. Table V shows that both methods give consistent results within the accuracy assigned to each measurement.

[1] Phyllis Freier, E. J. Lofgren, E. P. Ney, F. Oppenheimer, H. L. Bradt, and B. Peters, Phys. Rev. **74**, 213 (1948). The present work is a continuation of a preliminary investigation made jointly with Freier, Lofgren, Ney, and Oppenheimer. We are greatly indebted to them for the many discussions we have had.

TABLE II. Eastman improved NTB emulsion.

	max. energy E_{max}.	Range in emulsion R	K_0/K_{min}	$\beta_{max} = V/C$
proton	147 Mev	70,000μ	2.8	0.490
π-meson	24.5 Mev	11,700μ		
μ-meson	16.5 Mev	7,800μ		
electron	80 kev	38μ		
α-particle	all energies	all ranges	<1.0	
heavier	all energies	all ranges	<1.0	

A. Determination of Charge Z and Energy E from Range and Specific Energy Loss

In order to determine the specific energy loss of the particle for any portion of its track, we have to find a portion of equal grain density on a track produced by a known particle of known energy or residual range. At present α-particles are the heaviest particles available for comparison purposes. Their specific energy loss reaches its maximum value very near the end of their range and does not exceed $K_\alpha = 0.9$ Mev/mg/cm^2. Thus only values of K below this value can be accurately determined.

If the specific energy loss K and the range R can be measured, the charge and energy of the ions can be determined by the following procedure: Let E, R, K, β denote the kinetic energy, range, specific energy loss, and velocity in units of c of the particle, and let primed symbols designate the same quantity for a proton of equal velocity. We then have the relations:

$\beta \equiv \beta'$,

$E/2Z = E'$ representing the kinetic energy per nucleon,

$K = Z^2\varphi(\beta) = Z^2K'$,

$R = (M/Z^2)R' \approx (2/Z)R'$.

The three quantities $E/2Z = E'$, $Z/(K)^{\frac{1}{2}} = 1/(K')^{\frac{1}{2}}$, and $R(K)^{\frac{1}{2}} = 2R'(K')^{\frac{1}{2}}$ are known functions of the velocity:[2] therefore, for given values of R and K, the value of $Z/(K)^{\frac{1}{2}}$ and hence the charge Z and energy E can be determined. Figure 1 shows the relation between the quantities $E/2Z$ and $Z/(K)^{\frac{1}{2}}$ *vs.* $R(K)^{\frac{1}{2}}$. As can be seen from the graph, if only lower limits of R or K are known, one obtains a lower limit for Z and $E/2Z$. As an

[2] J. H. Smith, Phys. Rev. **71**, 32 (1947).

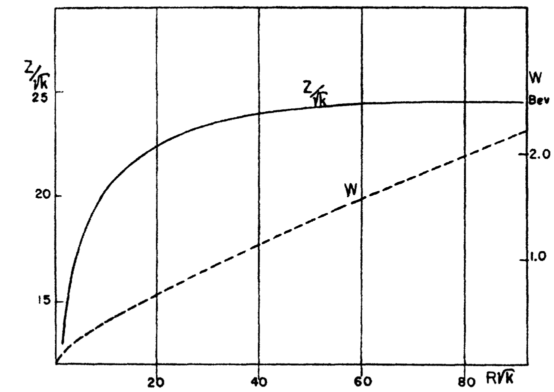

FIG. 1. Determination of the charge Z and the kinetic energy E from the range R and the specific energy loss K. Plotted are $Z/(K)^{\frac{1}{2}}$ and $W=E/2Z$ (kinetic energy per nucleon) ***versus*** $R(K)^{\frac{1}{2}}$. Range R in g/cm² Al equivalent (1 cm emulsion ≈ 1.07 cm glass ≈ 2.8 g/cm² Al). Specific energy loss K in Mev/(mg/cm²).

example, we consider a track which has a grain density equal to that of an α-particle with a residual range of 800–1000μ in the emulsion, as determined by grain counting. The specific energy loss K thus lies between the limits $0.11<K<0.125$ Mev/mg/cm². The particle travels through 17000μ in a single emulsion without any apparent change in grain density. The track enters the emulsion from the vertical and ends in the center of a large nuclear explosion leading to the emission of 22 fragments (Fig. 2).

Since for this particle we have certainly $K>0.11$ Mev/(mg/cm²), we deduce with $R>1.7$-cm emulsion (∼4.8 (g/cm²) Al) from the graph as lower limit for the charge $Z>5$ and as lower limit for the energy $E_{\text{kin}}>2$ Bev. Although a charge $Z=5$ is consistent with a specific energy loss of $K>0.11$ Mev/(mg/cm²) and a range $R>4.8$ g/cm², such a particle would have to increase its specific energy loss after traversing 4.8 g/cm² of material to a value $K>0.16$ Mev/(mg/cm²), while we observe a value of $K<0.125$ for all portions of the track. Taking into account that the increase in specific energy loss must lie within the observed limits, we find that the particle must have a charge of $Z\geqq 6$.

An upper limit for Z is obtained from the argument that the minimum specific energy loss of the particle may not exceed 0.125 Mev/(mg/cm²). Since the minimum value for a proton is 0.00166 Mev/(mg/cm²) we obtain

$$Z^2\cdot 0.00166<0.125 \quad \text{or} \quad Z<9.$$

The particle is therefore a fast moving carbon, nitrogen, or oxygen nucleus. If carbon, its energy is *ca.* 3.2 Bev where the track enters the emulsion and *ca.* 2.6 Bev near the star. If nitrogen, its energy lies between 5.1 and 6.5 Bev. If oxygen, its energy lies between 11 and 19 Bev.*

It is of some interest to discuss the star (Fig. 2) at the end of the above track. The star is very probably due to the disintegration of a silver nucleus by the particle responsible for the track. By counting the number of fragments and assigning the least possible charge to each fragment consistent with its track thickness, we obtain a minimum estimate of 37 charges emanating from the star. But the probability is high that a number of energetic protons which escape detection are also emitted and therefore the actual number of charges emitted is probably considerably higher. With the reasonable assumption that the carbon, nitrogen, or oxygen nucleus is incident on a silver atom and is the cause of the explosion, we estimate the energy dissipated in the explosion to be at least 3 to 4 Bev, in good agreement with the energy assigned to the incoming particle.

If the track density of a heavy particle is everywhere higher than that of an α-particle we get only a lower limit on the charge which, in the case of very heavy tracks, is far below the real value. For 25 very heavy tracks investigated, these (certainly, in most cases, far too low) lower limits range from $Z>8$ to $Z>16$. In these cases, however, much more accurate values for the charge can be obtained by the second method which we shall discuss now.

B. Determination of the Charge Z by Range and δ-Ray Density Measurements

For heavy tracks, the counting of the number of secondary electrons (δ-rays) in a given range interval per unit length can provide, together with the range measurement, a more accurate value for the charge Z than the rather qualitative estimate of the specific energy loss K from the track density.

* We have obtained in the meantime 12 tracks of light ions with ranges sufficiently long to permit much more accurate charge determinations. For these tracks we could determine Z uniquely by the above method. Z values of six, seven and eight have been found showing that atoms of carbon, nitrogen and oxygen are present in the primary cosmis radiation.

The number of δ-rays per centimeter with energies in the interval between W and $W+dW$ is given by Mott:[3]

$$
\begin{aligned}
dn = (2\pi NZ^2e^4/m_ev^2)(dW/W^2)\\
\times[1-\tfrac{1}{2}(1-\beta^2)(W/m_ec^2)\\
+(Z\pi\beta/137)[\tfrac{1}{2}((1-\beta^2)/\beta^2)(W/m_ec^2)]^{\frac{1}{2}}\\
\times[1-\tfrac{1}{2}((1-\beta^2)/\beta^2)(W/m_ec^2)]],
\end{aligned}
$$

where W, m_e are the kinetic energy and mass of the electrons; Z, v are the charge and velocity of the ion; and N is the number of electrons per cm^3 of stopping material.

We will be able to detect the tracks of δ-rays in the Ilford emulsion, provided they lie in a direction favorable for observation and provided their energies lie approximately between 10 kv and 30 kv. The upper energy limit is given by the sensitivity of our emulsion and the lower limit by the criterion used to exclude confusion with background grains (the δ-ray track must show at least four grains in a row). In the non-relativistic approximation the maximum energy of the δ-rays is given in terms of the velocity v of the ion by

$$W_{\max} = 2\cdot m_ec^2\cdot(v/c)^2.$$

The smallest value of the velocity which will lead to the production of δ-rays up to 30 kev is therefore determined by the condition

$$v^2/c^2 \geq 30 \text{ kev}/2mc^2 = 0.03.$$

For an α-particle this means that the formula can be applied for residual ranges greater than 325 mg/cm^2 aluminum or 1200μ in the emulsion. For six times ionized carbon the residual range is 110 mg/cm$^2\approx$400μ and for heavier ions still shorter. For most tracks it is therefore applicable to within a very short distance from the end of the track. For δ-rays between 10 kev and 30 kev the relativistic correction term in the brackets will give a correction of less than eight percent up to $Z=30$. Since none of the tracks measured so far gives a value for Z larger than about 30, we shall in general neglect the term in the brackets.

The number of δ-rays with energies between W_1 and W_2 is then given by

$$
\begin{aligned}
n_{\text{theor}} = 2\pi N(e^2/m_ec^2)^2\\
\times[(m_ec^2/W_1)-(m_ec^2/W_2)](Z^2/\beta^2).
\end{aligned}
$$

Whatever our criteria in selecting δ-rays for

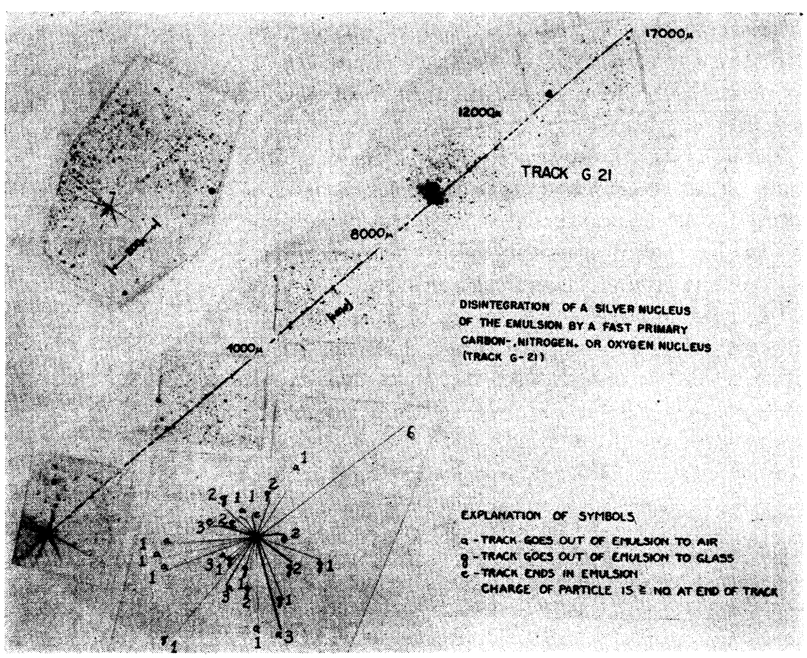

FIG. 2. Disintegration of a silver nucleus by a fast primary carbon, nitrogen, or oxygen nucleus (track G-21). The charge of the particle responsible for the 17,000μ long track G-21 has been determined to be $Z=6$, 7, or 8 from the specific energy loss $0.11<K<0.125$ Mev/(mg/cm^2) and the δ-ray density

$$n=(2.8\pm0.5)(\delta\text{-rays}/100\mu).$$

[3] N. F. Mott, Proc. Roy. Soc. **124**, 425 (1929). Mott's cross section for the elastic scattering of electrons by the Coulomb field of a nucleus of charge Z has been transcribed to the coordinate system in which the electron is initially at rest.

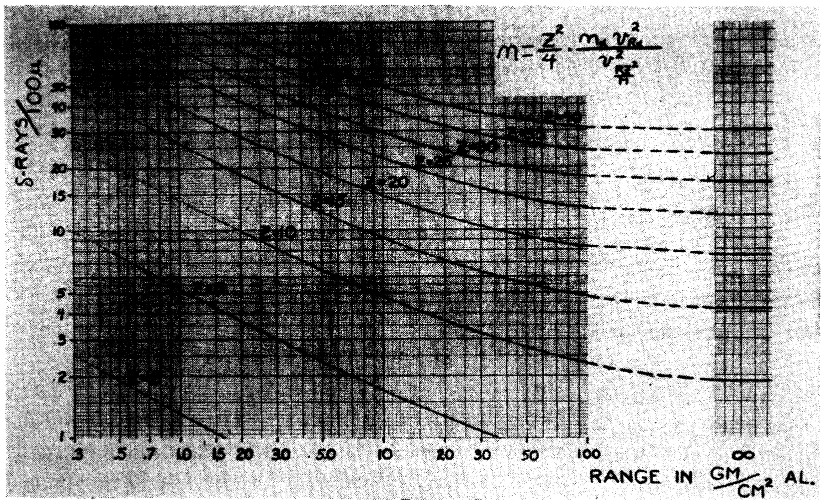

FIG. 3. Determination of the charge Z by range and δ-ray density measurements. Plotted is the number of δ-rays per 100μ n_δ *versus* the range R for Z values between 2 and 40, calculated with the unrelativistic formula $n_\delta=(Z^2/4)[n_\alpha\beta^2(R_\alpha)/\beta^2((Z/2)R)]$, with

$$n_\alpha\beta^2(R_\alpha)=0.075(\delta\text{-rays}/100\mu).$$

δ-Ray Density *vs.* Range

counting, we should always obtain a constant fraction of the theoretical δ-ray density and for a given set of criteria the densities obtained should vary like Z^2/β^2 in an emulsion of given sensitivity.

We have made δ-ray counts for improved Eastman NTB emulsions irradiated with α-particles from the 184″ Berkeley cyclotron.** The results are given in Table III. We estimate that with the counting criteria used, we count about 16 percent of the theoretical number of δ-rays produced in this energy interval.

Table III also shows the δ-ray densities obtained with the same criteria in the less sensitive Ilford C_2 emulsions using α-particles of cosmic-ray origin. In these emulsions we count about ten percent of the theoretical number.

In order to obtain the charge of an unknown ion, we have to compare δ-ray densities at a given residual range R with the δ-ray density of an α-particle n_α with known residual range R_α in the same emulsion type.

Since $n/n_\alpha=(Z^2/Z_\alpha^2)(\beta_\alpha^2/\beta^2)$ and since β^2 is a

TABLE III.

Emulsion type	α-particle energy	β^2	δ-rays/100μ n	$n\beta^2$
Eastman NTB	368 Mev	0.164	0.76±0.08	0.125±0.01
Eastman NTB	168	0.084	1.3 ±0.2	0.11 ±0.02
Ilford C_2	60	0.032	2.5 ±0.05	0.079±0.016

** We are greatly indebted to Dr. E. Gardner for making the exposures for us.

known function of the variable $RZ^2/M\approx RZ/2$,

$$\beta^2=\psi(RZ/2),$$

we obtain the relation

$$n=(Z^2/4)n_\alpha[\psi(R_\alpha)/\psi(RZ/2)]$$

For $n_\alpha\psi(R_\alpha)$ we use the values listed in Table III:

$n_\alpha\psi(R_\alpha)=0.12(\delta\text{-rays}/100\mu)$ for Eastman NTB emulsions and
$=0.079(\delta\text{-rays}/100\mu)$ for Ilford C_2 emulsions.

In Fig. 3 we have plotted $\log n$ *versus* $\log R$ for different values of Z. The main uncertainties in this graph, apart from the relativistic correction, derive from the fact that we have only very few suitable α-particle tracks for calibration in the Ilford plates exposed at 94,000 feet. If the accepted value for $n_\alpha\psi(R_\alpha)$ should be modified, this will only lead to a change of scale for n.

For a particle which traverses several emulsions and then ends in one of the emulsions, such that its residual range is accurately known, we can obtain, by selecting different sections of the track for δ-ray counts, several independent determinations of the charge. The consistency obtained supports the assumption that the δ-ray density varies very nearly like Z^2/β^2.

Let us take as example the track G-20 of a particle which enters the stack of plates under an angle of 10° from the vertical, traverses two glass plates and three emulsions, and comes to rest in the fourth emulsion (Fig. 4, Table IV). The track appears in the first emulsion about as heavy as an α-particle track.

The observed variation of δ-ray density with residual range follows closely the $1/\beta^2$-law** and agrees reasonably well with the one calculated (using the relativistic correction) for a charge $Z=20\pm2$. The energy of a calcium nucleus of range $R=5.4$ (g/cm^2) Al equivalent would be $E_{\text{kin}}=10.8$ Bev and the specific energy loss in the first emulsion $K=1.2$ Mev/(mg/cm^2), not inconsistent with the appearance of the track.

In cases where the actual range of the particle is not known but only a lower limit for it, the variation of the δ-ray density along the track can be used to obtain a value for both Z and R. If n does not change measurably over several g/cm^2 track length, the value of Z obtained will be good, though only a lower limit can be deduced for the range or the energy. For example, we find for the δ-ray density along the 17,000μ track G-21 of the light nucleus producing the nuclear explosion discussed above, the average value

$$n_{\text{Av}}=(2.8\pm0.5)\delta\text{-rays}/100\mu.$$

(Only near the star does the δ-ray count give a slightly larger value.) This δ-ray density cor-

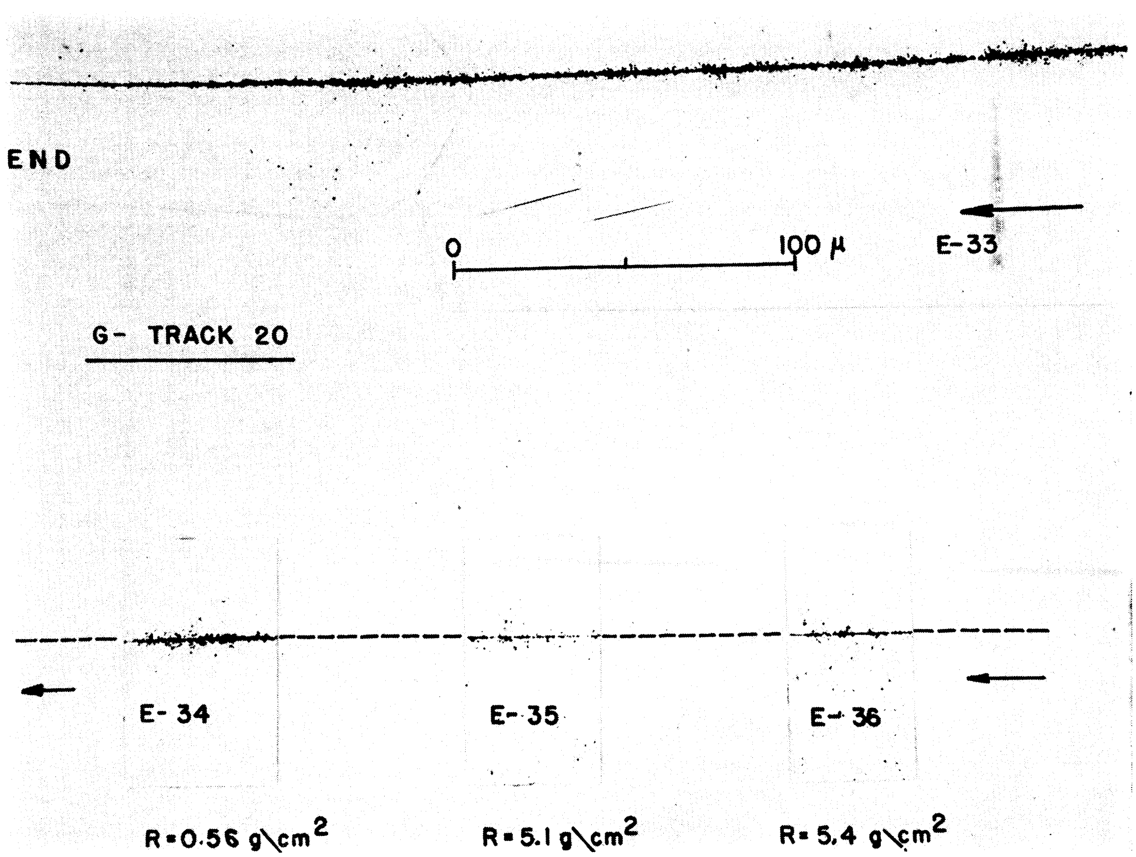

FIG. 4. Track G-20 of a particle with charge $Z=20\pm2$ entering the stack of plates in emulsion E-36 and coming to rest in emulsion E-33. The portions of the track in emulsion E-36 and E-35 shown in Fig. 4 correspond to a velocity $\beta=v/c\approx0.62$. In emulsion E-34, where the track is already considerably heavier, the velocity is reduced to $\beta=v/c\approx0.34$. The track density reaches a maximum in emulsion E-33 for a remaining range of approximately 100μ; then the track tapers off, due to the gradual filling up of the electronic shells.

** The increase of δ-ray density with decreasing range seems to be only slightly less rapid than calculated, a fact which may be due to the larger chance of missing δ-rays while counting in portions of the track with very high δ-ray densities.

TABLE IV. Observed and calculated δ-ray densities for track G-20 ending in emulsion E-33.

Emulsion	Remaining Range R Glass	Remaining Range R Emulsion	R in g/cm²/Al	n_{exp}	$n_{calc.}$ $Z=17$	$Z=19$	$Z=21$
	cm	cm					
36	1.68	0.37	5.4	23.5 ± 1.6	16	19	23
35	1.68	0.25	5.1	24.3 ± 1.5	17	20	24
$34_{(1)}$		0.20	0.56	53.0 ± 3.0	47	55	66
$34_{(2)}$		0.14	0.39	65.0 ± 4.0	56	66	74

responds to a charge $6<Z<12$. The value of 2.8 δ-rays/100μ is the value expected for a carbon nucleus of 2.6 Bev, a nitrogen nucleus of 6.1 Bev, or an oxygen nucleus of 11 Bev.

Comparing this with the values obtained for this particle from grain density measurements in the previous chapter, we find good agreement between the two methods of charge determination. Since the track is comparatively thin, the first method gives somewhat more accurate values.

For track G-23, which has a total length of 2.35 cm in two emulsions facing each other, we find a constant δ-ray density $n=(1.1\pm0.1)\times$(δ-rays/100μ), giving $5\leq Z\leq 7$ as limits for the charge. The specific energy loss has been determined accurately by grain counting to $K=0.055\div0.064$ Mev/(mg/cm²), using proton and deuteron tracks for calibration. With this value of K and the fact that it is constant to within five percent over the whole length of the track, only the charge values $Z=6$, for which the minimum ionization loss is $K=0.060$ Mev/(mg/cm²), and $Z=5$ are compatible. $Z=4$ would give a variation of energy loss of at least 15 percent over the observed track length. Hence, the track G-23 is the track of a relativistic carbon or boron nucleus.

In Table V we have listed a sample of 15 tracks to which we have applied the δ-ray analysis and counted δ-rays in all emulsions in which the given track appears. In order to obtain the number of δ-rays/100μ, we have in general combined the counts in the two emulsions facing each other. As a measure of uncertainty, we have used the square root of the number of counts obtained in these two emulsions.

In those cases where we know the range, a single measurement of δ-ray density gives us a value of Z and other measurements along the track can be used to test the consistency of the value obtained. This is the situation for the G-20 track already discussed and occurs also for track G1*** which stops in the glass between plates 10 and 11 and where therefore the range is known for any part of the track with an accuracy of 1.2 g/cm². We can carry out four independent measurements of δ-ray density on the latter track and they are all consistent with a value $20<Z<24$.

Most of the particles listed in Table V go through the entire stack of plates and leave tracks in varying numbers of plates, depending on their angle of incidence. From the observed minimum range and δ-ray count at any place along the track, we obtain upper and lower limits for Z.

Column 2 gives the δ-day density in the first and last plate traversed by the track. Column 3 gives the number of independent δ-ray determinations which could be carried out on the track. Column 4 gives the amount of material lying between the first and the last observed section of the track. Column 5 gives the limits on Z obtained if one assumes that the true δ-ray count may differ from the observed one in either direction by the square root of the counted number. Finally, column 6 gives the lower limit on Z obtained from the minimum observed range and estimated minimum specific energy loss.

The only track which cannot be fitted to a single value of Z if the observed track length is the actual range, is track G-13. The track shows no significant change of δ-ray densities in the four plates 7, 8, 9, and 10, indicating that it is not close to the end of its range. Yet it fails to emerge in plate 11 after passing through plate 10. It is probable that the particle lost its energy in a nuclear collision in the glass of plates 10 or 11.

Three tracks end in the emulsion. They all show a gradual decrease in track thickness towards the end of their range which is to be expected when the particle is slow enough to

*** This is the track discussed in reference 1. Due to the unjustified assumption of proportionality between the amount of reduced silver and energy loss, the estimate of the charge and energy of this particle given in that paper is too high.

collect electrons (see Fig. 4). Their appearance is similar to that of fission tracks. The range over which the decrease of track width takes place is, in one case, about 70μ, in the two other cases, about 100μ. In principle, the charge could be obtained from a measurement of the tapering. However, a satisfactory theory of energy loss of multiply charged ions of low velocity does not as yet exist.

In an aggregate of 15-cm track length of heavy primary tracks in the emulsion, we have seen four particles coming to rest but only one event (see above) which may be interpreted as a nuclear explosion caused by a heavy primary.

Since the energy per nucleon seems to be comparable to that of the proton component, one may expect meson production of high multiplicity from the nuclear collision of a heavy primary with a nitrogen or oxygen nucleus. It is therefore possible that heavy primaries will contribute appreciably to the number of large penetrating air showers at high altitudes. Helium nuclei if present in large numbers would contribute appreciably to meson production. However, in view of the relatively small number of primaries heavier than He and the strong competition of energy loss by ionization, *their* contribution to the total meson intensity would still be small.

THE HEAVY PRIMARIES AND THE ORIGIN OF COSMIC RAYS

Originally, it was not expected that the photographic technique would give any information on the primary cosmic radiation, supposed to consist of high energy protons, because even at high geomagnetic latitudes protons cannot reach the earth unless they possess several Bev kinetic energy and therefore leave no visible tracks in the emulsion. It turned out, however, that the photographic emulsions are an excellent tool for the study of the heavier nuclei of the primary cosmic radiation, among which we have found atomic numbers roughly between carbon and iron. The fact that such nuclei with energies of the order of 1 Bev per nucleon enter the earth's atmosphere may have some bearing on the question of the origin of cosmic rays. This fact obviously favors some mechanism for adiabatic acceleration as opposed to some catastrophic process, such as might result from a nuclear explosion. Any adiabatic mechanism for acceleration should be equally effective for protons and, since hydrogen is by far the most abundant constituent of stellar bodies and interstellar matter, the heavy primary radiation should be accompanied by a much stronger proton component. By means of this argument the presence of heavy nuclei among the primary cosmic rays gives added weight to the already well established hypothesis that the primary radiation consists predominantly of protons.

TABLE V.

1 Track G	2 δ-rays/100μ in first and last section n	3 Number of sections used for δ-ray count	4 ΔR in g/cm² Al between first and last section	5 Limits for Z from δ-rays	6 Estimate of Z from ionization density
1	19.7±0.4 52.7±0.8	7	3.75	$20<Z<24$	$Z\gtrsim 22$[a, b]
2	5.2±0.8 9.3±1.0	5	3.72	$8<Z<12$	$Z>8$
3	20.1±2.5 28.1±3.0	11	4.64	$25<Z<35$	$Z\gtrsim 25$[b]
4	10.7±1.8 21.5±2.0	6	2.26	$10<Z<15$	$Z>10$
5	9.2±1.8 17.6±2.2	11	6.8	$15<Z<16$	$Z>13$
7	4.9±0.7 6.3±0.7	8	11.0	$9<Z<18$	$Z>15$
9	5.2±0.9 7.0±1.0	4	2.66	$7<Z<18$	$Z>11$
10	8.8±0.7 8.8±0.7	11	6.48	$18<Z<22$	$Z\approx 25$[6]
11	10.9±1.8 10.9±1.8	11	7.4	$17<Z<24$	$Z>15$
13	10.1±1.5 10.4±1.5	4	1.75	$15<Z<24$	$Z>10$[c]
20	23.5±1.6 65.0±4.0	4	2.96	$18<Z<22$	$Z>15$[d]
21	2.8±0.5 (3.6±0.5)	1	3.4	$6\leq Z<12$	$6\leq Z<9$[e]
22	4.0±0.4 4.3±0.4	2	4.4	$10<Z<15$	$10<Z<14$
23	1.1±0.1 1.1±0.1	2	4.4	$Z\leq 7$	$Z=5$ or 6
24	11.0±1.0 11.7±1.0	2	4.9	$17<Z<26$	$Z>15$

[a] Particle stops in the glass after traversing eight plates.
[b] $K\cong 1.4$ Mev/(mg/cm²) estimated from comparison with track G-20.
[c] Probably loses its energy in nuclear collision in the glass.
[d] Ends in emulsion.
[e] Produces nuclear explosion in emulsion (Fig. 2).

It is clear that a comparison of the relative frequencies of nuclei heavier than hydrogen among the primary cosmic rays with the known abundance of the elements in the stars and interstellar space may shed light on the origin of cosmic radiation. Most interesting would be a measurement of the relative abundance of He, the element whose abundance is next to that of hydrogen. The astrophysical data suggest for planetary nebulae, the sun, and τ Scorpii a helium abundance of 1 to 2 He atoms for each 10 atoms of hydrogen,[4] a ratio which is in fair agreement with that calculated for the sun by Christy and O'Reilly,[5] using the recently measured cross sections relevant for the carbon cycle (He:H atomic ratio = 1:15).

Heavier elements such as oxygen, sodium, magnesium, silicon, potassium, calcium, and iron are known to occur in stellar bodies, planetary nebulae, and in interstellar space. The abundance of carbon and nitrogen is estimated by O'Reilly and Christy to be of the order of one percent by weight for the sun. For interstellar space, the relative abundance of various elements has been derived from spectroscopic data by Struve and Dunham,[6] leading to an estimate of 1:100 by atom for the oxygen: hydrogen ratio and an estimate of the order of 1:10,000 for the relative abundance of all the elements heavier than oxygen. Our preliminary data indicate that the flux of nuclei with $Z \gtrsim 10$ is about one thousandth of the flux of primary protons. This value is in fair agreement with the results of Freier, Lofgren, Ney, and Oppenheimer reported in this issue of the Physical Review.

The flux of nuclei of the carbon, nitrogen and oxygen group is about five times larger than the flux of the heavier nuclei, corresponding to one carbon, nitrogen or oxygen nucleus per 200 primary protons. These values have to be considered as lower limits, since the absorption of heavy primaries due to collisions in the residual air above the plates is not negligible.

A detailed comparison of the chemical composition of cosmic-ray primaries with the relative abundance of elements in stellar and interstellar matter as obtained from astrophysical data may be very instructive. In particular, we have some evidence that the abnormally low abundance of Li, Be and B and the high abundance of Fe in stellar matter repeats itself in the cosmic-ray flux. Thus far no tracks of primary Li, Be or B nuclei have been found.

Measurements to determine accurately the flux of nuclei as a function of their charge are in progress.

Further information bearing on the origin of cosmic rays can be obtained by investigating whether there exists a minimum range for heavy primaries of giving charge Z. Calculations by J. Ashkin† show that if heavy primaries traverse an appreciable fraction of the galaxy with the observed velocities, they will be stripped of electrons by the matter in interstellar space, assuming a density of one hydrogen atom per cm^3 or an effective hydrogen layer of 15 mg/cm^2 for the galaxy. Upon entering the sun's or earth's magnetic field the heavy primaries should therefore be subject to a magnetic energy cut-off, $E_Z{}^c$, which, in terms of the cut-off for protons $E_1{}^c$, is given by

$$E_Z{}^c = Z[((E_1{}^c+1)^2+3)^{\frac{1}{2}}-2], \quad (M \approx 2Z).$$

The particles should therefore possess a minimum energy and minimum range dependent on their charge.

If, however, the particles come from the sun, they will in general not be expected to be completely stripped (though this may occur occasionally) and partially stripped ions with comparatively low velocities should not be prevented by the earth's magnetic field from reaching its atmosphere. Thus the study of the geomagnetic effect for heavy primaries, by deciding whether they arrive completely stripped or only partially so, may contribute to a solution of the problem of the origin of cosmic rays.

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[4] L. H. Aller and D. H. Menzel, Astrophys. J. **102**, 263 (1945).

[5] J. O'Reilly and R. F. Christy, Pasadena Meeting of the American Physical Society, June 1948.

[6] C. S. Beals, Monthly Notices, Roy. Astr. Soc. **102**, 96 (1942).

† Dr. J. Ashkin states: "Taking $v/c = 0.3$ as an intermediate velocity of the ion, the stripping cross section in the Born approximation for most of the electrons of an ion like calcium ($Z = 20$) is of the order of 10^{-20} cm^2 for impact with a hydrogen atom at rest. This corresponds to a mean free path of 10^{20} cm. Since the mean free path decreases with the second power of the velocity for smaller velocities, any reasonable fraction of the total 10^{22} cm of the galaxy should be sufficient to remove most of the electrons of the ion."

Experiments to decide whether there exists a minimum range for particles of given Z equal to that calculated for complete stripping (using stopping material up to 120 (g/cm^2) in the form of photographic plates) are in progress.

We wish to extend our thanks to Messrs. S. Tamor and Tom Putnam of the University of Rochester for valuable help in carrying out measurements and preparing graphs, and to the cosmic-ray group of the University of Minnesota and the Aeronautical Research Group of General Mills for assistance in the exposure.

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On the Energy of Cosmic Radiation Allowed by the Earth's Magnetic Field

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Curves giving proton energies (a) below which no energy is allowed by the earth's magnetic field, (b) above which all energies are permitted, for all latitudes in case (a), for latitudes from 0° to 40° geomagnetic in case (b), are given for the following directions: (1) vertical, (2) zenith angle 45°, north, south, east and west azimuths. In addition the distance and angular corrections due to the longitude effect are given for geographic latitudes up to 40°.

IN the course of discussions on the east-west asymmetry of cosmic radiation which took place on occasion of the Symposium on Cosmic Rays held at the California Institute of Technology in honor of Robert A. Millikan's eightieth birthday, it became clear that additional information on the energy of cosmic radiation allowed through the earth's magnetic field was required to interpret high altitude experiments now being carried out. Such information is presented in the curves given in this paper.

In Fig. 1 the lower curve, labeled E_1, gives the least energy that a proton must have in order to penetrate through the earth's magnetic field in the vertical direction at the geomagnetic latitude given by the abscissa. This energy is determined either by the Störmer cone or by the simple shadow cone,[1] the former for low latitudes and the latter for intermediate and high latitudes.

The upper curve labeled E_2 gives the energy that a proton must have in the vertical direction, at the geomagnetic latitude given by the abscissa, above which all energies are allowed by the earth's magnetic field. This energy limit is determined by the main cone.[2]

Between the upper and lower curves lies the region of penumbra, in which only certain energies between these two limits are allowed, in the given direction, and others are forbidden.[3]

At low latitudes (less than 15°) the dark bands predominate in this region and the least allowed energy is practically given by the lower curve. At intermediate latitudes (between 15° and 35°) the dark and light bands are about equally important, but one cannot predict without further very difficult analysis whether an energy between these limits will actually arrive in the vertical direction. At 20°, for instance, it is known, that only energies higher than those given by E_2 (main cone) can actually arrive. At high latitudes light bands predominate in the penumbra and the least allowed energy is practically given by the lower

[1] E. J. Schremp, Phys. Rev. 54, 158 (1939).

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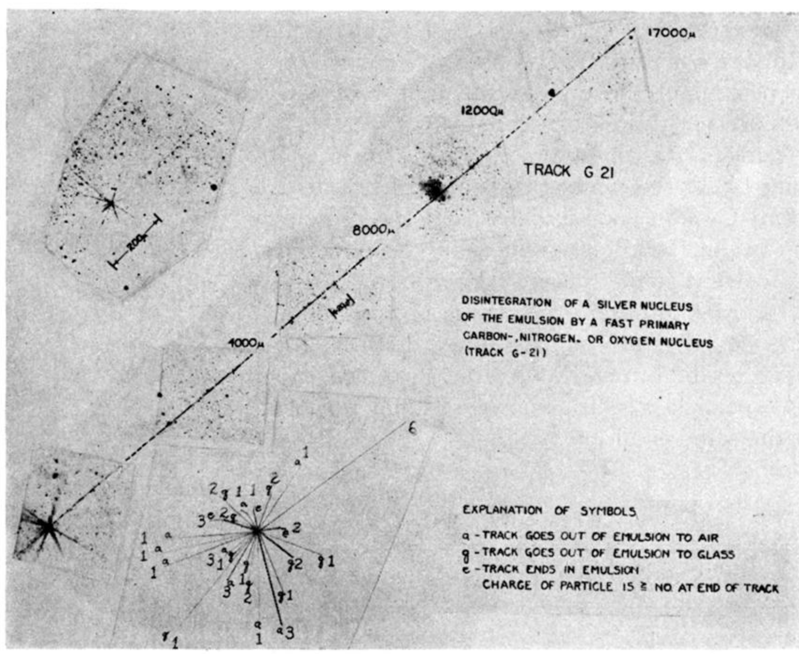
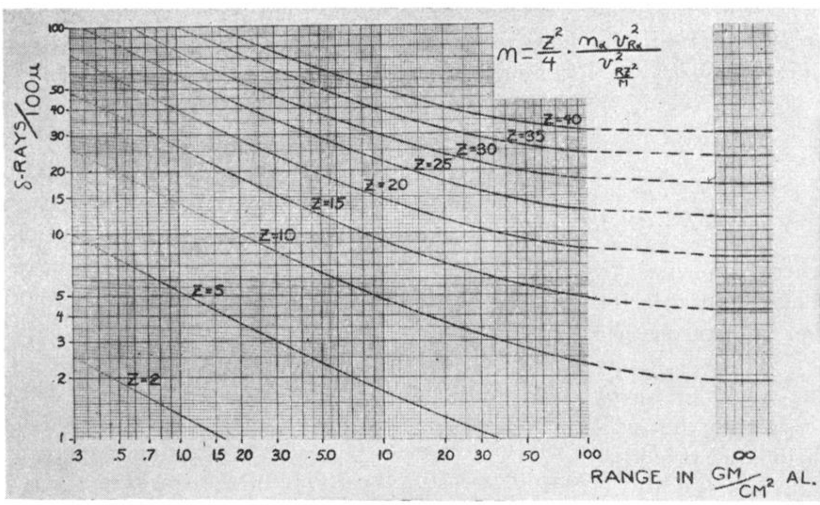
[3] G. Lemaitre, Ann. de la Soc. Sci. de Bruxelles 54, 162 (1935); R. Albagli Hutner, Phys. Rev. 55, 614 (1939); Tchang Yong-Li, Ann. de la Soc. Sci. de Bruxelles 59, 285 (1939); René de Vogelaere (unpublished, private communication to the author).

FIG. 2. Disintegration of a silver nucleus by a fast primary carbon, nitrogen, or oxygen nucleus (track G-21). The charge of the particle responsible for the 17,000μ long track G-21 has been determined to be $Z=6$, 7, or 8 from the specific energy loss $0.11<K<0.125$ Mev/(mg/cm²) and the δ-ray density

$$n=(2.8\pm0.5)(\delta\text{-rays}/100\mu).$$





δ-Ray Density *vs.* Range

FIG. 3. Determination of the charge Z by range and δ-ray density measurements. Plotted is the number of δ-rays per 100μ n_δ *versus* the range R for Z values between 2 and 40, calculated with the unrelativistic formula $n_\delta = (Z^2/4)[n_\alpha \beta^2(R_\alpha)/\beta^2((Z/2)R)]$, with

$$n_\alpha \beta^2(R_\alpha) = 0.075(\delta\text{-rays}/100\mu).$$

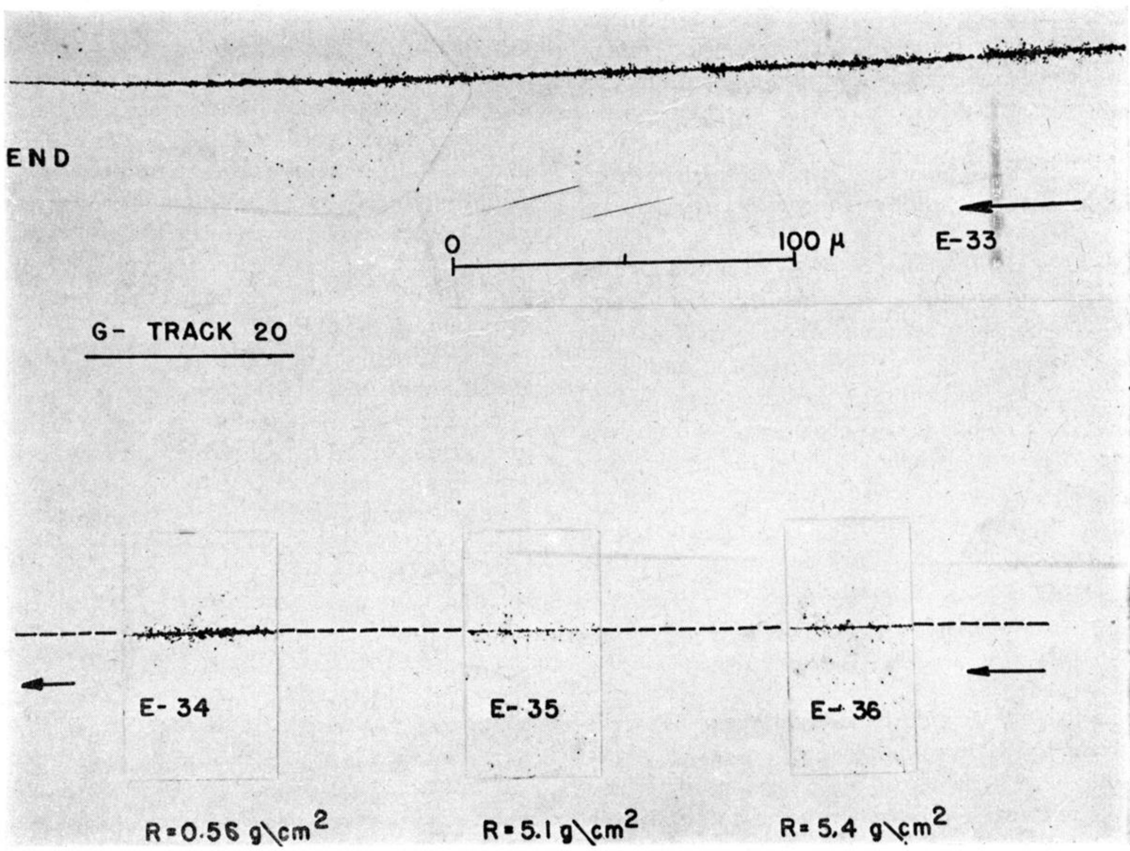


FIG. 4. Track G-20 of a particle with charge $Z=20\pm2$ entering the stack of plates in emulsion E-36 and coming to rest in emulsion E-33. The portions of the track in emulsion E-36 and E-35 shown in Fig. 4 correspond to a velocity $\beta=v/c\approx0.62$. In emulsion E-34, where the track is already considerably heavier, the velocity is reduced to $\beta=v/c\approx0.34$. The track density reaches a maximum in emulsion E-33 for a remaining range of approximately 100μ; then the track tapers off, due to the gradual filling up of the electronic shells.