Study of the Charge Spectrum of Extremely Heavy Cosmic Rays Using Combined Plastic Detectors and Nuclear Emulsions

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Tracks of 99 nuclei with $Z>36$ have been analyzed in a stack of Lexan polycarbonate, cellulose triacetate, and nuclear emulsion launched from Palestine, Texas, with an area-time factor of 900 m^2 h. Although the mean deviation in charge assignment between plastics and emulsion was $\sim$3 units, there was no systematic variation. One nucleus with charge estimated to be $Z\approx96$ ($\beta\approx0.95$) was identified in all three detectors. Combining all available data, 33 events have been found with $Z>70$, giving for the important ratio $(Z>83)/(70\leq Z\leq83)$ the value $\sim$0.3. The weakness of the Pb peak relative to the Pt peak indicates that little radioactive decay of the transbismuth nuclei has occurred. These results favor supernova explosions within the galaxy as the major source of cosmic rays and suggest that their average lifetime is less than 10^7 yr.

I. INTRODUCTION

Cosmic rays with $Z\gtrsim30$ represent a very small, but astrophysically valuable, fraction of the total radiation reaching the solar system. The number of nuclei with $Z\gtrsim83$ thus far detected is only eight, after a total of eight balloon flights with 87 m^2 day collecting power.[1–8] Table I summarizes these flight data, which include the present work. In order to establish with some confidence the relative numbers of the various radioactive nuclei above Bi, it will be necessary to expose large areas of detectors for periods of months or years in space. These detectors must withstand a hostile environment without deterioration or alteration of response. Plastic particle identifiers[9,10] are very attractive in this respect.

In the present paper we compare the response of plastic detectors and of nuclear emulsions to the same extremely heavy nuclei that passed through a sandwich consisting of three kinds of plastics and two kinds of emulsions. Preliminary data were reported at the Eleventh International Conference on Cosmic Rays in Budapest.[3,4] We also present an up-to-date charge spectrum for nuclei with $Z>36$ and remark on its astrophysical significance.

II. EXPERIMENTAL DETAILS

Two identical stacks of plastics, emulsions, and Fe absorbers were exposed in September, 1968, on two separate 40-h flights at $\sim$3 g/cm^2 altitude from Palestine, Texas. They are listed in Table I as Monsters I and II. The total area × time factor was 1200 m^2 h. Our present analysis includes 75% of the area; the remainder is being studied separately.[7] Figure 1 gives the composition of the two stacks. The upper portion of each stack contained a motor-driven, shiftable layer of G-2 emulsion + Lexan polycarbonate + Daicell cellulose nitrate so that events occurring at ceiling altitude could be singled out. The 0.5-g/cm^2 Fe slab was inserted to bring the total thickness to 1 g/cm^2 so that tracks of nuclei with velocity much less than that for the geomagnetic cutoff could be easily recognized and discarded.

About 10^{10} cosmic-ray primary particles, including $\sim3\times10^6$ nuclei of the Fe group ($24\leq Z\leq28$), passed through the stacks. The middle emulsion layer (G-5) was scanned under a low-power stereomicroscope for tracks of nuclei appreciably heavier than Fe. The charges were determined by photodensitometry as de-

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[9] P. B. Price, R. L. Fleischer, D. D. Peterson, C. O'Ceallaigh, D. O'Sullivan, and A. Thompson, Phys. Rev. **164**, 1618 (1967); Phys. Rev. Letters **21**, 630 (1968); Can. J. Phys. **46**, S1149 (1968).
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TABLE I. Balloon flights with large detectors for extremely heavy cosmic rays.

	Date	Depth (g/cm^2)	Area × time (m^2h)	Particles with $70 \leq Z \leq 83$	Particles with $Z > 83$	Ref.
Texas I	6 Oct. 1966	4.5	60	0	2	1
Texas II	5 May 1967	3.5	290	5	1	6
Barndoor I	23 Sept. 1967	3.7	120	0	0	2
Barndoor II	24 May 1968	3.5	190	2	0	2
Monster I	18 Sept. 1968	3.0	600	6	2	3, 4, and this work
Monster II	22 Sept. 1968	3.0	600	7	1	3, 4, 7, and this work
Barndoor III	19 Sept. 1968	<4.0	175	2	1	5
Sioux Falls	13 Sept. 1969	~3.0	75	2	1	8
Total			2110	24	8	

scribed in previous publications.[1,6] The upper and lower emulsion layers were of type *G*-2 and were used mainly for following tracks through the stack. Their sensitivity was lower than that desired by such a factor that we were not able to extract significant information from the tracks. Figure 2 shows the track of a heavy nucleus as it appears in the etched Daicell scanning sheet, in the etched Lexan, and in the *G*-5 emulsion layer. The particle that produced this track is believed to have a charge $Z \approx 82$.

The most sensitive plastic, Daicell,[2,9] records relativistic nuclei with $Z \gtrsim 30$, but because of its nonuniform composition and response, it was only used for location of tracks of heavy nuclei in the stack. After etching for 48 h in 6.25 *N* NaOH, tracks of heavy nuclei in Daicell were easily recognizable as cylindrical holes about 60 μ in diam, as illustrated in Fig. 2.

The Eastman cellulose triacetate without plasticizer (CTA) is quite uniform in composition and reliable in response.[11] It was used to identify nuclei with $Z \gtrsim 40$. One layer was etched 50 h at 40°C in two parts 15% NaClO + one part 6.25 *N* NaOH. All etched tracks that

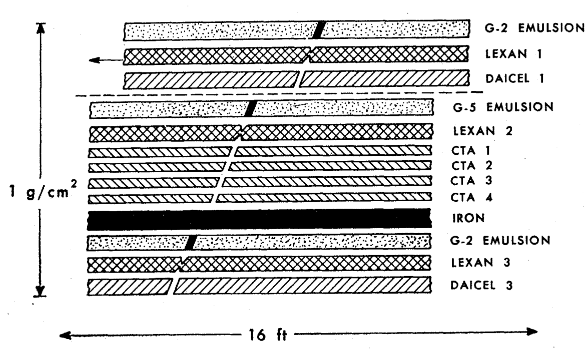

FIG. 1. Composite stack for simultaneous identification of extremely heavy nuclei in Lexan, CTA (cellulose triacetate), and nuclear emulsion. The three top layers were shifted when the balloon was at flight altitude. CTA 3 and 4 were of an inferior grade and were not used in the analysis.

completely penetrated the sheet thickness [path length $> (\csc\delta) \times (125\ \mu)$, where δ is dip angle] were found by passing ammonia vapor over the plastic sheets. Vapor flowed through the track holes and produced blue spots on chemically treated paper held underneath and in contact with the sheets.[12] The second CTA layer was cut up so that regions containing events of different *Z* could be etched for different times, chosen to give pairs of etched cones that were *not* touching but were long enough to be measured with good precision. The track-etching rate, defined as cone length divided by etching time, is the parameter that is related to the ionization rate of a particle. We were guided in our choice of etching times by estimates of charge made on the corresponding events in the *G*-5 emulsion. For a large number of events we were unable to obtain good values of track-etching rate because the two cones had become connected before the end of the etching period. In stacks now being assembled for a future flight, we have included three layers of 200-μ CTA sheets, so that the choice of etching time will not be so critical.

By scanning independently in CTA and *G*-5 emulsion and then comparing events, it was possible to evaluate scanning efficiency. With each method separately, interesting events were missed, but for different reasons. Tracks in emulsion are most easily seen if they are at small dip angles. Some of the steepest events were missed. Tracks in CTA are most easily detected by the ammonia process if the cones are well connected with large opening. Events at small dip angle, particularly those of small *Z*, may be missed because either the cones do not touch or else the constriction is so small that insufficient ammonia flows through. With the etching conditions used in the present work, many events with $Z \lesssim 50$ were missed in the CTA scan. Events near the edge of the plastic sheet tend to be missed because ammonia seeps in around the edges, obscuring the signals. For future work the most effective scanning procedure would appear to be one in which all events are

[11] P. B. Price and R. L. Fleischer, Radiation Effects 2, 291 (1970).

[12] J. Blok, J. S. Humphrey, and G. E. Nichols, Rev. Sci. Instr. 40, 509 (1969).

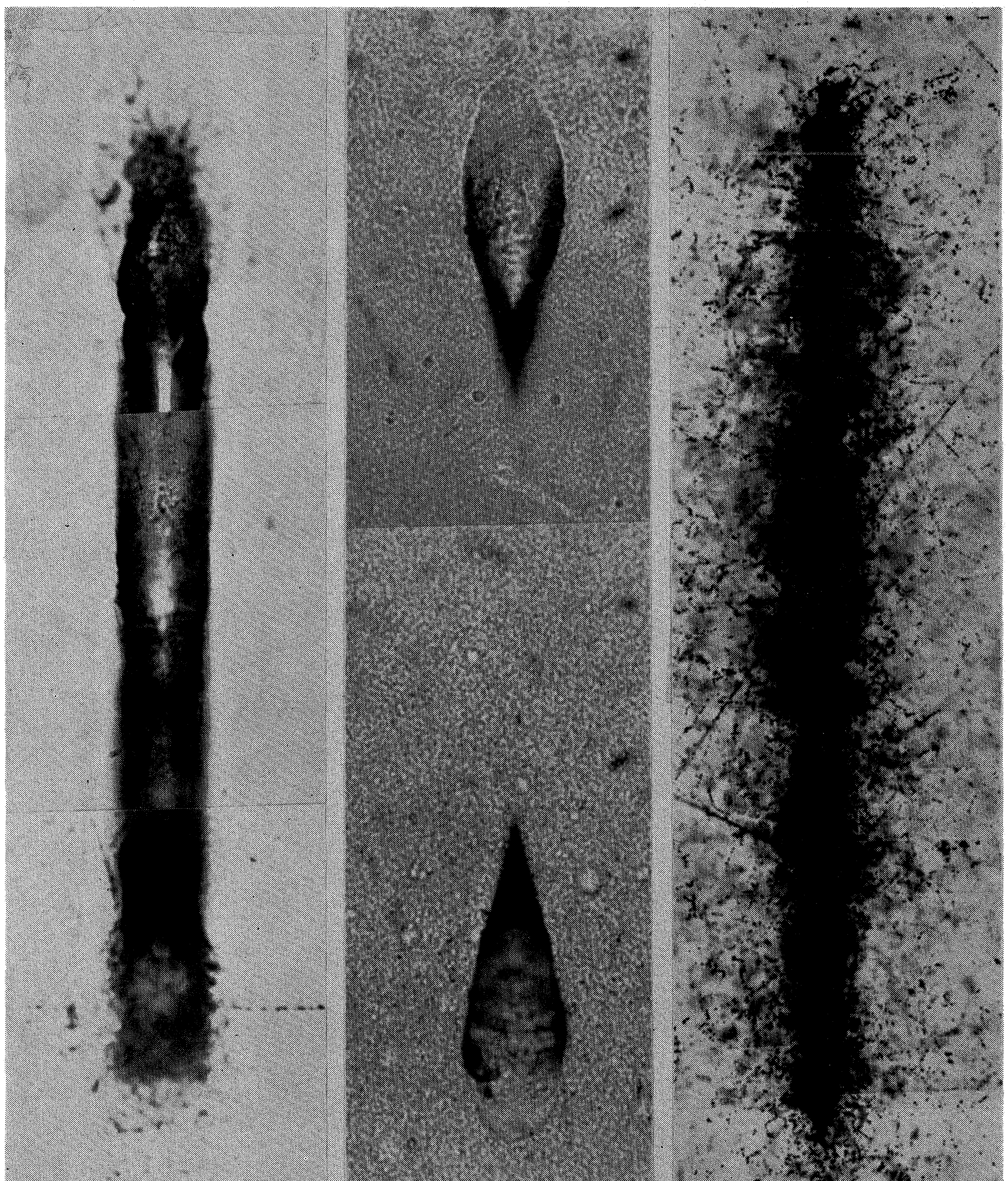

FIG. 2. Relativistic nucleus with $Z\approx 82$, whose track is depicted in Daicell cellulose nitrate, in Lexan, and in G-5 emulsion. The cones, chemically etched from opposite surfaces of the Lexan along the path of the particle, have lengths that indicate the ionization rate of the nucleus. The hollow, cylindrical etched track in Daicell is useful in locating the event rapidly by an ammonia-vapor process.

first found in Daicell by an ammonia method and are then checked in emulsion or CTA to see if their charge is acceptable. The efficiency of Daicell is low for detecting events with $Z\approx 28$ to ~ 30 but rapidly increases with Z and approaches unity for $Z\gtrsim 32$, if one excludes very shallow dip angles.

Two emulsion scans were made. The first was a rapid scan under low magnification which covered the whole area of the detector. The purpose of this scan was to find as many as possible of the heavy tracks quickly; as indicated earlier, such a scan was not fully efficient. A careful scan was made under a higher magnification over $\sim 6\ \mathrm{m}^2$ of the area to pick out tracks of nuclei above but as close to the Fe peak as possible for a restricted band of dip angles.

Events with $Z \gtrsim 55$ were traced into and measured in Lexan, which has a higher threshold than CTA but has been thoroughly studied and calibrated with stopping nuclei of $Z \approx 12$–30, as described in previous publications.[9,10] In this work the three Lexan layers were etched 48 h at 23°C in one part 6.25 *N* NaOH + one part ethanol. Track-etching rates were measured in these layers and charge values were assigned on the basis of the curves in Fig. 3, which were obtained as follows: We measured track-etching rates of many slowing nuclei with $Z \approx 12$–30 at various dip angles in Lexan sheets exposed in a separate flight over Fort Churchill. We make the assumption that track-etching rate depends on Z and β through an equation for ionization density,[9] which may be written

$$J = (Z_{\mathrm{eff}}^2/\beta^2)[\ln(\beta^2\gamma^2)+20-\beta^2-\delta(\beta)]. \quad (1)$$

The ionization density along its track in Lexan is thus the same for an extremely heavy, highly relativistic nucleus as for an Fe nucleus at some lower velocity that

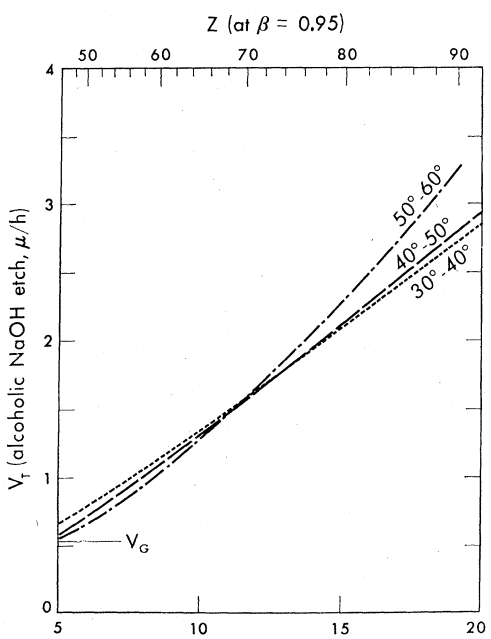

FIG. 3. Dependence of track-etch rate in Lexan on ionization density, determined from measurements of nuclei such as Si and Fe that came to rest in a stack exposed over Fort Churchill. Equation (1) was used to represent ionization density as a function of β and Z. The rate dependence is a slowly varying function of dip angle, a disadvantage that can be avoided in future by using a different etching process.

can be calculated from Eq. (1). For the effective charge in Lexan we used the semiempirical relation

$$Z_{\mathrm{eff}} = Z[1-\exp(-130\beta/Z^{2/3})], \quad (2)$$

determined by Pierce and Blann[13] for heavy ions with $\beta < 0.14$ slowing down in various solids including plastics. Even at relativistic energies, this relation predicts values of effective charge close to those calculated using theoretical equations of radiative capture and loss of electrons.[6]

The main contribution to track formation in plastics comes from low-energy delta rays, whose production rate goes as Z_{eff}^2 to a very good approximation, even for very large values of Z. No correction for higher-order terms in the Born approximation is needed, in contrast to the situation for tracks in emulsion, where a correction of as much as 2% is necessary.[6]

The additive constant 20 in Eq. (1) was chosen to give the best fit to data for nuclei with $Z = 12$–30 and $\beta = 0.1$–0.45. (Recent work[8] has shown that, with tracks etched in a new and improved chemical etchant, an extremely good fit can be made for all nuclei from $Z = 10$–92 and $\beta = 0.05$–0.95 with 20 replaced by a constant of the order of 60.)

We have also included a parameter $\delta(\beta)$, which takes into account the presumed reduction in ionization rate due to the polarization of the medium at relativistic velocity. This parameter is zero for $\beta \lesssim 0.8$ but represents a significant correction term at greater velocity. Sternheimer[14] has calculated its dependence on β. For a plastic medium he obtains

$$\delta = \begin{cases} 0 & \text{for } x < 0.14 \\ \ln(\beta^2\gamma^2) - 3.21 + 0.456(2.0 - X)^{2.78} & \text{for } 0.14 \leqq x \leqq 2.0 \\ \ln(\beta^2\gamma^2) - 3.21 & \text{for } x > 2.0, \end{cases} \quad (3)$$

where $x = 0.5 \log_{10}(e) \ln(\beta^2\gamma^2)$.

The most serious source of error in charge determination is our imperfect knowledge of β. There are two ways to assign a lower limit to β: by using the geomagnetic field as a velocity filter, and by looking for an increase in ionization rate as the particle goes through the stack. At the latitude of Palestine, Texas, a sizable fraction of nuclei with rigidities above the vertical cutoff rigidity, ~4.6 GV, can survive without nuclear interaction until their ionization rates are well above the minimum rates and can reach the detector before the balloon has reached ceiling altitude. The *shifting mechanism* allows us to distinguish events at altitude from those that occurred during ascent or descent. In this paper we reject nonaltitude events unless $Z > 60$, in which case we have studied them in order to improve our statistics for the heaviest nuclei, measured in Lexan and CTA.

[13] T. E. Pierce and M. Blann, University of Rochester Report No. 3591-8, 1968 (unpublished).
[14] R. M. Sternheimer, Phys. Rev. 103, 511 (1956).

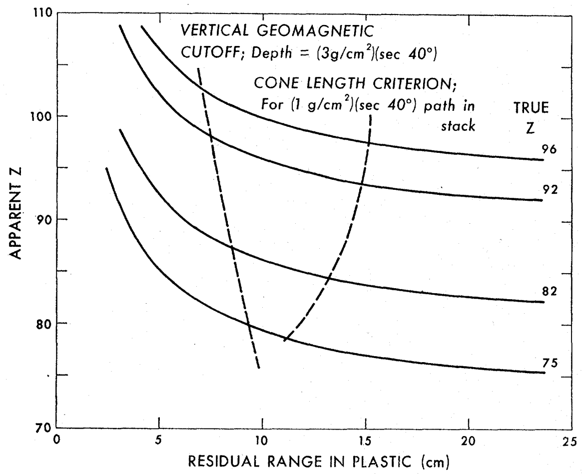

FIG. 4. Ability of Lexan to detect ionization changes of slowing heavy nuclei. For nuclei with $Z\gtrsim 75$, the criterion of no detectable change in cone length through the stack is more stringent than requiring that the event occur at altitude.

Even at ceiling altitude and at zenith angles smaller than 45°, there is a serious spread of velocities, ranging from $\beta\approx 1$ down to $\beta\approx 0.8$ in the worst possible case of nucleus with $Z\approx 96$ coming from the west. At a zenith angle of 45° the path length in our stack is equivalent in stopping power to $\sim$1.3 cm of plastic. For the heaviest nuclei the increase in track-etch rate in going through this path length should be detectable if the ionization is a few percent above minimum. Figure 4 shows how the track-etch rate in Lexan changes with residual range for some extremely heavy nuclei. The dashed curve labeled "cone length criterion" indicates the limits of our ability to detect a change of ionization in our 1-g/cm² stack thickness. Events with residual range less than indicated can thus be rejected as slow.

All altitude events with high Z that were measured in the three Lexan sheets were accepted because there was no perceptible change in etch rate in the three sheets. In addition all events with $Z>60$ that occurred during ascent were accepted for the same reason. Within only two CTA sheets, in contact with each other, it was not possible to make meaningful estimates of velocity of those nuclei too light to be detected in Lexan ($Z\lesssim 55$). All these events were accepted if they penetrated the entire stack. Future flights will have several CTA sheets at different positions in the stacks so that more restrictive lower limits on β can be set.

The value of β used in Eq. (1) in computing charges from track-etch-rate measurements was chosen so as to give the least-squares error in the assigned charge when integrating over the expected distribution in β. The effective value of β varies from $\sim$0.95 for nuclei with $Z\approx 40$ to $\sim$0.93 for the heaviest nuclei. To calculate the velocity spectrum at the detector, we assume (a) an energy spectrum $dN/d\gamma=A\gamma^{-2.5}$ outside of the influence of the earth's magnetic field, (b) a vertical cutoff rigidity of 4.6 GV, (c) an average zenith angle of 45°, (d) an azimuthal dependence of cutoff rigidity given by the Störmer cone, and (e) energy loss by ionization through the path length (3 g/cm²)(sec 45°). The difference between this best estimate of charge and the highest value it could have (at $\gamma\approx 8$) is about 3–4 units for the heaviest nuclei. This approach is treated in more detail in Ref. 6.

III. RESULTS

Figures 5–7 present measurements on events with $Z>40$ in several ways. CTA has not been calibrated in previous experiments. We have plotted etch rate in CTA as a function of charge deduced in Lexan (Fig. 5) and charge deduced in emulsion (Fig. 6). The dashed extension of the correlation curve in Fig. 5 was used to assign rough values of charge to those events that could be measured in CTA but not in Lexan. The extrapolation was made on the assumption that the etch rate in CTA is a linear function of ionization rate and thus is a parabolic function of Z.

Final charge assignment in plastics—entered in Fig. 7—was made by taking a weighted average of the charge deduced in one sheet of CTA and in the three sheets of Lexan. Many events with $Z>40$ are missing from the correlation plot in Fig. 7, either because the event could not be found in CTA or Lexan or because the CTA was overetched, with the result that the cones were connected. A total of 73 events with $Z\geqq 40$ were measured in both plastics and emulsions. The mean difference in charge assignments is $\Delta Z\approx 3$ units.

In the careful emulsion scan we attempted to pick up all tracks whose central density exceeded that of the Fe

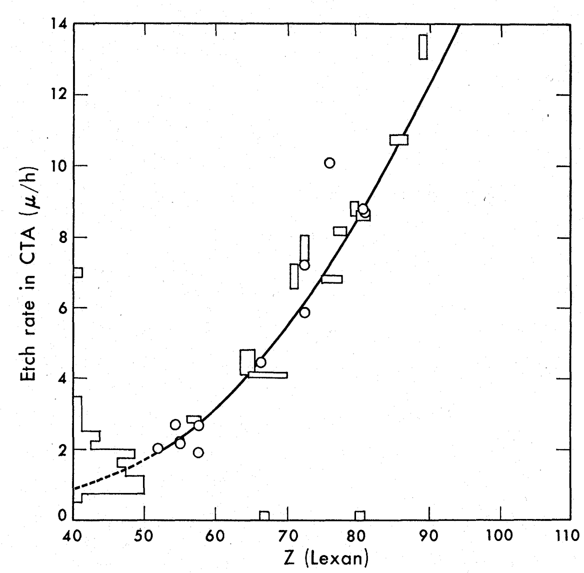

FIG. 5. Rate of lengthening of etch pits along tracks in CTA as a function of atomic number inferred from etch-pit measurements on the same events in Lexan. The histograms along the ordinate and abscissa pertain to events that were measured in only one of the two plastics.

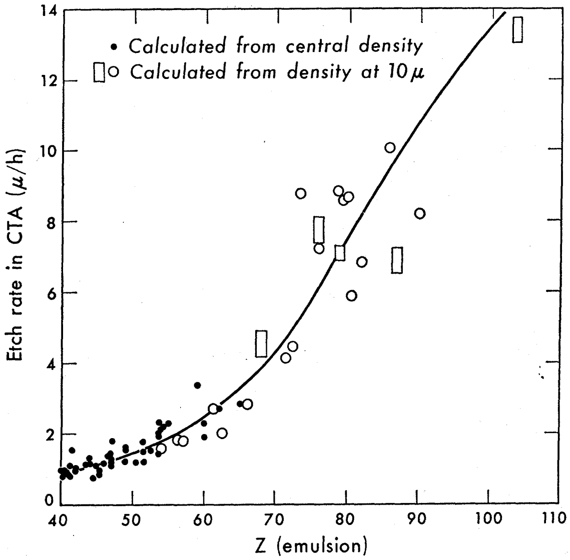

FIG. 6. Rate of lenthening of etch pits along tracks in CTA as a function of atomic number inferred from measurements on the same events in G-5 emulsion.

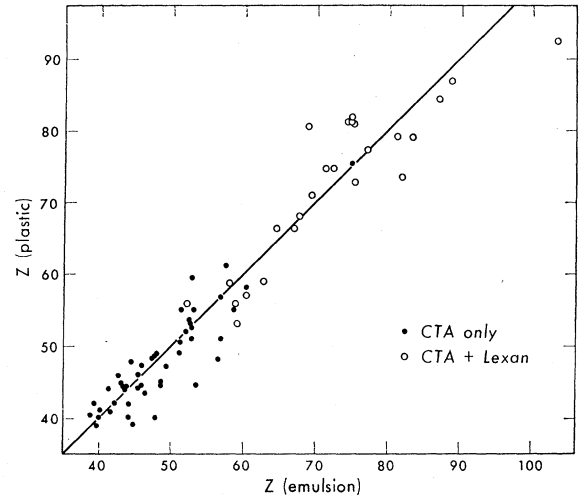

FIG. 7. Comparison of best charge assignment (weighted average) in plastics with charge assignment to the same events in G-5 emulsion.

peak by a factor of about 1.3. To be accepted for measurement, the zenith angle of the track had to lie between 27° and 56°. This restriction is necessary because of the difficulty of making adequate measurements on short steep tracks, and for tracks with large zenith angle, the geomagnetic shielding of particles coming from the west is reduced. The scanned area contained $\sim 3\times 10^5$ tracks of the Fe group with the appropriate zenith angles. Preliminary selection under the stereomicroscope gave ~ 1000 events that appeared heavier than Fe. Photodensitometry showed that 140 of these had a density greater than 1.3 times that of the Fe peak. From this sample, 28 tracks were produced by nuclei with charge estimated to lie between $36\leq Z\leq 48$, and are included in Fig. 8. This scan provided a significant fraction of the events on the correlation plot. Figure 8 shows separately the density distribution for altitude and ascent tracks.

Even with the limited zenith angle employed there is a serious spread in ionization values for each charge extending up to ~ 1.3 times the minimum value. For example, tracks with a density corresponding to that of a relativistic nucleus with $Z\sim 32$ can be produced by Ni coming from the west at the geomagnetic cutoff. Assuming the energy spectrum to be independent of charge, about 5% of all particles surveyed are expected to have an ionization sufficiently in excess of the minimum value so that the charge will be overestimated by an amount, ΔZ, given by $0.08\leq \Delta Z/Z\leq 0.16$. Thus, in the charge region just above Fe, where the abundances decrease very rapidly, the majority of tracks of a given ionization are likely to have been produced by particles of lower charge with rigidity near that at geomagnetic cutoff. We believe this to be the case with the tracks of lowest densities in Fig. 8. For $Z\gtrsim 36$ a reasonable estimate of charge can probably be obtained because the gradient in the abundance spectrum is likely to be much smaller than adjacent to the Fe peak.

Figure 9 is a histogram of all events with $Z\geqq 36$, constructed as follows.[15,16] For $Z>60$ all tracks, including those collected during ascent, are plotted. For $49\leqq Z\leqq 59$, altitude tracks with zenith angle less than 60° are plotted. For $36\leqq Z\leqq 48$, we restrict ourselves to the careful emulsion scan. For events measured in both plastics and emulsions, the mean has been taken as the best estimate of charge.

IV. DISCUSSION

A. Charge Resolution with Plastics

Prior to this work it had been established that slowing cosmic rays with $Z\gtrsim 12$ and with measurable residual range can be identified with Lexan detectors.[9] The present work demonstrates that Lexan detectors can also identify minimum ionizing nuclei with $Z\gtrsim 55$ and that cellulose triacetate detectors can identify minimum ionizing nuclei down to about $Z\approx 40$.

The fair agreement in charge assignment by plastic detectors and by G-5 emulsion is the most striking feature of our study. This agreement supports the hypothesis that the ionization Eq. (1) adequately represents the way in which Z and β contribute to track formation. Of course, it does not constitute a proof that each charge is well known, since it is possible that both detectors are subject to the same systematic errors. For example, at velocities above $\sim 0.7c$ the calculated

[15] A. G. W. Cameron, in *Origin and Distribution of the Elements*, edited by L. H. Ahrens (Pergamon, New York, 1968), p. 125.

[16] P. A. Seeger, W. A. Fowler, and D. D. Clayton, Astrophys. J. Suppl. **97**, 121 (1965).

velocity dependence of both detectors is about the same, so that a moderately slow nucleus (say, with $\beta \approx 0.8$) would have its charge overestimated in both detectors by about the same amount if β were taken to be higher. The stacks used in the work reported here were too thin to allow us to study the dependence of response on velocity. Recent results[8] on a stack of thickness 10 g/cm^2 show that Eq. (1), with the constant increased from 20 to 62, provides an excellent representation of the velocity dependence up to at least $\beta \approx 0.7$ and show that extremely heavy nuclei of known residual range can be identified with remarkable precision.

A second possible cause of the spread in charge assignments may be changes in ambient conditions during the flight. Plastics and emulsions probably respond differently to changes in humidity, atmospheric pressure, and temperature. Sealing the detectors in a controlled atmosphere may decrease the spread.

Due to uncertainties in the calibration of the plastics with low-energy cosmic rays of charge $12 \leq Z \leq 30$, all charge assignments in the plastics processed in an alcoholic NaOH solution are uncertain by $\sim 2\%$ in addition to any uncertainties resulting from imprecise knowledge of β. The main cause of this uncertainty is the unfortunate dependence of response on dip angle with the alcoholic NaOH solution. This necessitates a separate calibration at many dip angles. This uncertainty can be drastically diminished by using a different chemical-etching treatment recently developed by Peterson.[17] Our studies on the 10-g/cm^2 stack, using this new treatment, show that the uncertainty is considerably reduced.[8]

Plastic detectors may be subject to an additional small *systematic* error in charge assignment resulting from the necessity to calibrate on slow nuclei with $12 \leq Z \leq 30$. The velocity dependence of the effective charge used in

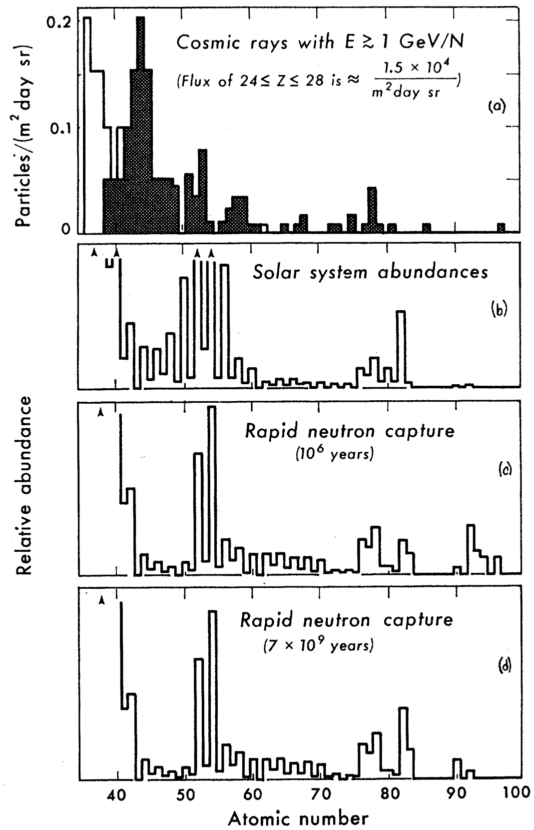

FIG. 9. (a) Charge spectrum found in this work for cosmic rays with $Z \geq 36$. The shaded events were measured in both plastics and emulsions and are assigned the mean value of the charges determined in the two kinds of detectors. (b) Abundances of elements in the solar system (Ref. 15). (c) Abundances of elements $\sim 10^6$ yr after synthesis by rapid neutron capture (Ref. 16). (d) Abundances of elements $\sim 7 \times 10^9$ yr after synthesis by rapid neutron capture.

Eq. (1) may be in error. For a particular low-energy ion, such as Fe, the velocity at which its ionization rate matches that of a minimum-ionizing very heavy nucleus of charge Z varies approximately inversely with Z and its effective charge decreases as its velocity decreases. For minimum-ionizing nuclei lighter than Pb, the corresponding effective charge of a slow Fe with the same ionization rate is very close to 26, according to Eq. (2). For the heaviest nucleus studied, the charge assigned with plastic is ~ 92 and the corresponding effective charge of a slow Fe with the same ionization rate is 24.7 from Eq. (2). If we say that Eq. (2) is wrong and that the effective charge of the Fe is actually ~ 26 (a very unlikely possibility), the charge of the heavy nucleus goes up to $Z=97$. The charges of lighter nuclei would also increase, but by a much smaller amount. The determination of effective charges of heavy ions is a difficult problem that may not be solved until high-energy heavy-ion accelerators are available.

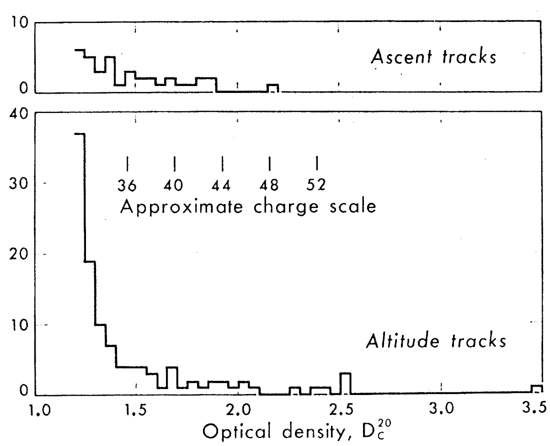

FIG. 8. Result of a careful scan of ~ 6 m^2 of emulsion, accepting only tracks with zenith angle between 27° and 56°.

[17] D. D. Peterson, Rev. Sci. Instr. **41**, 1254 (1970).

B. Transuranium Cosmic Rays?

Prior to the present work, one nucleus had been identified[6] in emulsions as having $Z>92$. Because of their significance for models of cosmic-ray origin and of nuclear structure, it is extremely important to have independent evidence for the existence of transuranium cosmic rays. Our heaviest event is one such candidate, the only one so far studied simultaneously in three types of detectors. The assigned charges are ~ 104 in emulsion, ~ 92 in Lexan, and ~ 93 in cellulose triacetate, all based on the assumption of $\beta \approx 0.93$. If the actual velocity were 0.995, the charges would go up to 107 in emulsion, to 96 in Lexan, and to 97 in cellulose triacetate. If the velocity were as low as 0.92, the charges would go down by less than 1 unit in all three detectors. No lower velocity than this would be consistent with the absence of a change in response from the top to the bottom sheet of Lexan.

From the known nuclides with $Z>96$ and from nuclear systematics it seems unlikely that there can exist nuclides with $Z\sim 104$–107 with sufficiently long half-lives to survive as cosmic rays. In view of the low charge assignments in plastics, it seems more likely that this event was one of the long-lived radionuclides with $Z\leq 96$ and $\beta \sim 0.95$ than that it was a superheavy nuclide with $Z\sim 110$–114. Both Cm^{247} and Pu^{244} are long-lived candidates. Although one cannot rule out completely the possibility that it is as light as uranium ($Z=92$) with $\beta \approx 0.93$, one is then forced to assume that the emulsion behaved in an unexpected and not understood way. We believe the best interpretation to be that $Z\approx 96$, $\beta \approx 0.95$, with the signal in plastics being ~ 1 standard deviation low and the signal in the emulsion being ~ 2 standard deviations high.

Clearly it is important in future flights to obtain more examples of possible transuranium nuclei that can be studied with both techniques. The problem of velocity spread can be avoided in future either by flying at a lower geomagnetic latitude or by flying at a sufficiently high geomagnetic latitude for heavy nuclei to come to rest within the stack.[8]

C. Origin of Heavy Cosmic Rays

Although, because of velocity uncertainty, the resolution for this flight is not adequate to determine individual charges, by grouping the apparent charges in this and in all experiments to date (summarized in Fig. 10), the ratio $[Z>83]/[70\leqq Z\leqq 83]$ turns out to be of the order of 0.3. This high apparent ratio is very significant: It cannot be attributed to the velocity spectrum of a pronounced peak at Pb or the Pt group. Instead, it strongly supports the previous suggestion of an *r*-process origin of the cosmic rays[1,6] with a lifetime of $\leqq 10^7$ yr, as can be inferred from the graphs in Fig. 9. What appears to be an excess of nuclei of the Pt group, $Z=76$–78, over nuclei of the Pb group $Z=81$–83, also

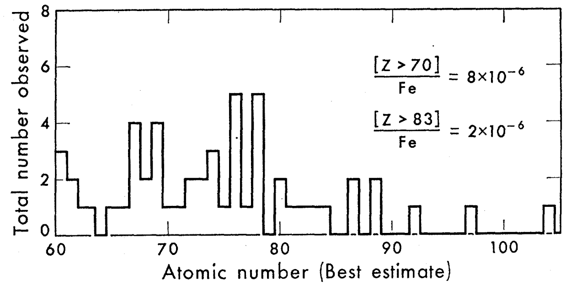

FIG. 10. Summary of all published data (Refs. 1–8) for cosmic rays with $Z\geqq 60$.

suggests that radioactive decay of nuclei with shorter half-lives than those of U and Th is not complete.

We believe these results provide considerable insight into the 50-year-old question of the origin of the nuclear component of the cosmic radiation. Because of their very great age, any contribution of primordial and of extragalactic nuclei to the ultra-heavy cosmic rays reaching our solar system must be small. Because of their composition [like that in Fig. 9(b)], the contribution of nuclei that originated in the interstellar gas and were accelerated to cosmic-ray energies must be small. Likewise, pulsars cannot make a major contribution to the ultra-heavy cosmic rays because the composition of their envelope is mainly Fe plus a few lighter elements.

Our abundance distribution and our lifetime limit point to supernova explosions in our own galaxy as the birthplace of most of the heavy cosmic rays that reach us.

V. CONCLUSIONS

(1) Assignments of charges to relativistic nuclei with $Z>40$ are generally similar in Lexan, CTA, and *G*-5 emulsion. The mean deviation in charge assignment between plastic and emulsion is ≈ 3 units.

(2) Charges can be identified with much greater precision either by flying stacks at lower latitudes, so that the range of velocities is more restricted than in the present work, or by flying at high latitude with a sufficiently thick stack to study slowing nuclei.[8]

(3) Because of their stability and insensitivity to lightly ionizing radiation, plastic detectors should be very useful for charge identification during prolonged exposures in Skylab or other space stations.

(4) One possible transuranium nucleus has been studied in Lexan, CTA, and *G*-5 emulsion. The best estimate of its charge is $Z\approx 96$, with $\beta \approx 0.95$.

(5) Combining all available data, the abundance ratio $[Z>83]/[70\leqq Z\leqq 83]\approx 0.3$, based on 33 events. This ratio, together with the over-all charge distribution of cosmic rays with $Z>40$, is consistent with the expected distribution from rapid neutron synthesis after $\sim 10^6$ yr. It is not consistent with a lifetime $\gg 10^6$ yr, nor with slow neutron synthesis, nor with solar-system

abundances. The major source of the heavy cosmic rays is supernova explosions in our galaxy.

(6) In order to study the extremely important charge region $Z > 92$, experiments with area-time factors much greater than 100 m^2 days will be required.

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1970 Solar Eclipse as "Seen" by a Torsion Pendulum

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During the solar eclipse of 7 March 1970, readings were taken and recorded electronically of the times required for the torsion pendulum to rotate through a given fixed part of its path, involving both clockwise and counterclockwise motions, on its first swing from rest. Significant variations in these times were observed during the course of the eclipse as well as in the hours just preceding and just following the eclipse itself. Between the onset of the eclipse and its midpoint there is a steady increase in the observed times. After the midpoint the times decrease suddenly and level off promptly to values considerably greater than those observed before the eclipse. Furthermore, before the eclipse there is a periodic variation in these times. This strange periodicity was essentially repeated two weeks later at the same hours, though the actual values were somewhat greater than the earlier ones. These increases in actual values exceed by a factor of 10^6 those that can be explained by the attraction of the moon due to its change in position relative to the sun and earth. All this leads to the conclusion that classical gravitational theory needs to be modified to interpret these experimental facts.

INTRODUCTION

In this paper a study is made of the variations in behavior of a torsion pendulum during the solar eclipse of 7 March 1970. The torsion pendulum is essentially the same as that used in studying the effect of added weights on its period,[1,2] but with modifications discussed later in this paper. With this setup, when the pendulum is started reproducibly from rest in a precisely defined release position, the time of traversing a constant portion of its path is timed accurately and recorded automatically. To do this, light from a fixed source is reflected from a mirror attached to the torus to fall on a photocell. Over a preamplifier the latter starts a crystal-controlled counter as the light beam travels clockwise across the photocell and stops it on its return counterclockwise trip, to record the times between these two passages of the light beam across the photocell. This gives recordings of the times used in traversing a constant fixed part of the total vibration path of the oscillating torus on the first swing from rest.

Some improvements had been made in the apparatus since the previous work, which increased its precision still further. Notably, a stronger light source was used which made it possible to narrow the vertical slit limiting the width of the light beam falling on the photocell. Preamplification of the signal received by the photocell and other minor changes (such as a constant voltage transformer for a uniform power supply and a nonferrous and nonmetallic manual release mechanism) were made to assure safe and reliable action of the electronic timing and printout mechanism. Earlier observations during other eclipses, taken before these needed improvements, agree qualitatively with the present results, but are not good enough for quantitative comparison.

Furthermore, it was possible to keep the temperature around the isoelastic Ni-Span "C" suspension wire at 21.7°C with a fluctuation of only ±0.6°C. This suspension has been kept under the given load for some 17

[1] E. J. Saxl and M. Allen, J. Appl. Phys. **40**, 2499 (1969).
[2] M. Allen and E. J. Saxl, J. Appl. Phys. **40**, 2505 (1969).

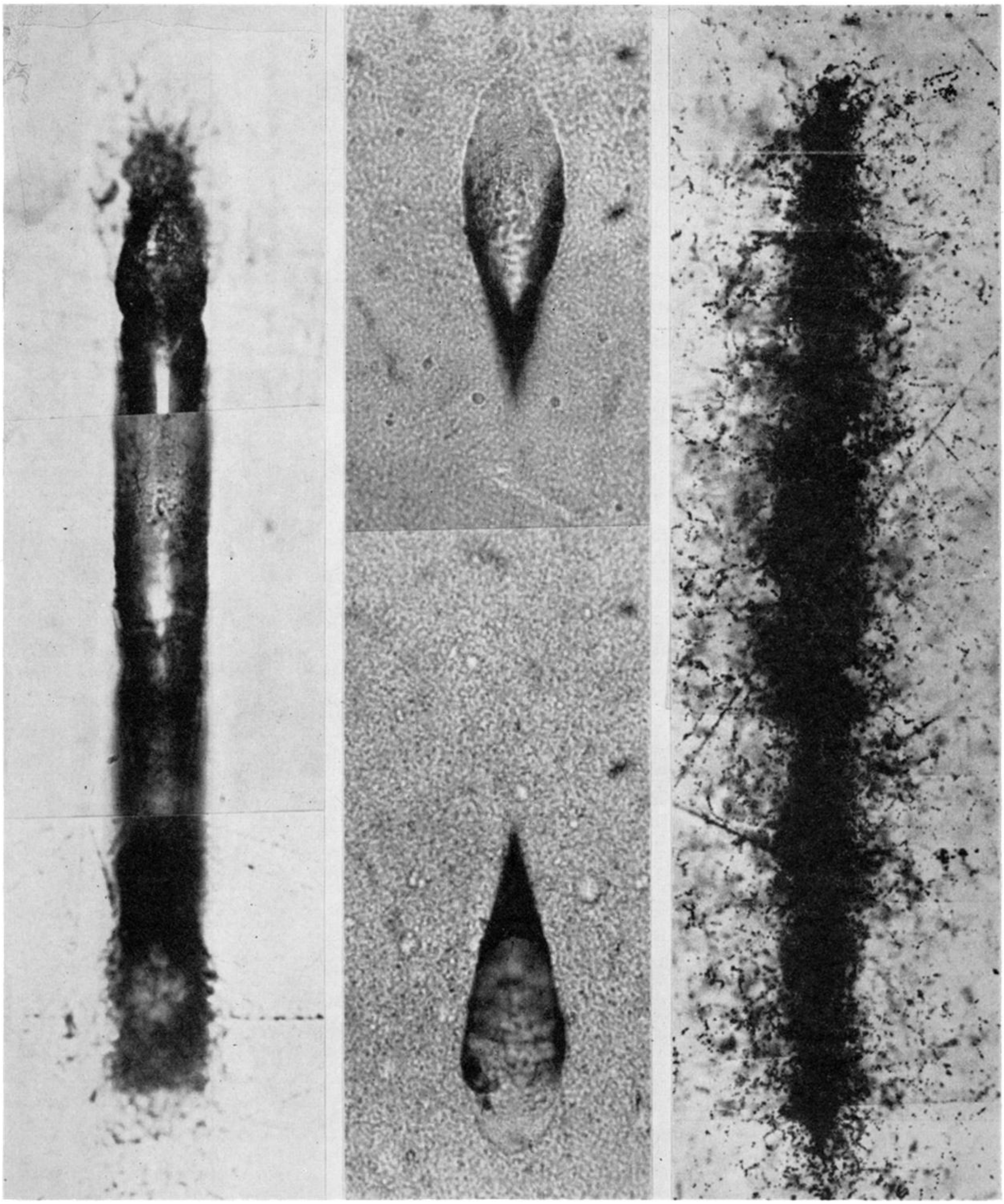

FIG. 2. Relativistic nucleus with $Z \approx 82$, whose track is depicted in Daicell cellulose nitrate, in Lexan, and in G-5 emulsion. The cones, chemically etched from opposite surfaces of the Lexan along the path of the particle, have lengths that indicate the ionization rate of the nucleus. The hollow, cylindrical etched track in Daicell is useful in locating the event rapidly by an ammonia-vapor process.