

Ultraheavy cosmic rays

The distribution of the high-Z nuclei, the youngest elements in the Galaxy, can help us understand the synthesis of matter in exploding stars and its interactions en route to Earth.

Martin H. Israel, P. Buford Price and C. Jake Waddington

Ultraheavy cosmic-ray nuclei, those with atomic number over thirty, constitute less than about one in 10^7 of the relativistic particles that stream through our solar system, yet they promise to lead to a major contribution in our understanding of the complex phenomena of the cosmic-ray gas that pervades interstellar space. The study of these nuclei should advance our understanding of the sources of cosmic rays as well as of the nature of the physical processes that influence the particles after their acceleration. This work is greatly accelerating with the advent of satellite experiments, such as the Skylab mission pictured in figure 1.

Discovery

Because of the rarity of these ultraheavy nuclei it was not until 1965, when fossil cosmic-ray tracks were first seen in meteorites,¹ that their existence was established. The transparent crystals within stony meteorites, though completely insensitive to charged particles with atomic number less than about twenty, have become riddled with tracks of iron and heavier nuclei during the tens of millions of years they were exposed to cosmic radiation while orbiting the sun. These tracks can be revealed by a chemical etching technique, as shown in the micrograph of figure 2, in which tracks of ultraheavy as well as iron nuclei are visible.

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In 1967, what was then considered a giant array of nuclear emulsions, 4.5 m^2 in area, was carried on a stratospheric balloon to an altitude of 37 km, where it floated for 14.5 hours and recorded the first tracks of contemporary ultraheavy cosmic rays.² Two of these tracks were identified as due to nuclei near thorium or uranium in atomic number, demonstrating that the composition of cosmic rays spans the known periodic table.

Since then, large-area detectors flown on high altitude balloons and in the Skylab spacecraft have recorded several hundred ultraheavy cosmic-ray nuclei. Most of these particles have been measured in the recently developed plastic track detectors, which are used to identify heavy charged particles by measuring the length of etch pits formed along particle trajectories when the plastics are immersed in a hot solution of sodium hydroxide.³ Measurements in nuclear emulsions have also contributed, and large-area electronic detectors are beginning to be used. Figure 3 shows the change in appearance of the track of a nucleus with $Z \approx 78$ that slows down and undergoes a nuclear interaction as it passes through many sheets of Lexan plastic detector, alternating with iron foil, and a layer of nuclear emulsion. The length of the etch pits revealed at the top and bottom of each Lexan sheet is roughly proportional to Z^4/v^4 , where v is the particle velocity, and so increases as the particle slows down. In the iron layer between the plastic sheets L18 and L19, the primary had a nuclear collision and the largest fragment, with $Z = 52$, leaves a track as it continues to slow down, coming to rest in the iron layer after L21.

The results to date give a crude picture of the composition of the ultraheavy cosmic rays at energies between several hundred and several thousand MeV/amu. We see relative abundances that are broadly similar to those of the matter in the solar system—but with tantalizing differences. In this article we shall summarize these results and indicate the prospects for obtaining improved data. Let us first, however, consider the question of why it is of such interest to study these nuclei.

Astrophysical significance

To appreciate the significance of the different nuclei that we find in the cosmic radiation we must consider the various physical processes that have influenced the composition. This means that we have to extrapolate back in both space and time from our observations near Earth to the different stages in the life history of the particles. In terms of our current models, we find three intervals of principal interest: Before we observe the nuclei they have spent some time as energetic particles propagating through the *interstellar medium*; prior to that they were accelerated in some *source* region, which is generally pictured as being localized in space; initially, before or possibly even during the acceleration, the nuclei were *synthesized* from lighter elements.

First we have to extrapolate our observations through the interstellar medium back to the regions where the particles are accelerated, the cosmic-ray sources. Data on the nuclei of iron and lower charges, which make up the bulk of the cosmic radiation, are well represented by models of the process of prop-



Inside the Skylab orbiting workshop during a space mission, bearded astronaut Bill Pogue sits in front of the array of detectors of ultraheavy cosmic rays that line the thin outer wall of the craft. Each of the 36 white cloth packets (some are marked "Transuranic cosmic rays") contain an 18 cm X 20 cm X 1 cm stack of Lexan plastic. NASA photograph. Figure 1



Etched olivine crystal from a stony-iron meteorite. The long tracks are due to ultraheavy cosmic rays ($Z > 30$). The densely clustered short tracks are those of iron nuclei ($Z = 26$); they are visible only near their intersections with tracks of ultraheavies. Nuclei lighter than iron do not produce etchable tracks in these crystals. Photo: D. Lal. Figure 2

agation in the interstellar medium.⁴ In our current picture of this propagation process, the particles diffuse within a trapping volume that is somewhat leaky, so that the distribution of path lengths, and thus presumably of the matter traversed, is well approximated by an exponential. Such a path-length distribution, when combined with the mass dependence of the mean free path for nuclear interactions, implies that the nuclei we detect have traversed a mean amount of matter that is less for the heavier than for the lighter nuclei. Thus we assume that the nuclei of carbon and oxygen that we see have traversed an average of some 5 gm/cm² of interstellar matter, whereas the lead and uranium nuclei have traversed only about 1 gm/cm².

For many of the less abundant elements, most of the nuclei that we observe are secondaries resulting from fragmentation of heavier nuclei in collisions with the interstellar gas. For the more abundant elements, where a significant part of the observed flux is primary, these propagation considerations permit accurate deductions about their relative abundances as they leave the sources. These relative source abundances are generally quite similar to the relative abundances of the corresponding elements in the nebula that condensed to form our solar system, as reflected today in the solar photosphere and certain undifferentiated meteorites.⁵ There are, however, small but significant differences between the solar-system abundances and those of the cosmic-ray source. These differences provide the astrophysicist with clues about the source region.

The source region

In the second stage of extrapolation we attempt to deduce the abundances of the nuclei in the region of the source before acceleration. Since we do not have a clear understanding of the acceleration mechanisms that are involved, this step is necessarily quite uncertain. In the Sun, the only example of an astrophysical particle accelerator that we can examine at all closely, we find evidence for acceleration mechanisms at low energies, below about 20 MeV/amu, that produce preferential acceleration of heavier nuclei in solar flares. Similarly, the differences between the cosmic-ray source abundances of the lighter elements (iron and below) and the abundances in the solar system show a good correlation with the first ionization potential. This correlation can be interpreted in terms of an injection process in which elements that are easier to ionize are preferentially accelerated.

However, these abundance differences correlate equally well with atomic number. This correlation could be interpreted either as a preferential accel-

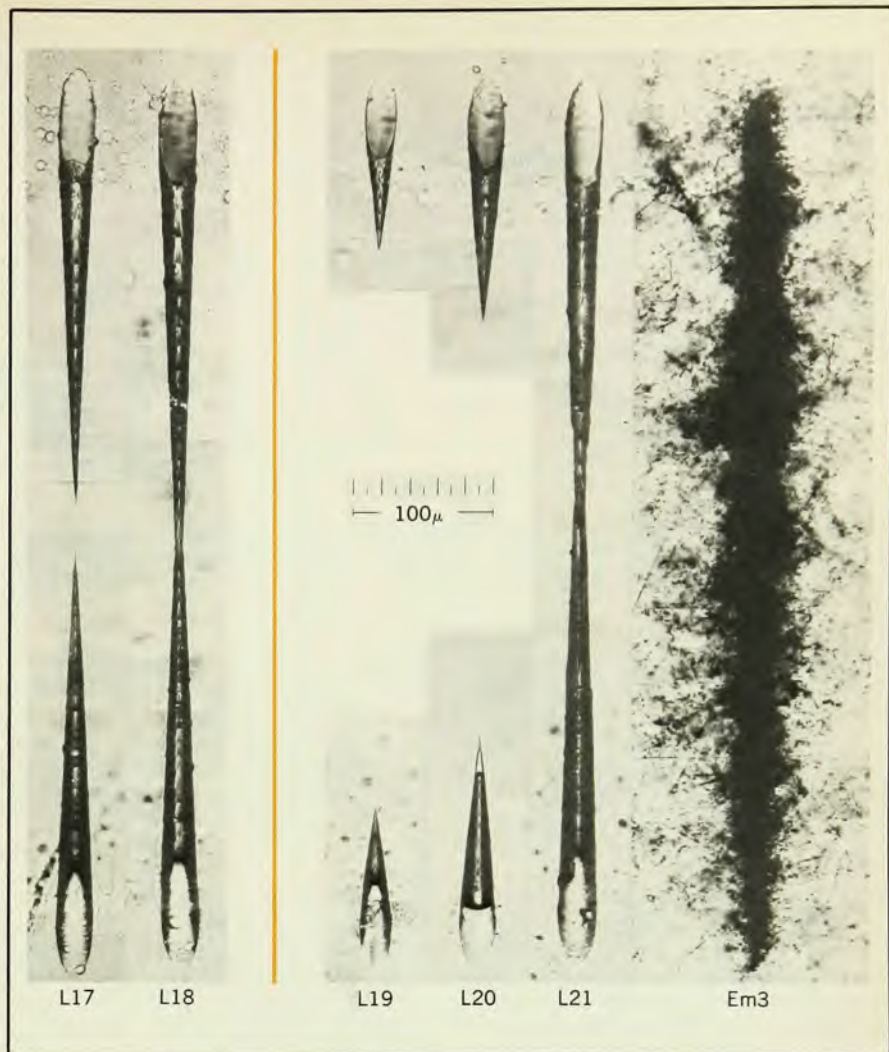
eration of heavier nuclei, analogous to that seen in the Sun at lower energies, or as indicative of differences between the composition of solar matter and the matter in the cosmic-ray source region. This problem of distortion of the composition by the acceleration process is one that we hope to be able to study with the ultraheavy cosmic rays. When we have measured relative abundances of individual elements in the last two-thirds of the periodic table as well as they have been measured to date in the first third, we will have many more primary nuclides with which to test hypotheses about the correlations of abundance with ionization potential or charge.

Synthesis of the nuclei

Our final stage of extrapolation is to attempt to deduce how the matter in the source was formed and its composition determined, so as to obtain a better understanding of the nature of the source itself. The theory of the nucleosynthesis of complex nuclides under a wide range of physical conditions has been advanced to a stage where we can be reasonably confident as to its validity. By determining the composition of a sample of matter we can therefore deduce some of the physical parameters that should have existed when it was being synthesized. In the case of cosmic-ray nuclei this opens the exciting possibility that we can examine matter that was synthesized as recently as in the past few million years in objects such as supernovae.

The nucleosynthesis of ultraheavy nuclei has a peculiarly simple history because there are only two important production processes, either slow or rapid capture of neutrons by nuclei.⁶ These two, known as the s and r processes, account for the overwhelming majority of material with atomic mass greater than about 70. Only a few rare, proton-rich nuclides cannot be produced by these processes; the production of these is attributed to a poorly understood mechanism known as the p process.

The r process occurs on time scales of a few seconds in explosive events, presumably supernovae. In a rapid flood of neutrons, unstable nuclides very rich in neutrons are created; these subsequently beta-decay, yielding the most neutron-rich stable nuclide at each atomic weight. The s process occurs over thousands of years, and is probably located in stars that are highly evolved, but not exploding. The density of neutrons is low enough that, after formation of an unstable nuclide by neutron capture, there is time for it to beta-decay to a stable nuclide before the next neutron capture. Some nuclides can be manufactured only in the r process, others only in the s process, and others yet,



A 700-MeV/nucleon cosmic ray with $Z = 78$ is captured by sheets of Lexan (L), iron foil (colored bar), and nuclear emulsion (Em), which alternate in the detector. The cones in the plastic sheets are etch pits, the lengths of which vary with the inverse fourth power of the particle velocity, therefore elongating as the ultraheavy nucleus slows down. Here the primary had a nuclear collision in the iron layer between L18 and L19; the largest fragment, with $Z = 52$, leaves a track as it continues to slow down. Photo: P. H. Fowler.

Figure 3

in both. The processes of nucleosynthesis that are possible are given for a partial chart of the nuclides in figure 4; only nuclides of half-life greater than 10^6 years are shown there.

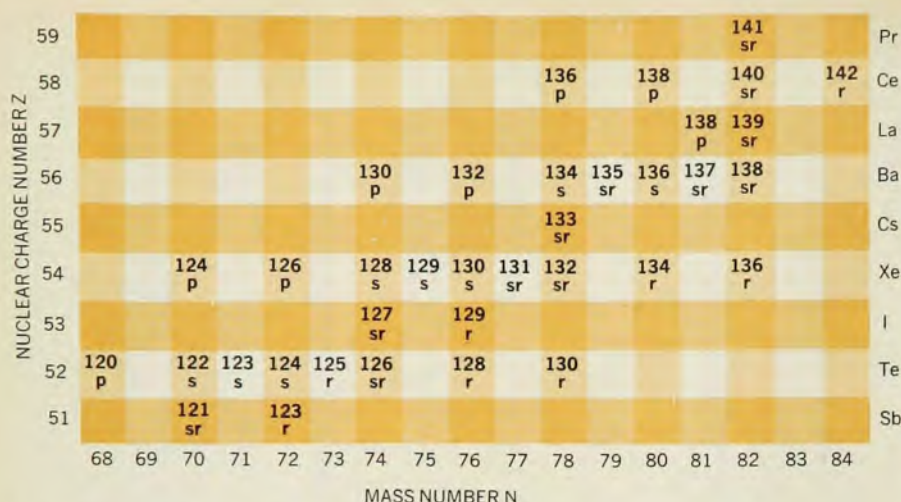
The theory of nucleosynthesis via the s process is well understood, and the neutron capture cross sections well measured; so it is possible to calculate the s-process yield as a function of mass number with some confidence. For nuclides that can be produced by both the r and s process one can deduce the fraction of the observed solar-system abundance due to the s process by using this s-process yield function to interpolate between the observed abundances of nuclides of purely s-process origin.

The remaining observed abundances of these mixed nuclei are then attributed to the r process. By summing over nuclides of the same element, we can then calculate the contribution each process makes to the observed solar-

system abundances. Figure 5 demonstrates that the two production processes give elemental abundances with distinctive features. Particularly striking are the peaks at tellurium and xenon and around platinum for the r process and the peaks in the region of krypton, strontium and zirconium, and at barium and lead for the s process. It must be emphasized that the s process terminates at bismuth because of the lack of stable nuclides at atomic number 84 and higher; hence any elements heavier than bismuth must be a consequence of the r process.

Theoretical predictions

The mixture of r- and s-process nuclides in the solar system can be regarded as typical of matter in normal main-sequence stars and thus of the overwhelming bulk of matter in the Galaxy. The fundamental question in a study of the ultraheavy cosmic rays is whether



On this portion of the chart of the nuclides, only stable nuclides (those with half-lives over one million years) are indicated. The letters p, r and s refer to the processes of nucleosynthesis, explained in the text, that can create each nuclide. Figure 4

they show a mixture different from this, and if they do, what the difference tells us about the source. If we assume the currently popular scenario that has the cosmic rays being accelerated during the explosive stage of a supernova with a great deal of nucleosynthesis occurring in a short time, then we would expect the ultraheavy nuclei to show a strong preponderance of r-process nuclei. At the other extreme, if the acceleration mechanism acts on normal stellar matter that was synthesized eons before, then we would expect a normal mixture of s- and r-process nuclei.

It has recently been suggested⁷ that cosmic rays come from massive stars (M greater than about eight solar masses) that have exploded, leaving as a remnant a rotating neutron star, that is, a pulsar, which supplies the power for the cosmic rays. The composition of the cosmic rays would then consist of some mix of elements synthesized during the explosion (such as neon, magnesium, silicon, iron and r-process elements) together with some old material from the

envelope (such as hydrogen, helium, carbon, oxygen and s-process elements).

Among the ultraheavy cosmic rays, those heavier than bismuth are of special importance. The relative abundances of these unstable nuclei indicate the time since their nucleosynthesis. These cosmic-ray nuclei are probably young, in the sense that they were accelerated no more than a few million years ago. If we postulate that their nucleosynthesis occurred in the same event in which they were accelerated, we would expect a very different composition from that of the several-billion-year-old material that formed the solar system.

Figure 6 shows how several of the elemental abundances are expected to vary with time after r-process production.⁸ The abundance of the transbismuth group compared to lighter stable nuclei, or the relative abundances of individual transbismuth elements, should permit a clear distinction between a lifetime of a few million years, typical of that expected in the explosive source model, and

one of billions of years. Unfortunately, the sensitivity is low in the most interesting period, between a few times 10^5 and a few times 10^6 years, with most of the element ratios remaining roughly constant.

Such a measurement of the cosmic-ray lifetime can be compared with those that should shortly be provided by isotope studies of the lighter radioactive nuclei, such as Be^{10} , that give a measure of the duration of cosmic-ray propagation in the interstellar medium.⁴

If the ultraheavy cosmic rays are indeed young nuclei that have been synthesized and accelerated in explosive r-process events, then there is at least a theoretical possibility that some nuclei might be found in the so-called "island of stability" predicted⁹ by theories of nuclear structure to be around $N = 184$, and $Z = 114$. Nuclides in this region have never been observed on Earth, but they could have half-lives comparable to the cosmic-ray lifetime and hence, if produced might be observable in the cosmic rays. Some theorists, however, believe that these half-lives would be much shorter than the cosmic-ray lifetime.^{10,11}

Experimental results

The table on this page summarizes ultraheavy cosmic-ray experiments to date. The electronic system was a device, 1 m^2 in collection area, consisting of ionization chambers and a Cerenkov counter.¹² Its geometry factor was $1 \text{ m}^2\text{-steradian}$. This quantity is

$$\int A \cos \theta \, d\Omega$$

where θ is the angle from the normal and $d\Omega$ the element of solid angle, and the integral is taken over those angles for which a particle passes through the entire depth of the detector. Both of these detectors give signals proportional to Z^2 but depending very differently on particle velocity; as a result charge and velocity are determined. Although this device was large compared to previous electronic detectors, its exposure is still small compared to that of plastic and emulsion track detectors and so it contributes data only for the relatively more abundant nuclei below charge 50.

The plastics and emulsions have produced almost all the data above charge 50. Both detectors produce a signal that increases with the particle's ionization rate, which is approximately proportional to Z^2/v^2 . In the case of the Lexan detector, the response is particularly simple: The etch rate, which is the rate of increase of length of the etch pit with etching time, is, as mentioned above, approximately proportional to Z^4/v^4 . Below charge 50, most of the data from these track detectors suffers from small and uncertain collection efficiency. This is because, in order to avoid a huge background from the very

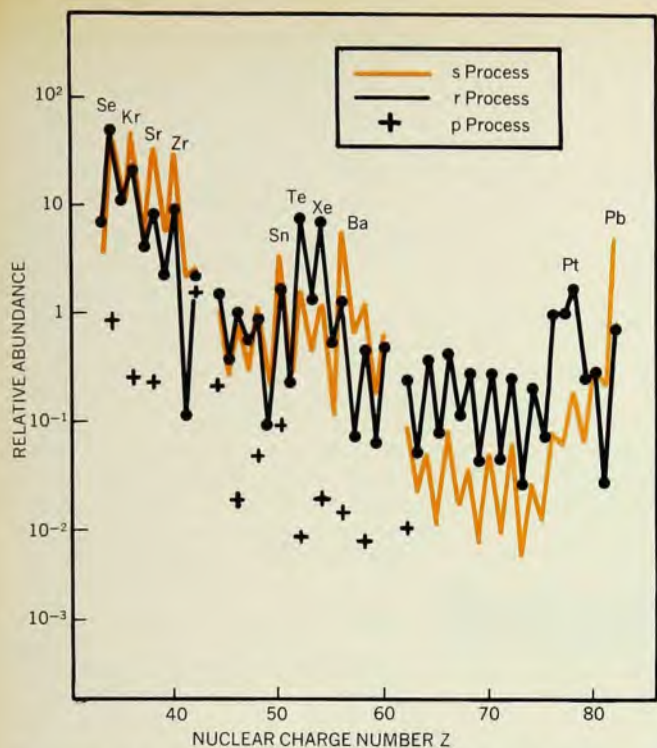
Ultraheavy cosmic-ray experiments

Flights	Reference	Exposure ($\text{m}^2\text{-ster-days}$)	Number of events for which Z is:			
			32-50	50-70	70-83	≥ 86
Electronic detector	18	4	50	1	0	0
All Texas, plastics and emulsion	2,13	332	b	173	50	11
North US, plastics and emulsion	15	226	32	109	47	12
SkyLab, Lexan	17	400 (a)	c	c	85	5-8

a The SkyLab exposure was under only 1 gm/cm^2 of aluminum, as compared to about 4 gm/cm^2 for the balloon flights in the first three lines. When the effect of reduced overlying matter is included, effective SkyLab exposure is equivalent to about 1.4 times the total in the table.

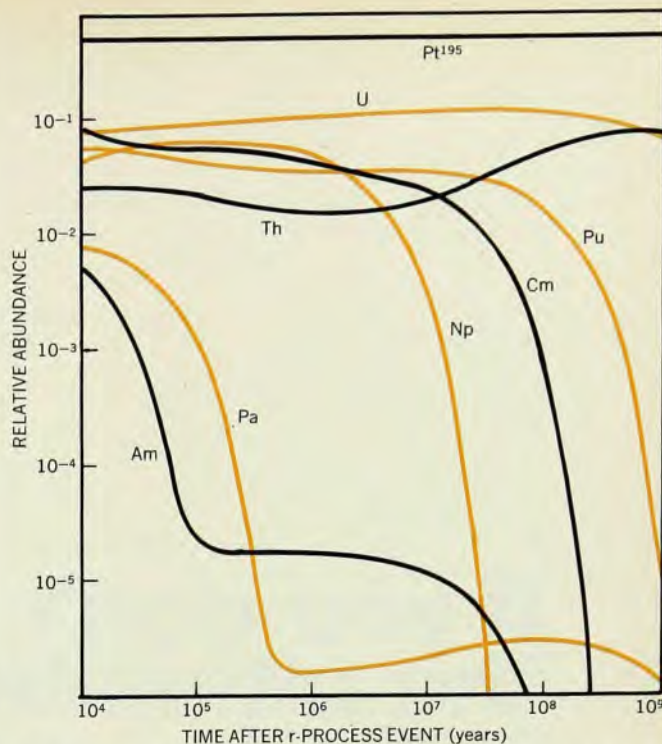
b Results unreliable¹⁴ because of contamination by slow nuclei of $Z \leq 26$.

c Lexan sensitivity is reduced below charge 70.



Decomposition of the abundances of the elements in the solar system into the contributions that each of the processes, s, r and p, make to the nucleosynthesis of each element. The abundances are normalized to $\text{Fe} = 10^6$. (Reference 5).

Figure 5



The abundances of the actinide elements from thorium to curium as a function of time after an r-process event in an explosive source, normalized to $\text{Pt}^{195} = 0.473$. The lead group (thallium, lead and bismuth) rises from 0.3 to 0.4 from 10^4 to 10^8 yr. (Ref. 8).

Figure 6

abundant iron and neighboring nuclei, the arrays are designed to be insensitive in this region.

The earliest balloon flights were launched from Palestine, Texas,^{2,13} with the expectation that the Earth's magnetic field would exclude all particles with $\beta = v/c$ below about 0.95. In principle, a single measurement of the ionization rate suffices to determine Z to within a few percent, and the early detectors consisted of only a few sheets of emulsion and plastic. For various reasons there is a background of particles of lower velocity at the latitude of Palestine, such that the data from those early flights are of uncertain quality. For example, two tracks appeared to have been produced by elements with $Z \approx 104$, giving rise to speculation that superheavy elements exist in the cosmic rays. Subsequent experiments of considerably greater collecting power and independent knowledge of Z and β failed to yield further examples of such heavy nuclei, and the participants in those early flights now believe the best interpretation of those two events is that they are elements in the vicinity of uranium ($Z = 92$), with β somewhat lower than 0.9. The background of low-velocity particles of lower charges was especially serious below charge 50, and data from the early flights at these lower charges are probably unreliable.¹⁴

All of the more recent balloon flights have been launched from sites in northern latitudes, where particles with energies down to a few hundred MeV/nucleon

are geomagnetically permitted.¹⁵ The detectors have consisted predominantly of stacks of Lexan sufficiently thick to provide information on both Z and β without any assumptions regarding magnetic cutoff. The track shown in figure 3 was recorded in one of those stacks.

The charge resolution of the measurements has varied from experiment to experiment, but in general the results have uncertainties of plus or minus about two charge units. As a result we cannot give abundances of individual elements, but rather present relative abundances for small groups of elements. Figure 7 summarizes the results¹⁶ of balloon flights through 1972. For this figure the observed data at the detector have been extrapolated with estimated fragmentation probabilities to the top of the atmosphere, but the gross features are unchanged by this extrapolation.

The balloon-borne experiments with adequate collecting power have revealed generally similar gross details of the charge spectrum, but with disturbing differences. Some experiments have reported a peak in the vicinity of the r-process maximum $Z \approx 78$ (Pt), coupled with an absence of an s-process peak at $Z = 82$ (Pb), while others have not been so definite. On the other hand, all seem to agree on a surprisingly high flux of nuclei with Z greater than about 90. A peak near the r-process maximum at charge 52 and 54 appears in some sets of data and not in others.

Presumably these differences are the results of statistical fluctuations, although systematic errors of a few charge units in some data cannot be ruled out. Taken at face value, the composite data of figure 7 indicate a combination of r- and s-process nuclei.

Nuclear fragmentation occurs in interstellar gas, which is mostly hydrogen, with a mean free path of only about 1 gm/cm^2 for the primaries with Z greater than about 70. Thus, the survival of ultraheavy cosmic rays in more or less the same ratio to iron nuclei as is observed in the solar-system abundances, and with peaks still identifiable with nucleosynthesis processes, suggests that a sizable fraction of the observed nuclei must have traveled through less than about 1 gm/cm^2 of interstellar gas, consistent with the propagation mode in which path length falls off exponentially, as discussed above. If a gas density as high as 5 atoms/cm^3 is considered, such as may be characteristic of a spiral-arm region of our Galaxy, and if an average time-dilation factor of three is used, then this corresponds to a flight time as low as 4×10^4 years. A less stringent result comes from the low lead-platinum ratio and the high ratio of nuclides of charge 90 and above to lead, which together imply an interval of less than some 10^7 years between the time of synthesis of these nuclei and the time of their arrival in the solar system. Before considering the implications of these balloon data any further, however, let us consider some newer (in

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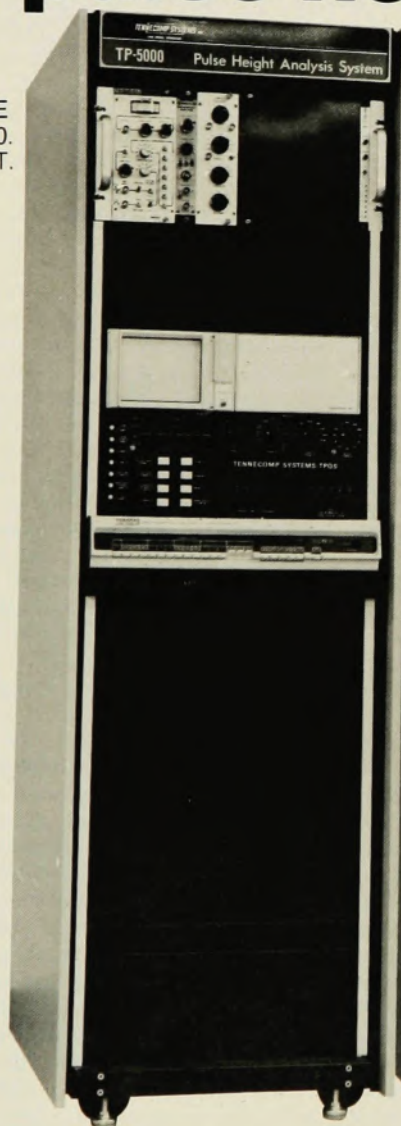
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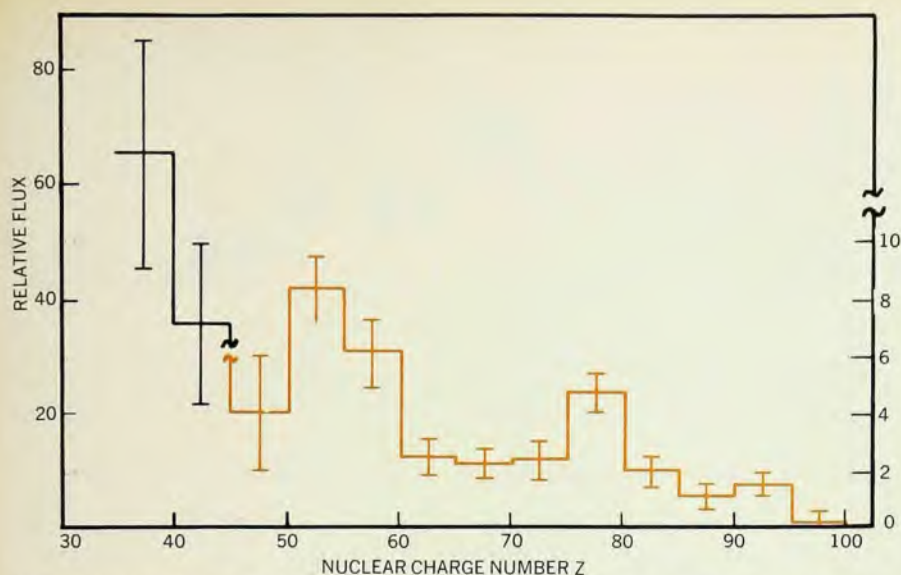
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Charge spectrum of ultraheavy cosmic rays summarizing balloon-flight data through 1972. Note the change of scale: the black line refers to the left-hand scale, the colored one to the right. The abundances observed at balloon altitudes have been extrapolated to the top of the atmosphere; this does not alter the principal features. (Reference 16.)

Figure 7

view of the preliminary nature of the results to date) results.

New, from Skylab

The first opportunity for making an observation with an array of large collecting power above Earth's atmosphere came with the Skylab mission.¹⁷ Figure 1 shows a portion of an array of 36 stacks of Lexan sheets, having a total area of 1.2 m², in individual cloth pockets mounted against an aluminum wall 1 gm/cm² thick in the orbiting workshop. Only a few percent of the ultraheavy nuclei interact in passing through the wall. During their 253-day exposure, these detectors doubled the world's statistics on cosmic rays with $Z > 70$, as can be seen in the Table.

Figure 8 gives a preliminary version of the charge distribution measured on Skylab, based on an analysis of one out of four sheets in each module. Assuming that the apparent peaks in the distribution do not change when the remainder of the sheets are processed and analyzed, two features appear to be different from those in figure 7. There is a rather strong peak at $Z = 82$ (lead), and the peak at $Z \approx 92$ is relatively small. It is possible, but unlikely, that the differences between the balloon results and the Skylab data represent statistical fluctuations. It is very unlikely that the differences can be accounted for by fragmentation in the atmosphere above the balloon-borne detectors. We cannot rule out systematic errors in charge assignment in some of the data, because the absolute charge scale in plastics is based on calibration of slower particles of lower charge. If the apparent peak at lead in the Skylab data survives after an analysis of the remaining three out of every four sheets, one

would confirm the important conclusion that some s-process material is present in the cosmic rays. In this case one could still argue that the relative abundance of uranium-group and platinum-group elements indicates a relatively short time, less than about 10^7 years between the r-process synthesis of these nuclei and their observation near Earth.

The most decisive conclusion of the Skylab experiment—and one that will not change as the remainder of the sheets is analyzed—is that there were no events with Z greater than about 110. Taking all data, balloon and Skylab, together, the abundance ratio

$$(Z \geq 110)/(70 \leq Z \leq 83)$$

must be less than 0.006 and the flux of superheavy cosmic rays ($Z \geq 110$) must be less than about 0.3 nuclei per square meter steradian year!

Future directions

Our current data on the composition of ultraheavy cosmic rays are comparable to that for the lighter nuclei ($3 \leq Z \leq 30$) about fifteen years ago. We have a coarse picture of the charge spectrum with indications of the locations of peaks and of the relative abundances of various groups of elements. The major advance in the past ten to fifteen years of studying the lighter nuclei was to sharpen this picture to the point of knowing the relative abundances of individual elements.⁴ Clearly, a similar sharpening of the abundance measurements of ultra-heavies is a principal objective of the next several years. The need for measurements with enough resolution to distinguish individual elements is further underscored by the disagreements among data sets as summarized above. Errors of a few charge

units in the charge assignments could account for the discrepancies. Only with a detector of sufficient resolution and exposure to show distinct peaks at individual elements from iron through the end of the periodic table will we be able finally to distinguish between r-process peaks and the nearby s-process peaks.

To achieve this objective we require detectors with root-mean-square error in charge measurement of about 0.3 charge units or better, and of course we require large detectors with long exposure times to record a significant number of nuclei. Achievement of this excellent charge resolution in very large detectors, although within the capability of current detector technology, is certainly not trivial. To illustrate the kinds of problems one encounters, charge is typically inferred from a measurement of the energy loss by ionization or the Cerenkov light produced as the nucleus penetrates a detector. The energy loss per unit path length and the Cerenkov light per unit path length are both proportional to the square of the nuclear charge, so the thickness and response of the detector at the point traversed by the particle, as well as the angle of the particle's trajectory, must be known accurately. A 2% error in the path length or response results in misidentification of a nucleus near uranium by a full charge unit.

Two satellite-borne electronic experiments to measure ultraheavy cosmic rays with single-charge resolution are currently in advanced stages of design. One, scheduled for launch in 1979 on the third of NASA's High Energy Astronomy Observatories (HEAO-C), has a geometry factor of 4 m²-steradian. Similar in concept to the balloon-borne detector of 1 m²-steradian described above, it utilizes parallel-plate pulse ionization chambers and a flat-slab acrylic Cerenkov counter. The HEAO heavy-nuclei experiment is a collaboration among W. Robert Binns of McDonnell-Douglas Research Laboratories, Martin Israel and Joseph Klarmann of Washington University, St. Louis, Edward Stone, Jr. and Rochus Vogt of the California Institute of Technology and C. Jake Waddington of the University of Minnesota.

The path length of the particle trajectory, as well as its location in the counters, is determined by a hodoscope, which consists of an array of ionization chambers with parallel-wire collecting electrodes. At the top of the detector are two such ionization chambers with their electrode wires at right angles. The x - y coordinates of the incident particle are indicated by which wire in each chamber detects the particle. Similar pairs of chambers located further down in the detector give the coordinates there; together they give a pic-

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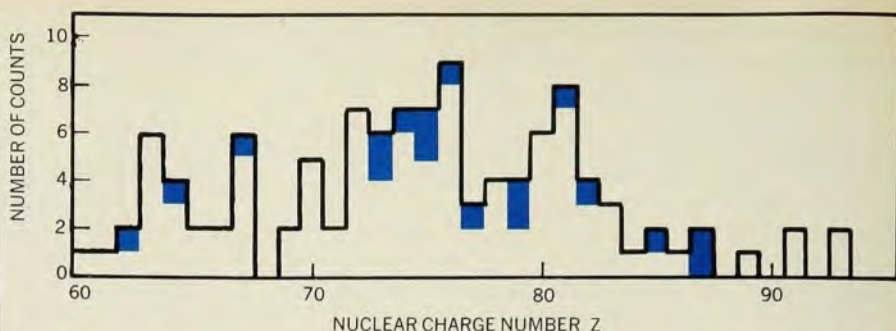
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Charge spectrum determined from measurements (of 112 events) in every fourth Lexan sheet in all 36 Skylab stacks. Colored squares in this preliminary study indicate charge assignments with unusually large probable errors, most likely to be revised. (Ref. 17.) **Figure 8**

ture of the particle trajectory through the detector.

The British satellite UK6, to be launched in 1977, will carry a spherical detector, with 2 m^2 -steradian geometry factor, which also makes use of ionization energy loss (measured in a gas scintillation counter) and Cerenkov light. The novel spherical design of the experiment, conducted by Peter Fowler of the University of Bristol, eliminates the need for a hodoscope, but requires excellent uniformity of response over the entire counter.

Either of these two satellite instruments will observe a number of nuclei at Z greater than about 70 comparable to the total recorded to date. Since many of the previous experiments were relatively insensitive much below charge 70 while these satellite experiments have no loss of sensitivity over the entire ultraheavy spectrum, these new experiments will give an even greater improvement in the world's accumulated inventory of measurements at these somewhat lower charges. For example, with a year in orbit, the HEAO experiment should see about 150 nuclei with $Z \geq 80$, 1000 above charge 50, and 3000 between charge 35 and 50. Furthermore, balloon flights of a detector similar to the HEAO instrument have demonstrated that single-charge resolution is in fact attainable on HEAO, and the calculated resolution of the UK6 instrument is comparable. Such a resolution would permit one to establish a unique charge scale, anchored on the well known and abundant iron nuclei.

While these satellite instruments will make a significant improvement in the data on elements through about charge 96, the new low upper limit for the flux of superheavy elements ($Z \geq 110$) from the Skylab data make it unlikely that these experiments will do more than decrease this upper limit by a factor of about 2. Thus, without a radically new approach we are not likely either to find superheavy elements in the cosmic rays or to place much stricter constraints on their lifetimes or rates of synthesis in nature. A possible radical approach ca-

pable of increasing our collecting power by at least a factor 10^2 would be to return to the meteorites, where ultraheavy cosmic rays were first discovered, or to lunar samples, and to develop a reliable means of assigning charges to individual tracks. A few square centimeters of meteorite crystals with a typical cosmic-ray exposure of the order of ten million years represent an exposure of over 10^5 m^2 -steradian-days.

Prior to the satellites, HEAO and UK6, we can expect data with single-charge resolution, at least up to charge 50 or 55, from two new electronic instruments scheduled for balloon flights in 1975. Both of these instruments have geometry factors around 10 m^2 -steradian, so with a few two-day balloon flights either of these instruments could observe several hundred nuclei in the interval $35 \leq Z \leq 50$, where the world's total reliable data to date are only a hundred nuclei measured with relatively poor charge resolution. One of these, under construction at Washington University, is similar to the HEAO instrument. It uses parallel-plate ionization chambers, a Cerenkov counter and a wire hodoscope, and is housed in a cylindrical vessel holding atmospheric pressure, 22 ft long by 7 ft in diameter. The other, built at the University of Bristol, is an 11-foot-diameter spherical gas scintillator similar to the UK6 instrument. These are by far the largest, although not the heaviest, electronic cosmic-ray detectors ever flown.

Thus we can expect in the next five or six years to fill in the detailed elemental composition of the cosmic rays in the last two-thirds of the table of elements, and so to sharpen our picture of the material accelerated, and probably synthesized, as a result of explosive stellar processes.

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On the world's largest
extended-chain
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crystals.



At the Materials Research Center Drs. R.H. Baughman and K.C. Yee have synthesized large polymer crystals which have extraordinary properties and unique internal structures. The crystals, which are formed by solid state reaction, have fully conjugated backbone structures. In addition to previously known single chain polymers, they include two new classes of polymeric molecules designated "ring-bridged" and "cyclically-bound ladder" polydiacetylenes. In appearance, the crystals exhibit metallic luster, intense coloration, and dichroism. They have negative macroscopic thermal expansivities, very high strengths and are semi-conductors.

Ordinary polymer crystals are microscopic in size and typically consist of molecular chains folded back upon themselves much like ribbon candy. In contrast, Baughman's and Yee's new polymer crystals are up to 15 cm in length and consist of parallel, unfolded chains. Their unusual properties are associated with the nearly perfect alignment of the molecular chains and the absence of gross structural defects. They are made by first crystallizing the molecules of an appropriate monomer and then photopolymerizing the monomer crystal with ultra-violet light or gamma rays.

Availability of large monocrystals provides a unique opportunity to explore the behavior of nearly defect-free polymeric materials. Fundamental understanding of the solid-state synthetic method has allowed template-like control of polymer structure on three levels: molecular, crystallographic and morphological. This provides a capability for synthetic tailoring of polymers to optimize properties dependent upon molecular structure and crystalline perfection.

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