PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Cosmic-Ray Nuclei up to 10^{10} eV/u in the Galaxy [and Discussion]

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Cosmic-ray nuclei up to 10^{10} eV/u in the Galaxy

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[Plates 12 and 13]

Of the nuclear cosmic rays arriving in the vicinity of Earth from interstellar space, more than 90% have energies less than 10^{10} eV/u.† Some effects of their modulation (including deceleration) in the Solar System are briefly discussed. The origin of particles at energies $< 10^7$ eV/u is still obscure. They could be due to stellar explosions or to solar emissions, or perhaps to interaction of interstellar gas with the solar wind. Between 10^8 and 10^{10} eV/u, the composition appears constant to *ca.* 30% within the statistics of available data. Cosmic rays traverse a mean path length of 6 g/cm^2 in a medium assumed to contain nine hydrogen atoms for each helium atom. Spallation reactions occurring in this medium result in enhancement of many cosmic-ray elements that are more scarce in the general abundances by several orders of magnitude. Cosmic-ray dwell time in the Galaxy seems to be $< 10^7$ years. The source composition of cosmic rays has been derived for elements with atomic numbers $1 \leqslant Z \leqslant 26$. A comparison with abundances in the Solar System implies that the latter is richer in hydrogen and helium by a factor of *ca.* 20, in N and O by *ca.* 5, and in C by a factor of *ca.* 2. Possible interpretations invoke (*a*) nucleosynthesis of cosmic rays in certain sources, e.g. supernovae, or (*b*) models of selective injection that depend, e.g. on ionization potentials or ionization cross sections. Calculated isotopic abundances of arriving cosmic rays are compared with the observed values now becoming available, and found to be in general agreement. Recent progress in probing the composition and spectrum of ultra-heavy nuclei is outlined.

Introduction

From remote, exotic regions of space the 'primary' galactic cosmic radiation (see Appendix) brings us samples of matter – nuclei as light as those of hydrogen and as heavy as uranium. These particles can be detected near the top of the atmosphere or in nearby space before they are transformed by interaction with the blanket of air surrounding the Earth. Their energies span some 15 orders of magnitude, from about 10^6 up to about 10^{21} eV, and the corresponding intensities range over about 30 orders of magnitude. Although the highest particle energies thus far observed in nature are about 10^9 times above those generated by our largest accelerators, the *mean* energy of cosmic-ray protons is about 100 times *lower* than the proton energies attained at the National Accelerator Laboratory in Batavia, Illinois.

In the energy domain up to 10^{10} eV/u, assigned to this review, are to be found more than 90% of the particles and more than one half of the total energy density in the arriving 'beam'. These particles may thus be considered characteristic cosmic rays; their intensities, composition, energy spectra, spatial and temporal variations, transformations, and other properties are better known than those of the lower-flux particles at higher energies. Accordingly, theories of cosmic-ray propagation and origin must lean heavily on the mass of data available in this energy region. We shall sketch some of the salient observations under the following headings:

1. The energy spectrum of the arriving nuclei after its modulation in the Solar System.

† Symbols are defined in the appendix, p. 345

2. The composition of the arriving cosmic rays below and above 1 GeV/u.
3. Calculated abundances of cosmic rays at the sources, and comparisons with those in the Sun and nearby stars.
4. Some ways in which the source composition might arise.
5. The relative abundances as a function of energy.
6. Transformation and propagation of cosmic-ray nuclei in space.
7. Isotopic composition of cosmic rays – observation and calculations.
8. Abundances and spectra of ultra-heavy nuclei.

1. The energy spectrum of the arriving nuclei after its modulation in the Solar System

Figure 1 displays the differential intensity of arriving cosmic-ray hydrogen and helium at solar-quiet times (q) and in periods of high solar activity (a). At quiet times, the intensity reaches a maximum at several hundred MeV/u. The reduced fluxes during solar-active times, at energies $\leqslant$ 1 GeV/u, result from solar modulation (see below).

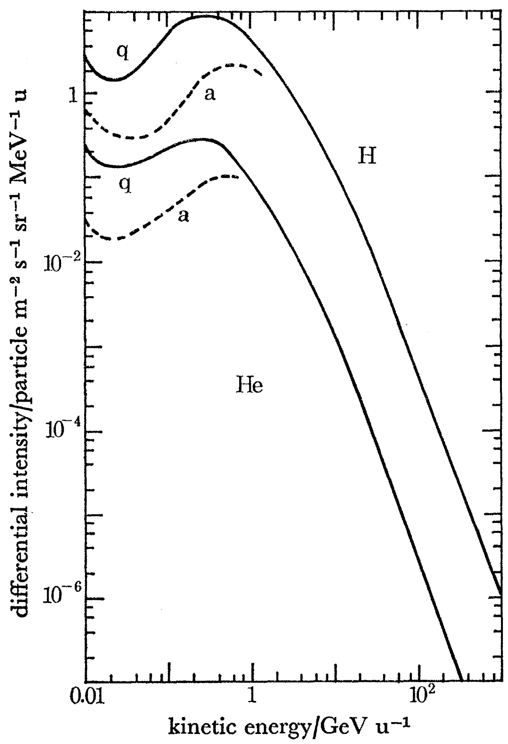

Figure 1. Differential energy spectra of cosmic-ray hydrogen and helium, at solar-quiet (q) and solar-active (a) times. (Adapted from Webber (1973) who provides the observations from which these curves derive.) For terminology and notation used in this and other figures, see the Appendix.

At about 30 MeV/u there is a minimum in each curve, and at progressively lower energies, a rise sets in. Whether this upturn is due entirely to galactic cosmic rays is unclear, but evidence that at least a part of it must be due to particles entering from outside the Solar System has been provided by the Chicago group (Fan *et al.* 1968); see figure 2. Both protons and helium nuclei showed an inverse correlation with solar activity, i.e. a higher intensity in the period

May–November 1965 than in late 1964, when the Sun was more active. Contrary behaviour would be expected if the particles were mainly of solar origin.

There are indications that some of the particles below about 10 MeV originate inside the Solar System. In 1966, for example, after the solar minimum had passed, the Chicago group (Fan *et al.* 1968) observed an *increased* proton intensity at these low energies.

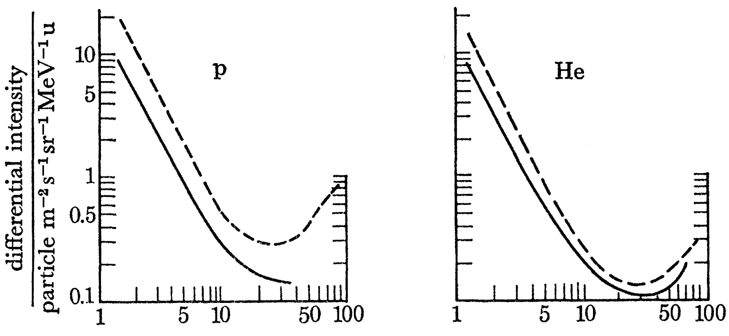

FIGURE 2. Spectra of protons and helium at energies < 100 MeV/u. The dashed lines show the intensities at solar minimum (May–November 1965) and the solid lines about half a year earlier (November–December 1964). (Adapted from Fan *et al.* 1968.)

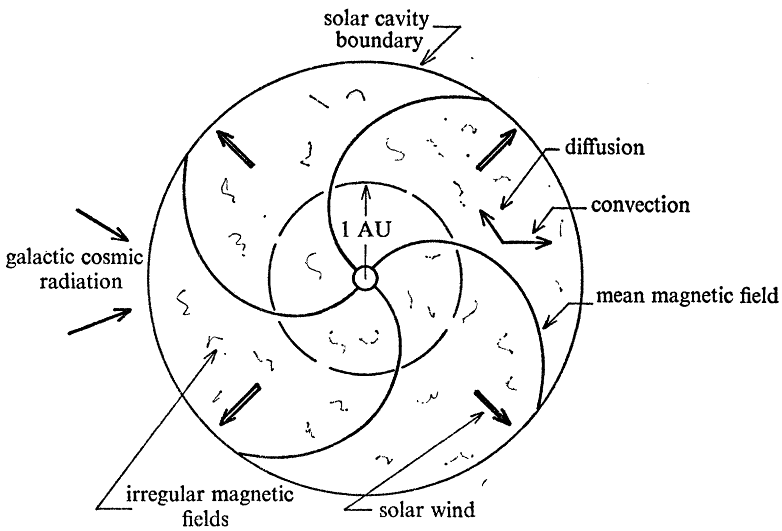

FIGURE 3. Processes and mechanisms that modulate galactic cosmic rays in the solar cavity (after Gleeson 1971).

As cosmic rays enter the Solar System, their intensity is reduced, and this occurs especially at low energies and at times of solar maximum. Moreover, the particles are subject to adiabatic deceleration; those observed at a given energy had possessed considerably higher energies before entering the region of the 'solar cavity'.

Figure 3, schematically illustrating various aspects of solar modulation, is adapted from Gleeson's (1971) rapporteur paper at the Hobart Conference on Cosmic Rays. The solar wind moves out radially from the Sun into the 'solar cavity', pulling out solar magnetic fields into a spiral structure, due to solar rotation. At the same time, the solar wind also transports irregular components of the magnetic field. Cosmic rays entering the solar cavity have their trajectories changed: while diffusing, they are also being convected outward. As a result of their interactions with the expanding magnetic fields, the particles suffer adiabatic deceleration.

The suppression of cosmic-ray intensities, and the effects of adiabatic deceleration are illustrated in figure 4, adapted from Goldstein, Fisk & Ramaty (1970). The intensities and energies of cosmic rays outside the Solar System are represented by dashed curves, those after modulation, by solid curves. The upper and lower curves show that particles with energies 50–60 MeV are reduced in intensity by four orders of magnitude, ending up with energies between 10 and 30 MeV. At 'arriving' energies ⩽ 40 MeV, the dominant contribution comes from particles of curves 3 and 4, i.e. from nuclei that possessed energies of 150–300 MeV prior to adiabatic deceleration.

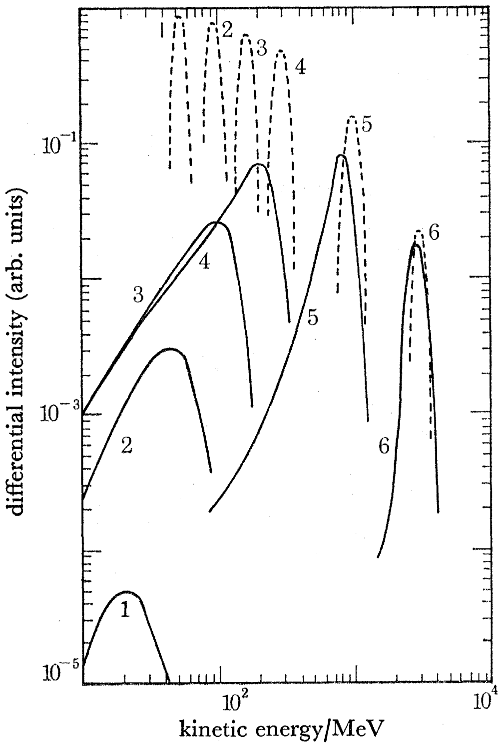

FIGURE 4. Modulation and adiabatic deceleration of protons. Fluxes at a selected set of (nearly) 'discrete' energies outside the solar cavity are represented by the dashed curves; the corresponding modulated distributions near the Earth appear in the solid curves. (Adapted from Goldstein *et al.* 1970.)

Below about 50 MeV, some unusual types of modulation may occur that are not accounted for by present theories. The low ratios of $^2H/^4He$ and $^3He/^4He$ near solar minimum, as well as the upturn in the energy spectra below about 25 MeV, suggest that some low-energy particles could somehow 'wiggle' their way into the Solar System without much adiabatic deceleration.

At the 13th International Cosmic-Ray Conference, reports were presented by the Chicago, Goddard and Iowa groups on the cosmic-ray gradient between the Earth and Jupiter, as measured on Pioneer 10. The gradient is rather small, about 2% per astronomical unit.† Van Allen (1973) reported a particularly small value, 1% per AU. Thus it appears that the major modulation processes are likely to occur beyond the orbit of Jupiter.

† 1 AU ≈ 1.5×10^{11} m.

2. The composition of the arriving cosmic rays below and above 1 GeV/u

The cosmic-ray nuclei arriving in the Earth's vicinity from interstellar space consist mainly – but not exclusively – of particles that started out at the cosmic-ray sources. Additionally, they include a rich admixture of secondaries generated *en route* by progenitor nuclei in collisions with interstellar matter. Collectively, these secondaries – nuclei, electrons, and γ-rays – are a veritable Rosetta Stone which enables us to decipher the transformations of cosmic rays in space, and to unravel the puzzles of their propagation and origin. We shall elaborate below on the nature of these secondaries, especially of the nuclear fragments, and their crucial role in cosmic ray astrophysics.

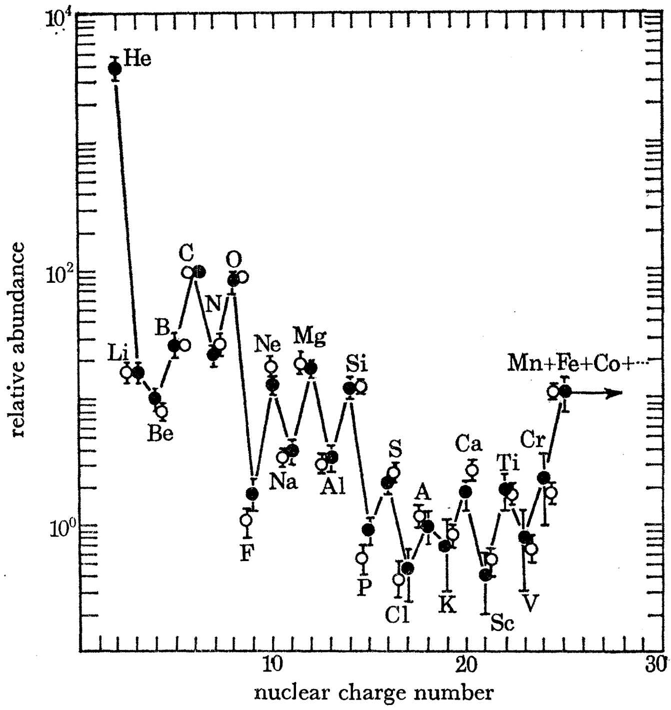

Figure 5. Relative abundance of elements in cosmic rays below 1 GeV/u at the top of the Earth's atmosphere. (Simpson 1971.) Abundances are normalized to 100 for carbon. ●, University of Chicago results at energies of 100 to 300 MeV/u; ○, data at 250 to 850 MeV/u obtained by the New Hampshire group.

First, however, we draw attention to the respective compositions of the arriving low-energy and relativistic cosmic rays. Figure 5, based on work by the Chicago and New Hampshire groups, gives the observed relative abundances at energies below 1 GeV/u. Included are the elements between helium and nickel. A factor of about 10^4 separates the flux of He from that of the most meagre cosmic-ray elements in figure 5. Helium is richer by two orders of magnitude than carbon and oxygen. These in turn are distinctly more plentiful than Li, Be, B, N, Ne, Mg, Si and the iron group, consisting predominantly of Fe itself. Still lower in intensity by an order of magnitude than Ne, Mg, or Si are the odd-Z elements F, Na, and Al. The *even*-Z nuclei from sulphur to chromium are also about 10 times lower in flux than Mg or Fe. These five elements – S, Ar, Ca, Ti, and Cr – show the familiar alternation relative to their odd-numbered neighbours (phosphorus to vanadium) – i.e. enhanced abundances relative to the latter five. Also striking is the apparent constancy of the cosmic-ray composition as a function of energy between *ca.* 100 and *ca.* 850 MeV/u.

We have been looking at the chemical composition of cosmic rays reaching the vicinity of the Earth at energies *below* 1 GeV/u. The corresponding composition at energies between 1 and 10 GeV/u is compared in figure 6 with that of ordinary ('thermal') matter in the Solar System. Estimates of the latter composition are close to the so-called 'universal' distribution. Derived mainly from optical spectra, the solar values are augmented by sampling of meteorites. In the diagram, solar abundances are plotted relative to 10^{12} hydrogen atoms, and the cosmic-ray composition has been normalized to the solar one at carbon. Focusing first on the cosmic-ray values (represented by circles) in figure 6, the relative fluxes are not notably different from those in figure 5. The meteoritic abundance values often differ significantly from the solar-optical values. Moreover, as will be shown below, the direct sampling, by rockets and satellites, of energetic solar particles emitted during flares, has partly clarified – yet partly confused – our image of solar abundances; cf. figure 8.

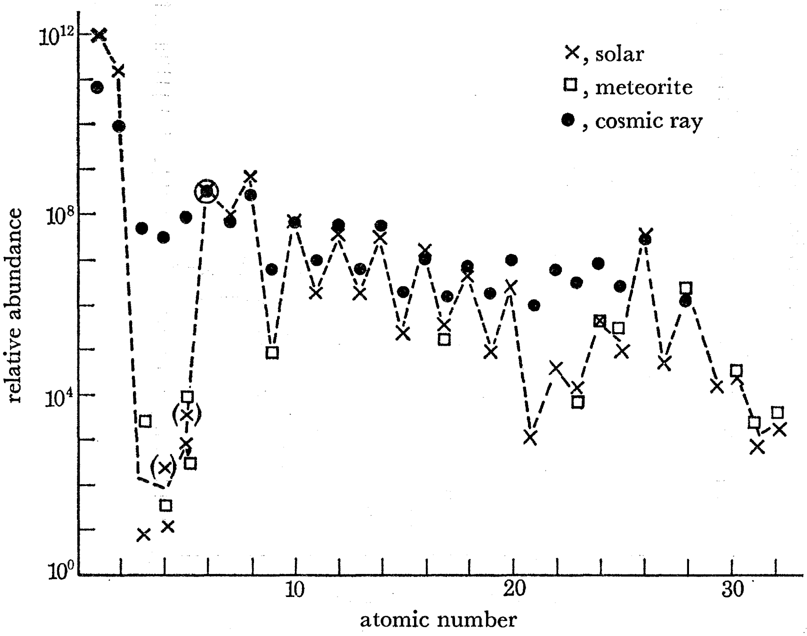

FIGURE 6. A comparison of the relative abundances of elements in cosmic rays above the Earth's atmosphere and in the Solar System. The solar hydrogen abundance is normalized to 10^{12}. Cosmic-ray abundances are normalized to the solar values at carbon. (Up-dated version of earlier graph of Shapiro 1971.)

Relative to carbon, the reference element in this diagram, both hydrogen and helium are deficient in the arriving cosmic rays compared to the Sun. The most impressive 'valley', due to the extreme scarcity of Li, Be, and B in nature, contrasts starkly with their substantial presence in the arriving cosmic rays. The sharp controversy that once raged about these important light ('L') nuclei was dispelled by the definitive work of the N.R.L. group (O'Dell, Shapiro & Stiller 1959, 1962). These three secondary elements have been the most revealing breakup products of cosmic-ray collisions in space. Moreover, in addition to the wealth of information they have already provided about propagation, path lengths, dwell times, and cosmic-ray confinement, they will yield further dividends as we solve the technical problems of measuring their isotopic constitution.

Beyond boron, the dominant peaks of cosmic-ray intensity are those of C, O, Ne, Mg, Si, and Fe. All of these have *even* atomic numbers. Oxygen and nitrogen are both 'under-abundant' in cosmic rays compared to the Sun, although the decrement might tend to escape notice in the logarithmic ordinate scale of figure 6. (The abundances span ten orders of magnitude, so many of the different values look deceptively close.) It is noteworthy that a choice of Mg or Si as the reference element would make nitrogen and oxygen appear even more deficient in the cosmic rays. Furthermore, by reference to Mg or Si, cosmic-ray *carbon* would also be deficient compared to solar carbon.

Looking beyond oxygen, the valleys of figure 5 are likewise evident in figure 6, at the higher energies; again, they occur mainly at odd-Z elements. However, it is plain that the valleys are not as deep as those in the solar-system distribution. So it seems that the nuclear transformations of the progenitor cosmic rays in space (or perhaps in the vicinity of the sources) tend to suppress the magnitude of the odd–even effect. This is particularly pronounced for the 'sub-iron' elements between sulphur and manganese.

Table 1. Chemical composition of arriving cosmic rays from Li to Si

(normalized to a value of 100 for carbon)

		at equal intervals of velocity		adjusted to rigidity threshold† > 1 GeV/u		rigidities			
atomic number	element	100–300 MeV/u (Cartwright 1971)	250–850 MeV/u (Webber *et al.* 1972)	(Webber *et al.* 1972)	(Lezniak *et al.* 1970)	> 5 GV (Cassé *et al.* 1971)	> 5 GV (Juliusson *et al.* 1972)	> 5 GV (Smith *et al.* 1973)	> 11 GV (Webber *et al.* 1972)
3	Li	17 ± 2	16.4 ± 0.8	17.1 ± 0.4	16.0 ± 1	—	—	—	16.5 ± 1
4	Be	10 ± 2	8.1 ± 0.6	9.0 ± 0.3	7.2 ± 0.6	13.1 ± 2	11.2 ± 1	—	8.8 ± 1
5	B	26 ± 3	27.3 ± 1.0	30.7 ± 0.5	27.2 ± 1	28.5 ± 2	28.1 ± 1	—	22.9 ± 1.5
6	C	100	100	100	100	100	100	100	100
7	N	22 ± 5	25.7 ± 2.3	25.4 ± 0.5	25.5 ± 1	23.1 ± 2	24.8 ± 1	27.0 ± 2	23.7 ± 1.5
8	O	88 ± 12	92.4 ± 2.1	88.8 ± 2.1	90 ± 2	97.3 ± 4	90 ± 2	93.7 ± 2	92.4 ± 6
9	F	1.8 ± 0.3	1.1 ± 0.3	1.6 ± 0.3	1.7 ± 0.4	2.2 ± 0.4	2.3 ± 0.3	2.1 ± 0.7	1.5 ± 0.8
10	Ne	14 ± 2	17.6 ± 0.8	15.5 ± 0.6	17.0 ± 0.7	14.1 ± 1	14.7 ± 0.5	18.9 ± 1.3	12.9 ± 1.5
11	Na	3.5 ± 0.5	3.5 ± 0.4	2.7 ± 0.2	3.3 ± 0.3	2.7 ± 0.4	2.9 ± 0.3	0.8 ± 0.5	2.3 ± 0.5
12	Mg	17 ± 3	18.5 ± 0.8	18.2 ± 0.5	17.5 ± 0.7	16.8 ± 1	18.3 ± 0.5	23.6 ± 1.4	19.9 ± 1
13	Al	3.5 ± 0.5	3.1 ± 0.4	2.7 ± 0.2	4.0 ± 0.4	4.5 ± 0.6	3.7 ± 0.3	1.8 ± 0.5	4.0 ± 0.7
14	Si	12 ± 2	12.4 ± 0.6	12.2 ± 0.4	13.1 ± 0.6	13.9 ± 1	15.3 ± 0.5	19.6 ± 1.3	15.6 ± 1

† Since the isotopic composition is not well known, this transformation can introduce errors of 1 or 2 % in the adjusted numbers. The errors quoted do not include uncertainties due to this transformation.

We could elaborate further on the various similarities and differences between the observed cosmic-ray and solar distributions of elements, but what is really of prime interest – for its implications as to origin, acceleration, and propagation of cosmic rays – is a comparison of the composition at the *sources* with that in the Sun and nearby stars. Fortunately, it has become possible to make a good start in deriving a source composition, so that revealing comparisons can now be made with the 'universal' abundances (see §§3 and 4).

The general concordance among various observers as to the relative fluxes of the arriving cosmic rays, and the remaining spread in their respective estimates can be discerned in table 1 for the elements lithium to silicon. The 'rigidity adjustment' mentioned in one of the table headings is required for meaningful comparison with other data. High-altitude observations in a balloon flight are typically confined to a localized geographic area having a narrow range of values for the vertical rigidity cutoff imposed by the Earth's magnetosphere; the resulting fluxes

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

are often obtained as integral values above the local cutoff. For direct comparability with such integral intensities, other measurements, performed over equal intervals of *energy per atomic mass unit* (i.e. equal velocity intervals), have been converted to an equivalent rigidity threshold. This has been done as required for energies > 1 GeV/u, but not at lower energies, since fluxes of such 'slower' nuclei have generally been measured as a function of velocity. The consolidation of abundance data at high and low energies would, in any event, be complicated by effects of solar modulation.

In table 2, similar results have been collected for the heavier cosmic-ray elements up to Ni. Here the relative uncertainties are often several times larger than most of those in table 1, especially for the sparse nuclei, Cl to Mn. Most of the elements in this sub-iron group are considered to be largely secondary and predominantly due to the fragmentation of iron, which has a high cross-section for breakup in collision with the 'target' material in the interstellar medium.

TABLE 2. CHEMICAL COMPOSITION OF ARRIVING COSMIC RAYS FROM P TO Ni

(normalized to a value of 100 for carbon)

		at equal intervals of velocity		adjusted to rigidity threshold,	rigidities		
atomic number	element	100–300 MeV/u (Cartwright 1971)	250–850 MeV/u (Webber *et al.* 1972)	> 1 GeV/u (Webber *et al.* 1972)	> 5 GV (Cassé *et al.* 1971)	> 5 GV (Juliusson *et al.* 1972)	> 11 GV. (Webber 1972)
15	P	0.9 ± 0.3	0.55 ± 0.09	0.53 ± 0.1	1.0 ± 0.2	0.63 ± 0.3	0.56 ± 0.2
16	S	2.3 ± 0.4	2.6 ± 0.3	3.1 ± 0.2	2.6 ± 0.5	2.9 ± 0.2	3.6 ± 0.6
17	Cl	0.45 ± 0.3	0.39 ± 0.11	0.64 ± 0.1	0.7 ± 0.2	0.7 ± 0.2	0.30 ± 0.1
18	Ar†	1 ± 0.5	1.2 ± 0.2	1.5 ± 0.2	1.0 ± 0.3	1.3 ± 0.2	0.56 ± 0.2
19	K	0.8 ± 0.3	0.83 ± 0.17	0.87 ± 0.1	1.5 ± 0.3	1.0 ± 0.2	0.8 ± 0.3
20	Ca	1.8 ± 0.6	2.7 ± 0.3	2.3 ± 0.2	1.5 ± 0.3	2.25 ± 0.2	1.1 ± 0.3
21	Sc	0.3 ± 0.2	0.52 ± 0.14	0.49 ± 0.07	0.8 ± 0.2	0.63 ± 0.2	0.22 ± 0.1
22	Ti	1.8 ± 0.8	1.8 ± 0.3	1.2 ± 0.1	1.8 ± 0.3	1.6 ± 0.2	1.7 ± 0.3
23	V	0.8 ± 0.4	0.65 ± 0.14	0.65 ± 0.10	0.55 ± 0.2	1.5 ± 0.2	0.14 ± 0.1
24	Cr	2.4 ± 1.5	1.9 ± 0.3	1.4 ± 0.1	1.0 ± 0.2	1.7 ± 0.2	0.92 ± 0.2
25	Mn		1.1 ± 0.2	1.0 ± 0.1	1.2 ± 0.3	0.5 ± 0.2	
26	Fe	10.3 ± 2‡	9.2 ± 0.6	11.0 ± 0.4	—	10.6 ± 0.5	14.2 ± 1
27	Co		0.15 ± 0.08	—	—	< 0.4	—
28	Ni§		0.27 ± 0.10	0.5 ± 0.1	0.7 ± 0.3	0.54 ± 0.2	0.44 ± 0.2

† Söderström *et al.* (1973) have reported 2.7 ± 0.8.

‡ For elements Mn to Ni, Smith *et al.* (1973) at > 5 GV, report 12.0 ± 1.1

§ Binns *et al.* (1971) have given 0.42 ± 0.06; Shirk *et al.* (1973), $0.1^{+0.1}_{-0.05}$.

Clearly, the adoption of a set of 'best' flux values is required if one is to investigate cosmic-ray propagation or calculate a source distribution. This was done by the authors a few years ago (Shapiro & Silberberg 1970*a*), using data such as those of Garcia-Munoz & Simpson (1970), Webber & Ormes (1967), Kristiansson, Mathiesen & Stenman (1963). Recent observational refinements and measurements have impelled us to update the foregoing estimates. The revised data for all the elements between Li and Ni at rigidities exceeding 4 GV are shown in table 3, in which abundances have been normalized to 100 for carbon.

Comparison of table 3 with tables 9 and 13 of our 1970 review reveals that, despite the inclusion of new data, changes in the 'best values' have not exceeded the quoted standard errors (the scarce element chromium is the sole exception). This stabilization of flux values indicates that the intensities measured by different experimenters are really converging; it provides reassurance and encouragement to use the best estimates for astrophysical calculations. To be sure, the task of adequately measuring elemental abundances even in this accessible part of the periodic table is still incomplete. Considerable uncertainties remain, for example, in the region of the sub-iron nuclei, and even for some lighter ones, such as F, Na, Al. Beyond this task we envisage the formidable but essential programmes of learning: (*a*) the *isotopic* makeup of the cosmic-ray elements in table 3 – a pursuit that began a decade ago, but one which has yielded definitive results only for helium – and (*b*) the detailed composition of the *ultra-heavy* nuclides with $Z \geqslant 30$. We shall summarize some recent research in these areas in §§7 and 8 below. First, however, we turn to the subject of *source* composition.

TABLE 3. COSMIC-RAY ABUNDANCES ABOVE THE ATMOSPHERE AT RIGIDITIES $R \geqslant 4$ GV†

Li	18 ± 2‡	Mg	19 ± 1	Sc	0.4 ± 0.2
Be	10.5 ± 1	Al	2.8 ± 1	Ti	1.7 ± 0.3
B	28 ± 1	Si	14 ± 2	V	0.7 ± 0.3
C	100§	P	0.6 ± 0.2	Cr	1.5 ± 0.4
N	25 ± 2	S	3 ± 0.4	Mn	0.9 ± 0.2
O	91 ± 2	Cl	0.5 ± 0.2	Fe	10.8 ± 1.4
F	1.7 ± 0.4	Ar	1.5 ± 0.3	Co	< 0.2
Ne	16 ± 2	K	0.8 ± 0.2	Ni	0.4 ± 0.1
Na	2.7 ± 0.4	Ca	2.2 ± 0.5		

† Values adopted from data available by February 1974.
‡ In the light of additional data, the value for Li is slightly higher than that reported by Shapiro *et al.* (1973*b*).
§ Normalization: 100 for carbon.

3. CALCULATED ABUNDANCES OF COSMIC RAYS AT THE SOURCES, AND COMPARISON WITH THOSE IN THE SUN AND NEARBY STARS

Since the time of its discovery some sixty years ago, the cosmic radiation has presented many puzzles, but none so challenging as the riddle of its genesis. The site(s) of origin, the nature and history of the source(s), and the remarkable processes by which so much energy is concentrated into so few particles – all these riddles have fascinated the investigator of these problems and of related ones in astrophysics. The sources of the galactic cosmic rays are still an elusive mystery; yet there is no dearth of hypotheses as to their mode and place of birth.

A crucial test confronting any model of origin is the requirement that the proposed source and the mechanism(s) of acceleration be consistent with what we know of cosmic-ray composition. This 'composition' is one that must be calculated – i.e. it is the one injected at the *source* – inasmuch as the arriving composition is very different from the original one. Early attempts to deduce 'primordial' abundances from those observed in our vicinity were necessarily crude, since many of the required nuclear and astrophysical data were lacking. (References to early papers have been given by Shapiro & Silberberg 1970*a*; see p. 370 of their review.)

Five years ago the N.R.L. group launched a comprehensive programme of investigating the transformations that cosmic-ray nuclei undergo in interstellar space (Shapiro, Silberberg & Tsao 1970*a*, *b*, *c*). Their extensive treatment of the breakup of cosmic rays into secondary nuclei had begun three years earlier with an analysis of the transformations that give rise to the 'tracer clock' ^{10}Be, useful in determination of cosmic-ray confinement time (Shapiro & Silberberg 1967, 1968).

A central question in propagation theory is this: what distribution of nuclei must have been injected into the cosmic-ray 'gas', if its subsequent transformation is to yield the arriving composition? In treating this problem, the N.R.L. workers solved numerically the diffusion equations of Ginzburg & Syrovatskii (1964), describing the fragmentation of cosmic rays in space, and the consequent production and attenuation of daughter nuclides in successive increments of path length (Shapiro *et al.* 1972*a*). From a critical compilation of the arriving cosmic ray fluxes, they adopted a trial source composition resembling the solar one. Since most of the required fragmentation yields at high energies had not been measured, they also devised semi-empirical formulae, and fitted these to the relevant data on cross sections available in the literature (for recent values of the semi-empirical parameters, see Silberberg & Tsao 1973*a*, *b*, *c*, *d*).

In their interstellar journeys, the cosmic rays traverse a variety of path lengths. Various provisional distributions in path length have been tried, and a recent function that fits a wide array of observed abundances is the following:

$$\mathrm{d}N/\mathrm{d}\lambda = [1-\exp(-2.8\lambda^2)]\exp(-0.23\lambda),$$

where N is the number of particles having a material path length λ.

The diffusion equations were applied to the production of the principal stable nuclides from ^{6}Li to ^{56}Fe generated in collisions of cosmic-ray progenitors. Included were tertiary and quaternary nuclides, and residues of the decay of radioactive secondaries. Also taken into account were energy losses by ionization and nuclear collisions, the dependence of cross sections upon energy, modulations by the geomagnetic field and by plasmas in the solar system, and the effect of the shape of the cosmic-ray source spectrum. After an arriving composition had been derived in first approximation, this was compared with the observed composition; the trial source composition, as well as the shape of the distribution function of path lengths, were modified to improve the fit with observations.

Recent results of this iterative procedure (which converges rapidly) are displayed in figure 7. Included are the relative abundances of cosmic rays at the sources and near the Earth. The latter are subdivided into the surviving 'original' nuclei and the secondaries generated *en route*. All abundances have been normalized to a value of 100 for the total flux of arriving carbon. For each element in figure 7 (with few exceptions), there are two adjacent ordinates. The diagonally hatched column represents the primordial abundance; the column with black and white portions represents the overall abundance of the arriving element. Of the two latter portions, the white (blank) column gives the surviving flux of nuclei which started out at the *source*, and the dark portion specifies the surviving *secondary* nuclei produced *en route*. In order that ordinates for the scarcest elements be visible, the lower part of the histogram was expanded in scale compared to the upper part in which only the fluxes of C and O appear (each is greater by one or two orders of magnitude than any others for $Z \geqslant 3$).

From figure 7 it appears that, of the principal arriving cosmic-ray elements, very substantial fractions of C, O, Ne, Mg, and Si have survived with their chemical identity intact. On the other hand, each of these includes an appreciable admixture of secondaries. Li, Be, and B are entirely secondary, as is fluorine, and more than half of the arriving nitrogen is secondary. Indeed, the total arriving nitrogen exceeds the primordial contribution. As would be expected from its large geometric cross-section, cosmic-ray iron is severely depleted during its galactic journey, much of it being converted into nuclides of the sub-iron group.

Table 4 gives the calculated source abundances, relative to 100 carbon nuclei, of the cosmic-ray elements from hydrogen to nickel. It represents an updated version of table 3 of Shapiro *et al.* (1973*b*). It will be noticed that the value for hydrogen depends upon the type of interstellar energy spectrum that is assumed. The abundance value given in table 4 is based upon a power-law spectrum in total energy. At the Hobart Conference, Simpson (1971) concluded that the source spectra of ^{1}H and ^{4}He are adequately approximated by power laws in total energy with an exponent close to -2.6. More recently, from satellite data obtained during solar-quiet times on deuterium and ^{3}He, steeper interstellar spectra appear to be required (Anglin, Simpson & Zamow 1974).

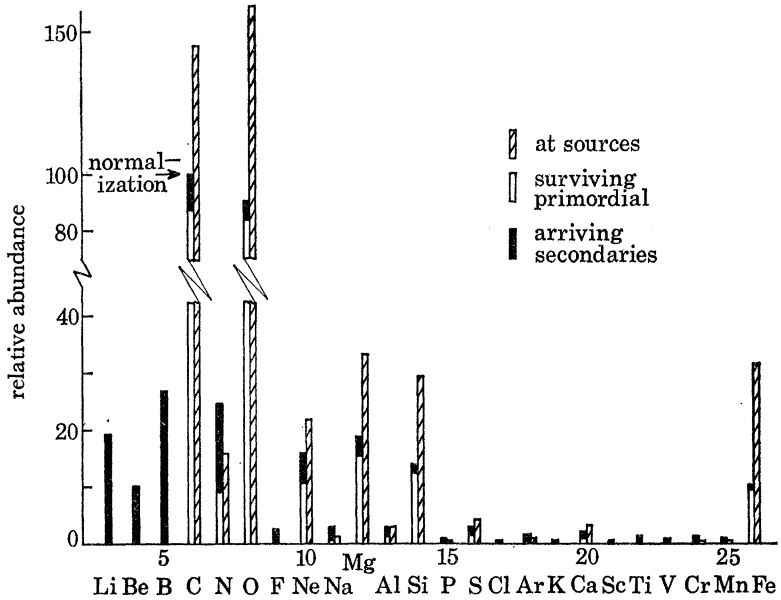

FIGURE 7. Relative abundances of cosmic rays at the sources (cross-hatched) and near the Earth (at the *left* in each pair of columns). Arriving carbon is normalized to 100. In columns that represent the arriving composition, the dark areas show the secondary contributions, while the white areas denote the surviving source-components. (Updated version of earlier calculated composition of Shapiro *et al.* 1971.)

TABLE 4. CALCULATED SOURCE ABUNDANCES OF COSMIC RAYS WITH $Z \leqslant 28$

H†	5×10^{4}	Na	0.8 ± 0.4	Ar	0.7 ± 0.5
He	2600	Mg	23 ± 2	Ca	2.2 ± 0.8
C‡	100	Al	2 ± 1	Cr	0.3 ± 0.3
N	11 ± 2	Si	20.5 ± 3	Mn	$0.2^{+0.4}_{-0.2}$
O	109 ± 2	P	$0.2^{+0.4}_{-0.2}$	Fe	22 ± 3
Ne	15 ± 2	S	3 ± 0.6	Ni	0.8 ± 0.2

† Would be 2×10^{4}, if the spectrum is rigidity-dependent. Such a spectrum, flattening at $R \lesssim 1.5$ GV (Burger & Swanenburg 1971), might also fit.
‡ Normalization.

4. SOME WAYS IN WHICH THE SOURCE COMPOSITION MIGHT ARISE

Nuclides in the 'general' composition with mass number $\geqslant 12$ are considered to have originated from the nucleosynthesis of hydrogen and helium in stellar interiors. Even the light nuclides ^{6}Li, ^{9}Be, $^{10, 11}$B can in a sense be attributed to this process, since their likely progenitors, the carbon and oxygen nuclei, were formed in this way. Only the lightest elements – hydrogen, helium, and possibly ^{7}Li – could have been produced in the primordial fireball.

Stars of a given mass and age undergo characteristic processes of element synthesis; it is thus natural to enquire whether cosmic rays originate in special events such as supernova explosions, and whether their composition arises from the special types of nucleosynthesis that occur in such cataclysms or in their aftermath. The composition of the Sun and similar stars is attributed to a conglomerate of explosive and evaporative objects that enriched the interstellar gas out of which the Solar System was formed. Examples of sources and processes that contributed to the make-up of the Sun are: evaporation from red giants, novae, planetary nebulae, mass-spills due to tidal forces of binary stars during expansive phases, and supernovae.

The ejecta of supernovae contain an admixture of elements formed during a brief phase of explosive carbon-, oxygen- and silicon-burning, as well as products of the '*r*-process' (rapid neutron capture). Even if cosmic-ray nuclei are born in such catastrophic events, however, their composition may thereafter also be affected by the mechanism of injection into the acceleration region. Havnes (1971) has, for example, proposed a dependence of cosmic-ray composition on the first ionization potential. Kristiansson (1971), on the other hand, suggested a dependence on the ionization cross-sections: injection of nuclei with a low ionization cross-section would be suppressed. The latter models are characterized by rather cold pre-injection temperatures, such as that of the interstellar gas. Acceleration processes that depend on the mass of the nucleus have been considered, e.g. by Cowsik & Wilson (1973).

It is helpful in such problems to make a detailed comparison between the source abundances of cosmic rays and the solar-system or stellar abundances. In figure 6 this was done for the *arriving* cosmic rays versus those of the Solar System; in figure 8 a similar comparison is made with cosmic rays at the *sources*. The relative abundances are normalized to unity for carbon. As a measure of progress in this field, it is instructive to look at figure 19 of Shapiro & Silberberg (1970*a*): the number of elements that can be included has doubled in four years. In figure 8, abundances in the Solar System are denoted by the symbol X. In general, these are based on optical spectra of the Sun, adopted from Unsöld (1971). However, when the latter were unavailable or subject to question, other sources of solar-system abundances were utilized. These are noted by (*m*) for *meteorites* (carbonaceous chondrites), by (*c*) for ultraviolet lines from the *corona*, and by (*f*) for solar *flare* particles.

The statistical errors in abundances of elements at cosmic-ray sources tend to be large if the abundance relative to carbon is less than 2%, owing to contamination by fragmentation products. The errors in solar abundance determinations are not shown. For the more plentiful elements ($\geqslant$ 0.1% of carbon), the abundance estimates based on photospheric spectra generally agree (within a factor of 2) with those derived from meteorites. On the other hand, estimates based on coronal lines or on flare particles may deviate from those based on photospheric spectra by a factor > 2. Nitrogen and oxygen are seen to be *under*abundant in the source composition (relative to carbon) by a factor $\geqslant$ 2. The elements Mg, Si and Fe are *over*abundant by a factor of about 2. Likewise, Al, Ca and Ni are notably overabundant in cosmic rays. Possible interpretations of these differences are discussed below.

Figure 9 shows the ratios of the element abundances for cosmic rays at the source regions to those of matter in the Solar System. The two sets of data are normalized at a value of unity for iron. For atomic numbers $Z \leqslant 28$, the solar abundances recently compiled by Unsöld (1971) are used; these agree well with the values favoured by Withbroe (1971). For elements with

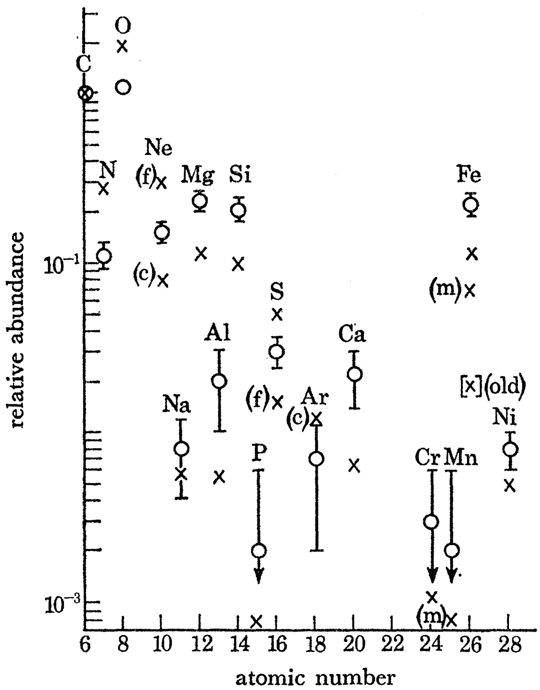

FIGURE 8. Relative abundances of elements in the Solar System (×) and in cosmic rays (○) at the sources. The two sets are normalized to unity at carbon (up-dated version of Shapiro *et al.* 1972*b*). Symbols are explained in the text.

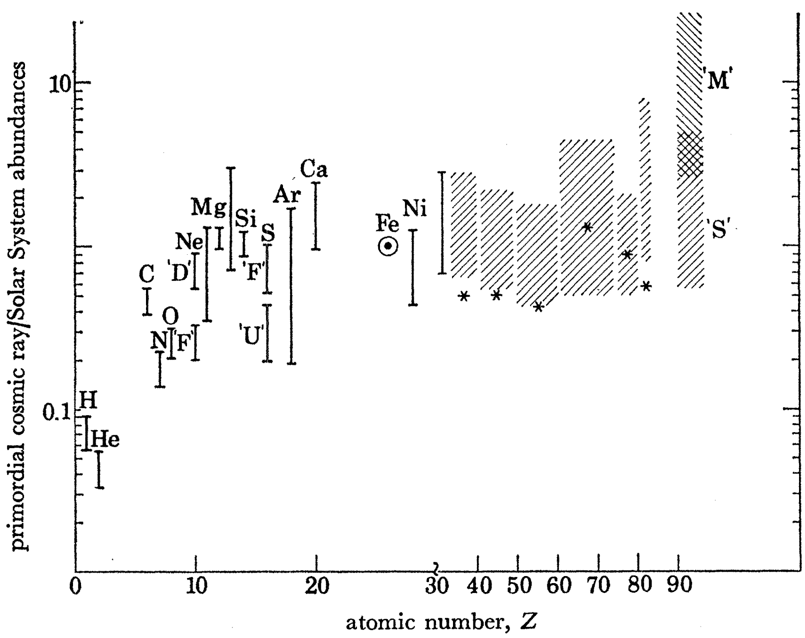

FIGURE 9. Ratio of the elemental abundances of cosmic rays at the sources to those in the Sun and meteorites. The two sets of data are normalized to unity at iron (Shapiro *et al.* 1973*b*). * $r+s+p$ components of solar material.

$Z \geqslant 29$ good data on solar abundances are scarce, hence the recent *meteoritic* values of Cameron (1973) were adopted. For Ne, and also for S, two conflicting solar values are shown; these elements, and argon too, are poorly known in the Sun. The symbol 'F' denotes an estimate based on solar flare particles (Bertsch, Fichtel & Reames 1972), 'D' is based on solar spectra in the ultraviolet, measured by Dupree (1972), and 'U' refers to Unsöld (1971). For the actinide elements, 'S' denotes the comparison of cosmic-ray with solar-optical abundances while 'M' denotes comparison with the meteoritic values.

Figure 9 reminds us that, relative to *iron*, cosmic rays at the sources are 'deficient' by an order of magnitude in hydrogen and helium; similarly, C, N and O are low by factors of 2 to 5. Elements produced by hydrogen-burning and helium-burning are thus considerably less prominent in cosmic rays than in the Sun. On the other hand, the relative supplies of elements produced in explosive C-, O-, and Si-burning, and in the *r*-process, are much alike in the two compositions. Arnett & Schramm (1973) have calculated the makeup of supernova ejecta and find that it resembles that of cosmic rays.

As alternatives to the foregoing class of models in which nucleosynthesis directly accounts for cosmic-ray composition, another class of models has been proposed. Various processes of selective acceleration are central to the latter hypotheses. For example, the rate of injection might be proportional to the ionization cross-sections, or acceleration might depend on the mass number of the nuclide. Such models could account for some features of figure 9, and it seems premature to exclude these alternatives.

Let us suppose, for example, that cosmic rays are samples of the interstellar medium, ionized and injected by magnetic fields or intense radiation fields in the vicinity of certain sources (e.g. supernova remnants, white dwarfs, magnetic stars, etc.). Since most of the interstellar material is very old (*ca.* 10^9 years), it follows that only stable or only very long-lived nuclides could have survived in appreciable numbers until their injection.

In order to discriminate between models of the nucleosynthesis and selective acceleration types, certain tests could be applied, some of which were discussed by Shapiro *et al.* (1973*a*). Among these would be the determination, in the arriving cosmic rays, of the U/Th ratio; another would be the reliable detection of transuranic nuclei, such as Np, Pu and Cm. If cosmic rays come from 'recent' supernova ejecta, with an age $< 10^7$ years, then they should contain surviving transuranic elements; moreover, the U/Th ratio should be of the order of 10, since most of the radioactive progenitors of Th are effectively 'stopped' at ^{244}Pu and ^{236}U. Only if cosmic rays have been subject to selective acceleration mechanisms, could they contain enough Th to make the ratio U/Th $\leqslant 10$.

5. The relative abundance as a function of energy

We have noticed in §2 that the composition of cosmic rays seems to be insensitive to energy in the region from 10^7 up to 10^{10} eV. Lately, a significant drop has been discovered in the ratio of certain secondaries to their cosmic-ray parents; it occurs above 10^{10} eV. Figure 10 and figure 11 (Webber 1973) each plots the ratio of a set of predominantly secondary elements to their principal cosmic-ray progenitor(s). The notable decrease in the elements Li, Be, B and N relative to C and O sets in at *ca.* 20 GeV/u (figure 10), while in the ratio of sub-iron elements to Fe, it begins at *ca.* 10 GeV.

These striking variations are apparent notwithstanding the spread in ordinate values. We shall say no more about them here: the compositional changes, and their possible implications (e.g. diminution in path lengths and escape times at energies above 10 GeV), will be amply discussed in Professor Meyer's review in this volume. However, in the context of the present paper (which deals with the nuclei *below* 10^{10} eV) it is noteworthy that the abundance ratios in figures 10 and 11 show no significant departure from constancy in the region 1 to 10 GeV.

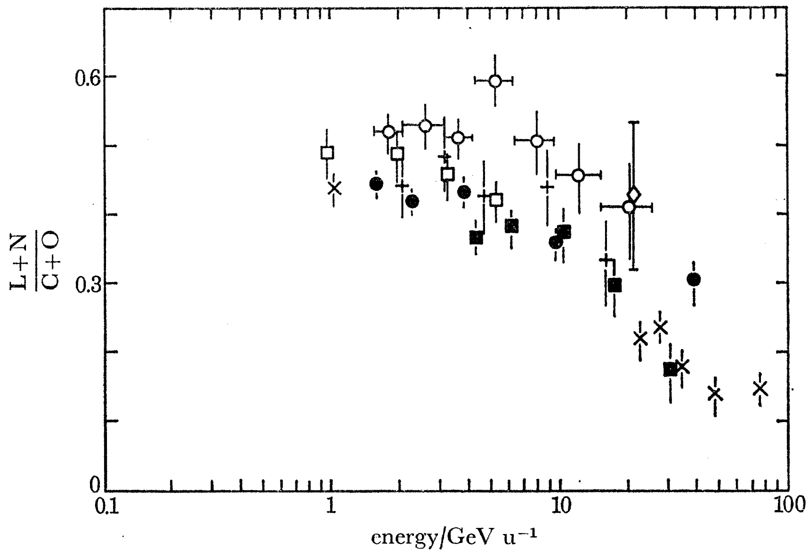

FIGURE 10. Plotted against the energy per atomic mass unit is the ratio of a set of predominantly secondary elements to their principal progenitors. (The L-nuclei are, of course, considered to be exclusively secondary.) (After Webber (1973) and references therein, augmented by data of Durgaprasad (1965).)

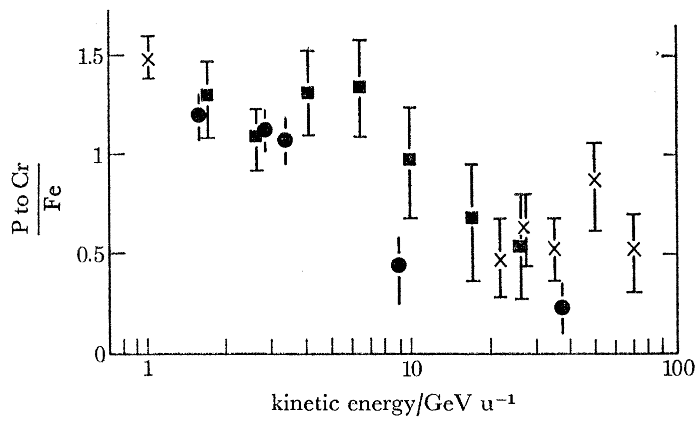

FIGURE 11. As in figure 10, this diagram displays the variation with energy of a flux ratio of secondary-to-progenitor elements. In this case, the elements ($15 \leqslant Z \leqslant 24$) are largely the spallation products of iron. The data are those of (■) Balasubrahmanyan *et al.* (1973), (×) Juliusson (1973), and (●) Webber *et al.* (1973*c*). (After Webber 1973.)

(The present values are, to be sure, afflicted by large statistical errors, especially in figure 10.) There have been indications of compositional variation between 10^7 and 10^{10} eV, but these are not firmly established.

A remarkable effect, based on satellite observations at very low energies, $\leqslant$ 40 MeV/u, has been reported by McDonald, Teegarden, Trainor & Webber (1974). Displayed in figure 12 is the differential intensity of C, O and He against kinetic energy. The flux of oxygen exceeds that of carbon by an order of magnitude, and, with decreasing energy, it becomes comparable to that of He at about 10^7 eV/u. Nitrogen, not shown in this diagram, behaves similarly to oxygen. Among the tentative hypotheses to explain these effects is that of Hoyle & Clayton (personal communication), who invoke special conditions for production of these elements in the atmospheres of certain white dwarfs. In their model, under special conditions of mass transfer from a companion, a nova explosion is triggered; CNO-cycle reactions in the white dwarf envelope then give rise to the anomalous composition. Fisk, Kozlovsky & Ramaty (1974), on the other hand, suggest selective ionization of neutral C and O atoms, and their subsequent acceleration within the solar-system cavity.

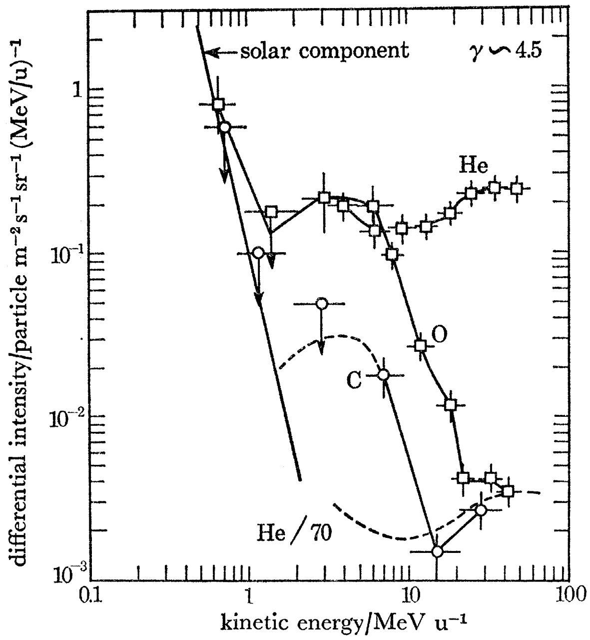

FIGURE 12. The energy spectra of He, C and O between 1 and 50 MeV/u. (After McDonald *et al.* 1974; see also Webber 1973.)

In addition to the unexpected phenomenon just described, there were other hints in a few reports at the recent Denver Conference on Cosmic Radiation (1973) of various surprises in store for us at the lowest energies.

6. Transformation and propagation of cosmic-ray nuclei in space

About half of the heavy cosmic-ray nuclei have been fragmented by collision in the time interval between their acceleration and arrival in our vicinity. Along with this depletion of the primordial nuclides, many rare species have been built up by spallation, occasionally by as much as several orders of magnitude.

In order to learn of the amount of material traversed by the cosmic rays, their confinement time in the galaxy, the mean density of the material traversed, etc., it is essential to know the relevant nuclear breakup cross-sections. The Orsay group (Yiou, Seide & Bernas 1969; Yiou, Raisbeck, Perron & Fontes 1973) have performed a particularly urgent task in measuring the yields of the Li, Be and B isotopes from various progenitors.

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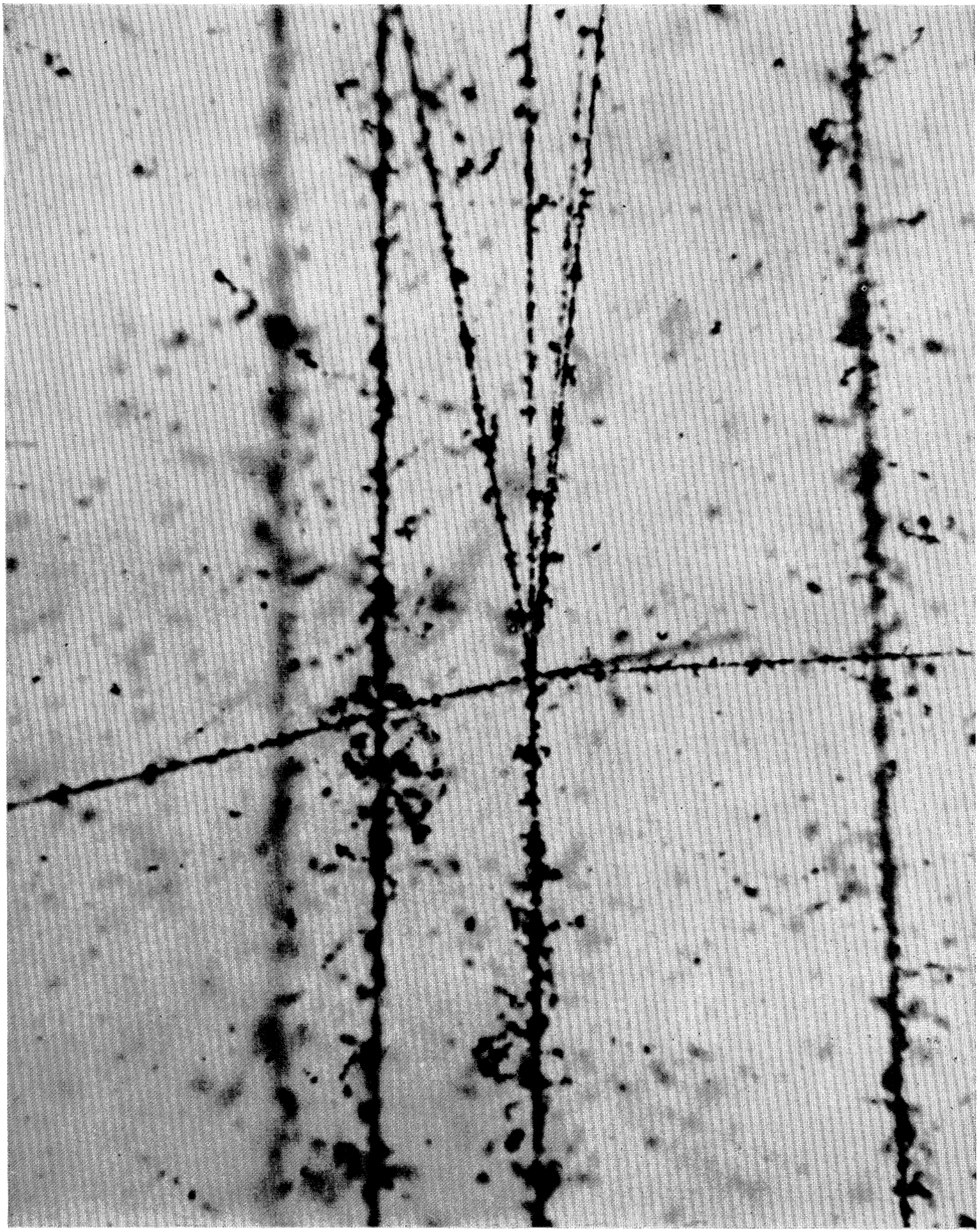

FIGURE 13. The breakup of a relativistic nitrogen ion from the Princeton Particle Accelerator upon collision with a nucleus in photographic emulsion; see text for particulars (Kidd, Shapiro & Wefel, N.R.L., unpublished).

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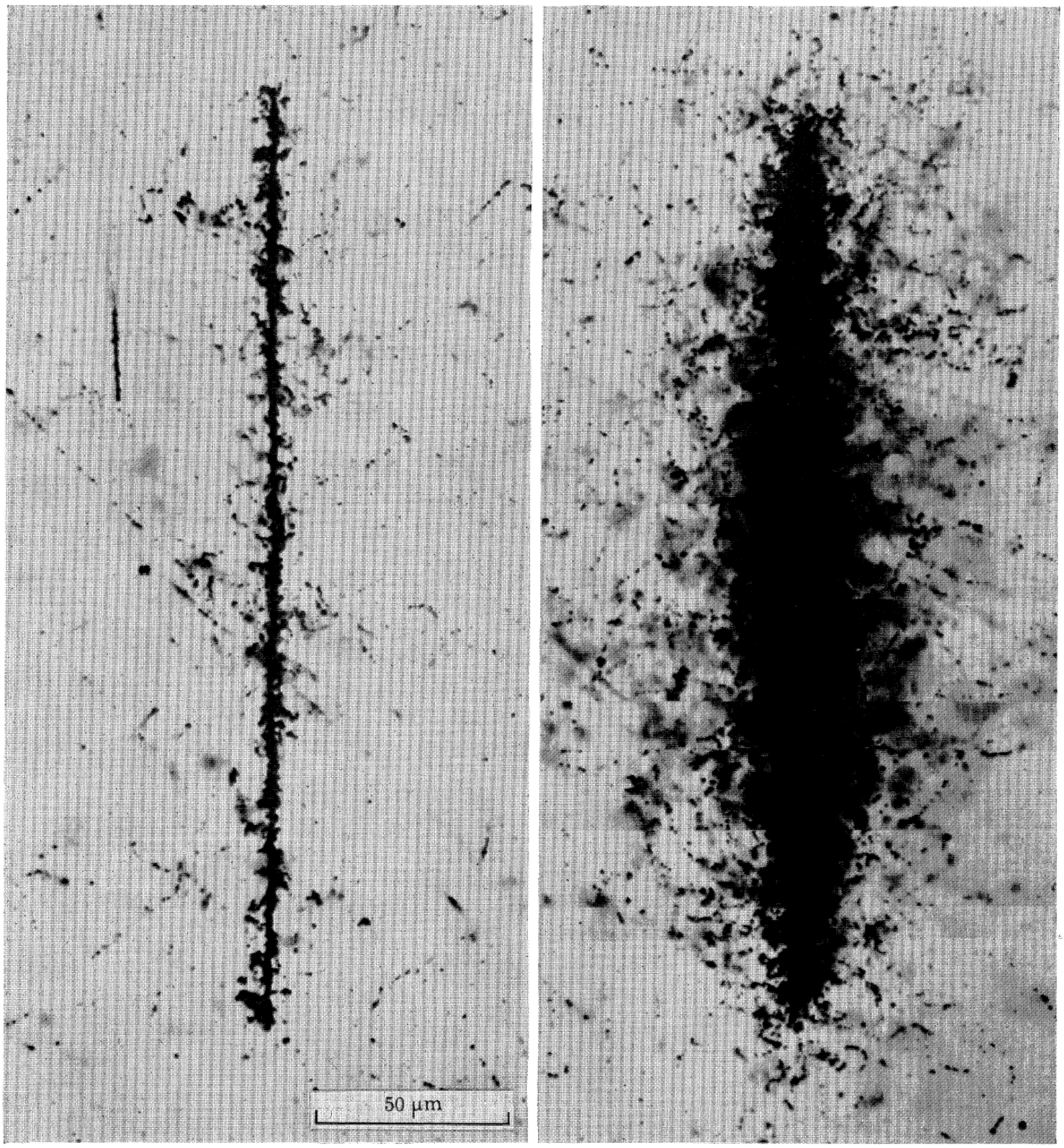


Fe $Z = 26$ $Z \approx 90$

FIGURE 22. Cosmic-ray tracks recorded by a fast iron nucleus and by a nucleus of one of the actinide elements in a photographic emulsion (courtesy of P. Fowler). The scale of this photomicrograph appears at the bottom.

The high-energy ($\approx 10^3$ MeV/u) heavy-ion beams achieved since 1971 at Princeton and Berkeley enable us to measure production cross-sections over a wide range of stable and radioactive nuclides. The energies and transformations resemble those of characteristic cosmic rays in space. The photomicrograph in figure 13, plate 12 – the first for a laboratory beam of relativistic ions (with $Z > 2$), shows the breakup of a nitrogen ion (278 MeV/u in energy)

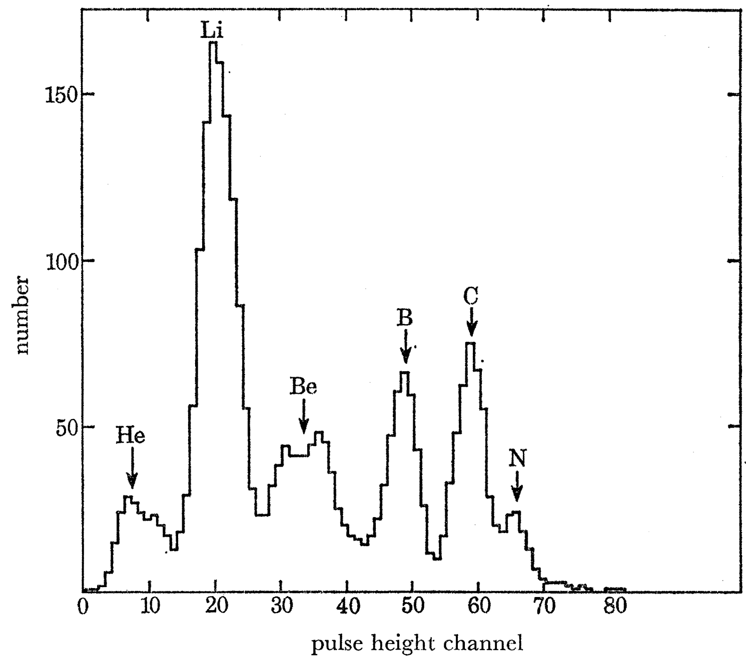


FIGURE 14. Breakup products from collisions of *relativistic* nitrogen ions (Wefel *et al.* 1973). Sensitivity threshold was set to discriminate against He. (Heavy ions formerly available in the laboratory had about 10 MeV/u.)

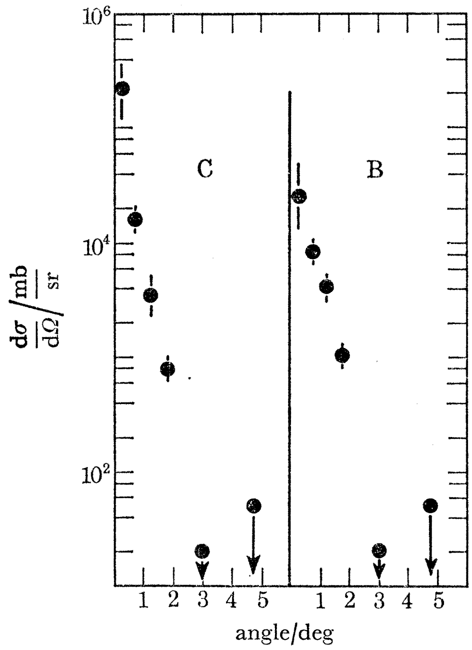


FIGURE 15. Angular distributions of fragments of carbon and boron generated in the breakup of relativistic nitrogen ions in a liquid hydrogen target (see also figure 14).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

from the Princeton accelerator upon collision with a target nucleus in a photographic emulsion. Three fast helium nuclei and a proton emerge in the forward direction; also visible are the tracks of three wide-angle 'evaporation' products from the target nucleus.

Wefel, Kidd, Vosburgh & Schimmerling (1973) have studied the interactions of a nitrogen beam (530 MeV/u) in a liquid hydrogen target. Figure 14 shows the distribution of various elements at a production angle of 2° with the incident beam. (To obtain cross sections, it is necessary to integrate over the production angles. More helium nuclei are produced at larger angles, and more of the heavier secondaries at smaller angles.) The angular distribution in the differential cross-sections for producing carbon and boron is given in figure 15. Useful data such as these may be expected to accumulate as the Berkeley Bevatron devotes additional time to this work. A new facility – the Bevalac – will soon also play a major role. (The Princeton accelerator, where the foregoing research was carried out, is currently in 'moth balls' owing to lack of operating funds.)

Today, throughout the periodic table, many of the important modes of breakup are still unmeasured. Silberberg & Tsao (1973 *a*, *b*) have extended and refined Rudstam's (1966) semi-empirical equation for calculating cross-sections. For target nuclei with mass number $A_t < 35$, the values calculated with the best-fit semi-empirical parameters have standard deviations of about 20–30% from the measured ones. Table 5 lists the available cross sections for production of the Be and B isotopes at energies exceeding 2 GeV/u. The small number of *measured* values are in italics, while the rest have been calculated by semi-empirical equations. Numbers like those in this table are essential for calculating the confinement time of cosmic rays in the Galaxy, using the long-lived radioactive ^{10}Be as a tracer.

TABLE 5. CROSS SECTIONS (IN mb†) FOR COSMIC-RAY PRODUCTION‡ OF Be AND B ISOTOPES ($E > 2$ GeV/u)

	^{11}B	^{12}C	^{14}N	^{16}O	^{20}Ne	^{24}Mg	^{28}Si	^{56}Fe
^{7}Be	*4*§	*10*	*12*	*10*	10	*12*	10	*8.5*
^{9}Be	6.4	3.5	3.5	*3.5*	3.5	3.5	3.5	5.4
^{10}Be	*14*	*3*	2	*1*	2	2	2	*4.4*
^{10}B	26	16	14	*13*	11	9.6	8.6	8.6
^{11}B	—	*51*	25	*25*	18	15	12	12

† 1 mb = 10^{-31} m^2.
‡ By collision with hydrogen.
§ σ, *measured* cross-section, in italics.

Figure 16 illustrates the method of using long-lived radioactive tracers for deducing the dwell time of cosmic rays. Limiting values of the relative abundances, calculated for the extreme cases of total decay or complete survival of a given radionuclide are shown as a function of energy. Besides ^{10}Be, there are other tracers or 'propagation clocks' for cosmic rays: ^{26}Al, ^{36}Cl and ^{54}Mn, but these are harder to resolve and also less available; their flux is very low. *Atomic* ^{54}Mn would normally decay in about a year by electron capture, but fast cosmic-ray nuclei (devoid of electrons) have an exceedingly low probability of capturing an ambient electron in space. The nuclide ^{54}Mn accordingly undergoes β-decay in a period of about 10^6 years (Cassé 1973).

Applicable in principle to any of the foregoing tracers is the technique of comparison shown in figure 16. However, there are practical difficulties – e.g. of low intensity and limited isotopic

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

resolution – that have thus far impeded the successful estimation of cosmic ray 'age' through *direct* measurement of any radionuclidic abundance. Even the most promising candidate, ^{10}Be, is produced with so meagre a yield that it is expected to constitute less than 15% of the arriving beryllium. Hence, measurement of its flux at the low energies where it can be resolved from ^{7}Be and ^{9}Be has not yet been accomplished at a statistically significant level.

Meanwhile, however, an alternative approach has been pursued that can give at least limiting values for the dwell time. The ratio of arriving *elemental* Be to B must depend on the production and decay of ^{10}Be, hence on the confinement time of its progenitors. This is an

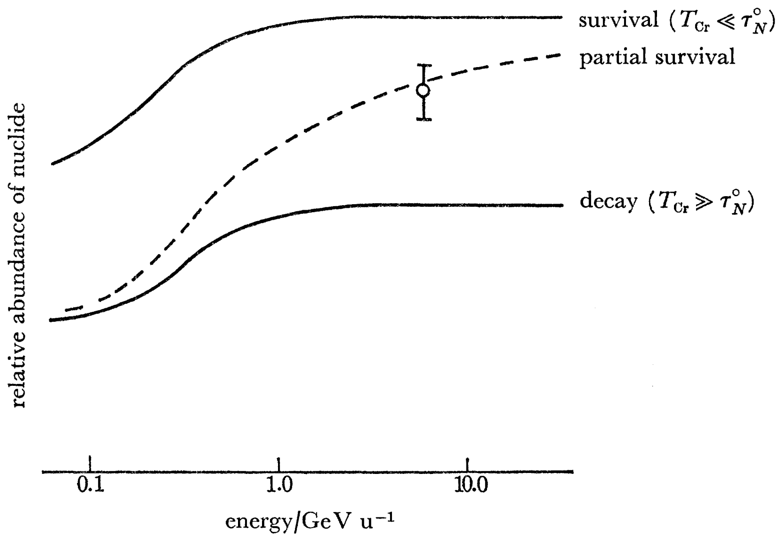


FIGURE 16. Tracer method for determining the galactic confinement time of cosmic rays. Limiting values of calculated relative abundances of the tracer are shown for the extreme possibilities of survival and (complete) decay of a long-lived radionuclide. The dashed curve illustrates a hypothetical case in which the half-life is somewhat shorter than the dwell time.

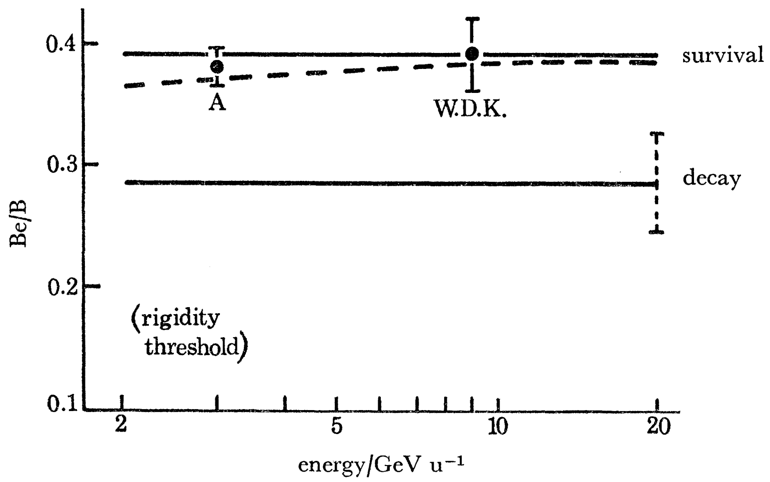


FIGURE 17. Experimental and calculated ratios of Be/B (corrected to integration above rigidity thresholds). The dashed curve displays the expected Be/B curve for a dwell time of 3×10^6 years, assuming an exponential distribution of path lengths. The point labelled 'A' is based on measurements of O'Dell *et al.* (1973), Juliusson *et al.* (1972), Smith *et al.* (1973), and Cassé *et al.* (1971); point W.D.K. is from Webber *et al.* (1973*a*). The dashed error bar near the word 'decay' is the estimated error in the calculated ratio. The half life (at rest) of ^{10}Be is 1.6×10^6 years.

insensitive index, and one which is unlikely, in the early foreseeable future, to give a *value* for the dwell time. But it can yield a very useful *upper limit*. For this reason, and because of its important astrophysical implications, the ratio has been measured by several groups using different techniques of detection. Calculations essential to the use of the Be/B ratio for estimation of cosmic-ray 'age' have been carried out and updated – especially by the N.R.L. group – Shapiro & Silberberg (1967, 1968, 1970*b*, *c*) and O'Dell, Shapiro, Silberberg & Tsao (1971, 1973) – as a function of cosmic-ray lifetime.

Figure 17 summarizes recent results on the Be/B ratio. It compares calculations with observations at energies greater than 1 GeV/u, where most of the data have been obtained, and where agreement among various observers is now quite satisfactory. The calculated functions for survival and decay of ^{10}Be are shown by the solid curves. An intermediate case is represented by the dashed curve, i.e. that for a confinement time of 3×10^6 years, in a hydrogen medium of density 1 atom/cm^3. The observed ratios are marked by the symbols A and W.D.K.; the former value (0.38 ± 0.02) is the weighted mean of data from four different laboratories, obtained at nearly the same rigidity threshold. The experimental result at higher energies was reported by the New Hampshire group (see legend for figure 17). (A recent measurement by Brown, Stone & Vogt (1973), not shown in this figure, yielded a value of 0.43 ± 0.03.) These results are consistent with the survival of most of the ^{10}Be, and they set an upper limit $T < 10^7$ years, for the cosmic-ray confinement time, taking into account the Lorentz dilation affecting the decay of relativistic ^{10}Be. This limit is quoted at a confidence level of about 95 %: the observed ratio departs by two standard deviations from the decay curve. The overall standard error in the *calculated* ratios is indicated by the dashed vertical bar at the lower right of the diagram; it was computed by propagating the estimated uncertainties in the various parameters, notably those in the relevant cross-sections.

An independent method for deducing a confinement time T, based on observations of the e^+ component, tends to support the upper limit quoted above. Positrons are generated in the cosmic radiation mainly by the chain of processes:

$$p + p \rightarrow p + n + \pi^+;$$

$$\pi^+ \rightarrow \mu^+ + \nu;$$

$$\mu^+ \rightarrow e^+ + \nu + \bar{\nu}.$$

Fanselow, Hartman, Hildebrand & Meyer (1969) and Buffington, Smoot, Smith & Orth (1973) have measured the e^+/e^- ratio as a function of energy. From their results it appears that the e^+ spectrum is unaffected by synchrotron or Compton losses up to 10 GeV. Accordingly, it is reasonable to deduce that T is less than 2×10^7 years for the progenitor protons. It may also be concluded that, irrespective of the origin(s) of other cosmic rays, the arriving *secondaries*, e.g. positrons, Li, Be, B, and most cosmic-ray nuclides in the group $17 \leqslant Z \leqslant 25$, must be generated within our Galaxy. (It is also worth noting that the shape of the e^- spectrum at *high energies* – though still poorly known especially above 100 GeV – is consistent with an electron dwell time of $< 4 \times 10^6$ years. Moreover, the negative electrons, like the positive ones, must not only be confined to the galactic disk, but must *originate* there. In the vast metagalactic regions, electrons would have enough time to lose their energy by Compton collisions with the photons of the universal microwave background.)

7. Isotopic composition of cosmic rays – observations and calculations

Research on isotopes in cosmic rays is likely to resolve basic questions about their nucleosynthesis, propagation, and origin. Progress in this field for nuclei with $Z > 2$ has barely begun. About a decade ago, the isotopic composition of helium alone had been well determined (see O'Dell, Shapiro, Silberberg & Stiller (1965) and references therein). Soon thereafter, deuterium was measured (see Simpson review (1971) and references therein). Very recently, a promising start has been made all the way up to iron.

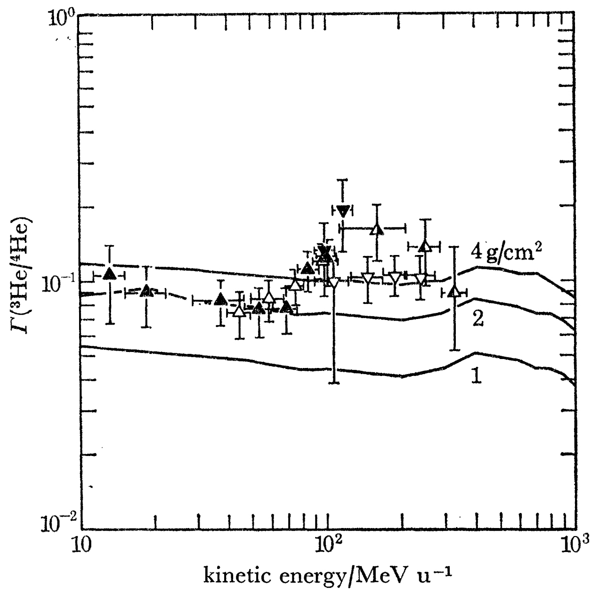


Figure 18. Observations of the ratio ^{3}He/^{4}He, plotted against energy, and calculated ratios for several assumed mean path lengths (Simpson 1971). References to the measurements are given by Hsieh & Simpson (1970).

Figure 18 shows the ratio Γ of ^{3}He/^{4}He as a function of energy; its value is 0.11 ± 0.02 [0.10 for ^{3}He/(^{3}He + ^{4}He)]. However, at the lowest energies (*ca.* 15 MeV/u), Anglin *et al.* (1974) have lately obtained a value only one-fourth as great at a time near solar minimum. They also found a low ^{2}H/^{4}He ratio, similar to that reported recently by Teegarden, von Rosenvinge & McDonald (1973) and Hurford, Mewaldt, Stone & Vogt (1973). These observations suggested to Anglin *et al.* (1974) a steeply falling local interstellar spectrum, and reduced effects of adiabatic deceleration at the very lowest energies, near solar minimum. The conclusions differ from those reached earlier near solar maximum by Comstock, Hsieh & Simpson (1972).

Above 50 MeV/u, the ratios ^{3}He/^{4}He and ^{2}H/^{4}He become nearly independent of the solar cycle, and can be used (like the L/M ratio) to calculate the mean path length $\bar{\lambda}$ of cosmic rays in interstellar space. The value so obtained, $\bar{\lambda} \approx 4 \pm 1$ g/cm² of *hydrogen*, agrees satisfactorily with the value 5 ± 1 g/cm² derived from the ratios (Li, Be, B)/(C, N, O) and (Cl to Mn)/Fe. If we take into account that 10 % of the atoms in the interstellar gas are helium, the mean path length becomes 6 g/cm².

Recent work by Webber, Lezniak, Kish & Damle (1973*a*), on the isotopic constitution of lithium through nitrogen, is reproduced in figure 19. For Be and N, the results differ markedly from the general isotopic abundances, as was predicted by Shapiro & Silberberg (1968) and by Tsao, Shapiro & Silberberg (1972, 1973). While, in ordinary matter, practically all beryllium is ^{9}Be, the isotope ^{7}Be in the cosmic rays not only survives – it predominates over ^{9}Be and ^{10}Be. In figure 19, only seven events were attributed to ^{10}Be. This result, when confirmed with better statistics, would support the survival of a goodly fraction of ^{10}Be even at the low energies where the relativistic time dilation factor γ does not exceed *ca.* 1.5. (On the basis of this result, Webber *et al.* (1973*a*) suggest $T \approx 3 \times 10^{6}$ years, within a factor of two.) In the same histogram, about half of the observed nitrogen is seen to be ^{15}N, derived from single-nucleon stripping of the abundant ^{16}O.

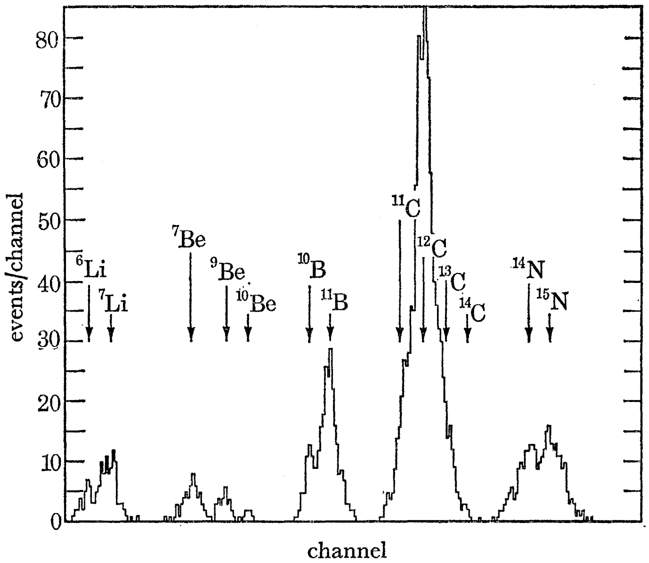


FIGURE 19. Isotopic abundances of elements Li to N in the arriving cosmic rays (Webber *et al.* 1973*a*).

Observations of isotopic abundances from Mg to Fe by Webber, Lezniak & Kish (1973*b*) are displayed in figure 20. The composition of calcium deviates appreciably from the 'universal' abundances, as could be expected. In the latter, almost all the calcium is ^{40}Ca, while in cosmic rays, fragmentation of Fe builds up the isotopes with mass numbers 42, 43 and 44. Thus, the arriving cosmic-ray calcium detected in our vicinity is largely the result of spallation. The distribution of iron isotopes in figure 20 includes much ^{58}Fe. This is surprising: in the Solar System, only 0.3 % of iron is ^{58}Fe. From theories of nucleosynthesis, source production of substantial amounts of ^{58}Fe appears unlikely. Truran (1972) shows that this isotope arises deep in the stellar interior, close to the region collapsing into the neutron star, where the neutron density is high.

Tsao *et al.* (1973) at N.R.L. have calculated the isotopic composition of the arriving cosmic-ray elements from lithium to nickel ($3 \leqslant Z \leqslant 28$). They assumed (*a*) a source composition of elements like the one described in §3, (*b*) an isotopic composition of these source-elements similar to that adopted by Cameron (1973) for the general abundances, (*c*) fragmentation in an interstellar gas in which H:He = 9:1 (according to *numbers* of atoms), and (*d*) a quasi-exponential distribution of cosmic-ray path lengths, with a mean value $\bar{\lambda} = 6$ g/cm^2.

Some results of these calculations are illustrated in figure 21, in which the calculated 'arriving' isotopic abundances are compared with Cameron's (1973) table of general abundances. In this diagram, the total amount of each element is normalized to unity. Predicted to be observed among the cosmic-ray nuclides are some radioactive ones that decay only by electron capture (e.g. ^{7}Be and ^{37}Ar), some long-lived species like ^{10}Be, and stable spallation products like ^{15}N, ^{33}S and ^{34}S. Comparison of the various calculated abundances with measured distributions should reveal whether – and in what ways – cosmic-ray sources have an unusual isotopic composition. (Indirectly, they may also provide improved estimates of cross sections.)

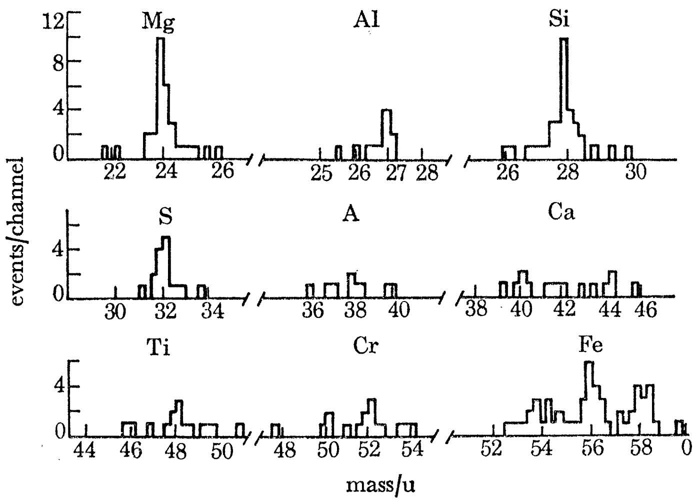


FIGURE 20. Mass distribution of nine elements at energies of about 500 MeV/u (Webber *et al.* 1973*b*).

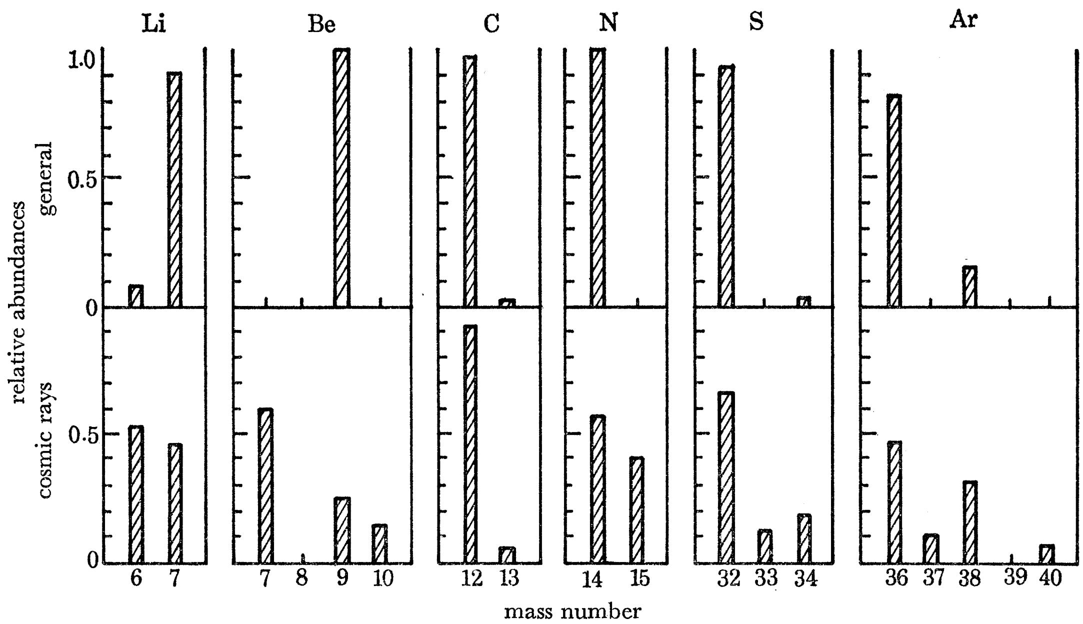


FIGURE 21. Comparison of the *calculated* isotopic abundances for six elements in the arriving cosmic rays with observed abundances in solar-system material (Tsao *et al.* 1973). The ordinates are adjusted so that the total for each element is normalized to unity.

Radionuclides that decay only by electron capture, and thus survive among the fast cosmic rays, do begin to capture electrons and decay at lower energies of the order of 100 MeV/u (higher for nuclei of greater charge). In principle, it should therefore be possible to use the fraction of such surviving nuclides observed at various energies to explore the effects of adiabatic deceleration in the Solar System, as well as acceleration or deceleration in interstellar space. Among the nuclides that decay only by electron capture are ^{7}Be, ^{37}Ar, ^{41}Ca, ^{44}Ti, ^{49}V, ^{51}Cr, ^{53}Mn, ^{55}Fe, and several others with $Z > 26$. The nuclide ^{44}Ti is of special interest; it is formed in explosive Si-burning, and decays into ^{44}Sc and then into ^{44}Ca, with a half-life of about 50 years, unless stripped. Thus, if cosmic rays are accelerated in supernova remnants within several years after nucleosynthesis, as proposed by Kulsrud, Ostriker & Gunn (1972), then ^{44}Ti should survive in cosmic rays (Silberberg 1974). However, additional ^{44}Ti will also be formed subsequently by spallation, and a correction would be needed for this secondary contribution.

Altogether, it may be expected that studies of cosmic-ray isotopes in the coming years will expand the horizons of cosmic-ray astrophysics.

8. Abundances and spectra of ultra-heavy nuclei

Ultra-heavy cosmic rays ($Z \geqslant 30$) were first observed in meteoritic crystals through ancient particle tracks revealed by chemical etching (Fleischer *et al.* 1967). The tracks of *contemporary* ultra-heavy nuclei were detected by Fowler, Adams, Cowen & Kidd (1967) who boldly challenged the odds against their observation – the discouraging ratio $< 10^{-6}$ of ultra-heavy nuclei to all lighter nuclei – by deploying large-area stacks of photographic emulsion at high altitudes. A lively summary of the history of the subject in its first half decade (1966–71), including a description of experimental techniques, has been given by Price (1971).

Table 6. Abundances of Fe, Ni–Cu, and ultra-heavy elements in the arriving† cosmic rays‡§

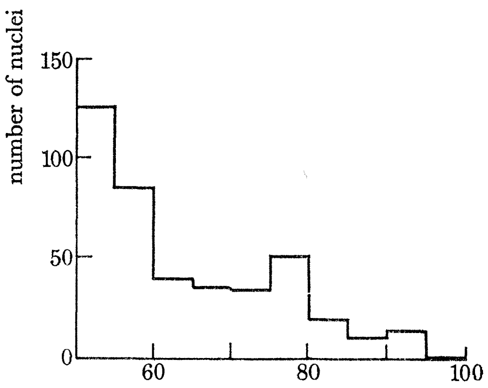
atomic number	relative abundance	atomic number	relative abundance
26	10^6	55–59	6.1 ± 1.2
28, 29	$(44 \pm 4) \times 10^3$	60–64	2.5 ± 0.6
30, 31	$(4.5 \pm 1.1) \times 10^3$	65–69	2.2 ± 0.6
32–34	$(0.5 \pm 0.1) \times 10^3$	70–74	2.3 ± 0.7
35–39	65 ± 20	75–79	4.7 ± 0.7
40–44	35 ± 14	80–84	2.0 ± 0.5
45–49	4 ± 2	85–89	1.1 ± 0.5
50–54	8.3 ± 1.2	90–94	1.5 ± 0.4

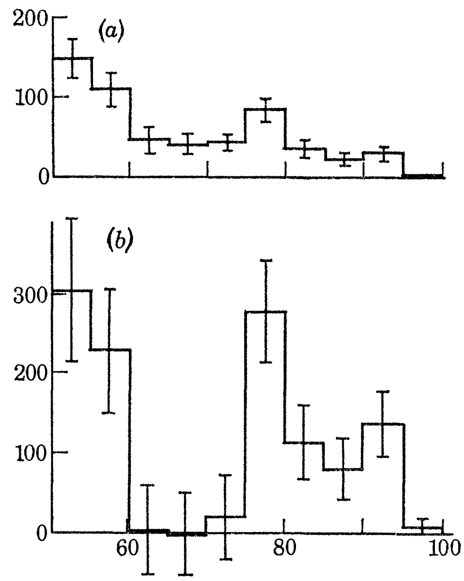
† At the top of the atmosphere.
‡ Adapted mainly from Fowler (1973); for $Z \leqslant 34$, the data are those of Binns *et al.* (1973).
§ Normalized to 10^6 Fe nuclei.

Being highly charged, ultra-heavy nuclei passing through emulsions leave tracks so dense that they can sometimes be seen with the naked eye. Some idea of the prodigious rate of ionization loss due to one of the heavier nuclei thus far recorded ($Z \approx 90$) is conveyed by figure 22, plate 13, in which the track of a relativistic iron nucleus looks anaemic by comparison.

After about seven years of research with detectors including etchable plastics and ionization chambers, $< 10^3$ ultra-heavy nuclei have been observed, and the integrated aperture-time factor, i.e. the total exposure to ultra-heavy nuclei, has been about 5×10^7 m^2 sr s, most of it with vast layers of sandwiched plastics, absorbers, and photographic emulsions. The data in the region between iron and bromine have been obtained mostly with electronic instruments.

Table 6, adapted from a recent review by Fowler (1973), summarizes the present state of our knowledge of the relative fluxes of the arriving ultra-heavy nuclei in the cosmic rays. In the arbitrary scale adopted for this table, all fluxes are compared to 10^6 arriving iron nuclei. The last entry in table 6 extends up to atomic number 94 which is due to limited charge resolution – not because there has yet been an unambiguous identification of any transuranic elements. For the same reason, the final entry (for $Z > 94$) in Fowler's table has been omitted here: as of this writing, any indications of *possible* transuranic cosmic-ray nuclei have not yet been confirmed. (Evidence for transuranic nuclides in the cosmic rays may yet show up in future observations, especially if ultra-heavy cosmic rays were *synthesized* in sources less than 10^8 years ago.)





atomic number

FIGURE 23. Distribution in atomic number of ultra-heavy cosmic rays with $Z \geqslant 50$ at balloon-altitudes near 4 g/cm² (Fowler 1973).

FIGURE 24. Relative abundances of ultra-heavy cosmic ray nuclei, extrapolated (*a*) to the top of the atmosphere, and (*b*) to cosmic-ray sources, for elements with $Z \geqslant 50$ (Fowler 1973).

Figure 23 shows the composition at balloon altitudes of those ultra-heavy nuclei with $Z > 50$. The calculated relative abundances at the top of the atmosphere and at the cosmic-ray sources, also summarized by Fowler (1973), are seen in figure 24. The composition in the lower portion of this figure can be compared to those calculated by Shirk *et al.* (1973) and by Shapiro, Silberberg & Tsao (1973*a*); also see figure 9 of the present paper. Within the wide limits of error there is fair agreement among these groups as to the source composition of the ultra-heavy nuclei. However, figure 24 shows negligible flux in the region $60 \leqslant Z \leqslant 74$, while Shirk *et al.* and Shapiro *et al.* deduce the presence of an appreciable abundance of source elements in this group. The apparent disagreement may not be significant, as it amounts to < 2 standard deviations.

Prominent in figure 24 are two of the peaks attributed to the *r*- and *s*-processes of element synthesis. In the region of the 'valley' between atomic numbers 60 and 74, the arriving particles are probably due mainly to the breakup of heavier nuclei.

It is still unknown whether the abundances of the ultra-heavy nuclei in the source(s) can be accounted for just by rapid-neutron capture or by a combination of *r*- and *s*-processes. Both types of nucleosynthesis seem to contribute to the composition of the Solar System, and while both probably go on in evolved stars, the two processes tend to occur under different conditions. The slow-neutron capture process gives rise to abundance peaks at atomic numbers slightly above peaks due to the *r*-process.

To date, the quality of resolution between neighbouring elements makes it difficult to judge whether the ultra-heavy elements in the cosmic rays result from *both* *r*- and *s*-processes, or from the *r*-process alone. The difference is important, inasmuch as the presence of a combination of the two would support a model in which ultra-heavy cosmic-rays were once a part of the interstellar medium. On the other hand, a *dearth* of *s*-process elements would suggest that the ultra-heavy nuclei were generated in supernovae before their injection into the cosmic-ray 'beam'.

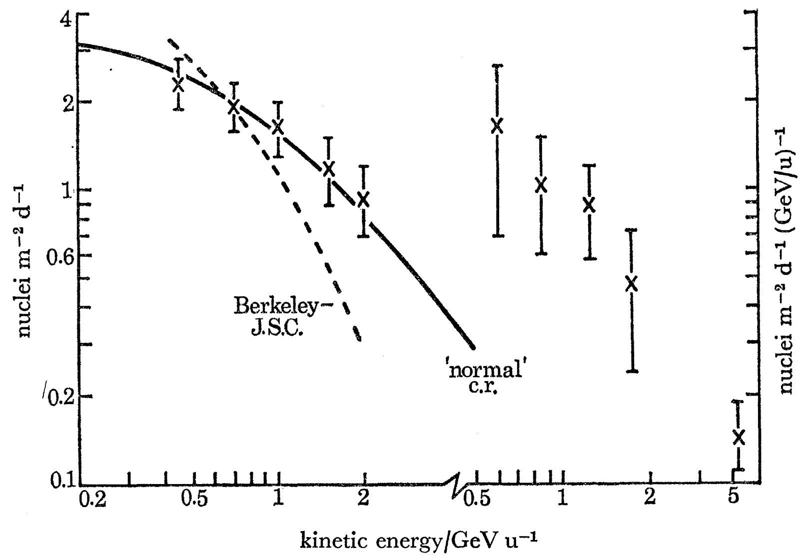


FIGURE 25. A comparison of the integral energy spectra of ultra-heavy nuclei according to Fowler *et al.* (1973) for $Z > 60$, and Osborne *et al.* (1973) (the dashed curve) for $Z \geqslant 60$. The differential spectrum of the Bristol–Dublin group is also shown, at the right.

The relative contributions of *r*- and *s*-process nuclei in *cosmic rays* is still open to question. According to Binns *et al.* (1973) and Fowler (1973), an origin in the *r*-process can explain the composition deduced for the source(s). Shapiro *et al.* (1973*a*, *b*) and Shirk *et al.* (1973) find that while the *r*-process fits the data better, a combination $r+s$ is also admissible within present statistics, and uncertainties in charge assignment. Blanford *et al.* (1973*a*, *b*) favour a mixture of *r*- and *s*-elements, but one that differs from the solar mixture.

Figure 25 displays both the differential and integral energy spectra (Fowler *et al.* 1973) of ultra-heavy nuclei with $Z > 70$ (experimental points labelled '×'). These authors consider that, within the limited precision based on 36 particles, the distribution is a 'normal' cosmic-ray spectrum conforming to a power-law having an exponent consistent with -2.6 (differential spectrum). By contrast, the spectra of Osborne *et al.* (1973) (for nuclei with $Z \geqslant 60$) are considerably steeper. Further details and possible explanations of the discrepancy are discussed by the authors just quoted, i.e. by the Bristol–Dublin and the Berkeley–Houston collaborations respectively.†

† Professor B. Price of Berkeley informs us that more recent, enhanched statistics on ultra-heavy nuclei favour a spectrum similar to that for lighter cosmic ray nuclei.

In its brief exciting history, the study of ultra-heavy cosmic rays has generated several intriguing controversies. In the years ahead, this important phenomenon in high-energy astrophysics will surely offer further challenges and yield additional rewards, particularly when it becomes possible to carry out detailed comparisons with the solar-flare composition of ultra-heavy nuclei.

We appreciate the advice of Dr C. H. Tsao and the help of Mrs D. Frazer of our laboratory. We have benefited from the reviews of several Rapporteurs at the 13th International Cosmic Ray Conference in Denver, Colorado, in particular those of Professors P. Fowler (1973), M. Garcia-Munoz (1973), E. C. Stone (1973), and W. R. Webber (1973). Finally, we thank Professor G. Rochester, F.R.S., and Professor A. W. Wolfendale for their organization of the Royal Society Discussion Meeting which provided the stimulus to prepare this (necessarily sketchy) review.

Appendix. Nomenclature and notation

The designation 'primary galactic' cosmic rays has, until recently, encompassed all energetic particles ($\gtrsim 10^6$ eV) of extra-solar origin incident upon the top of the Earth's atmosphere. The term 'primaries' served to distinguish these incoming particles from the mélange of secondary ones generated in the atmosphere. However, it has been understood for some years that the 'primary' radiation itself includes many secondaries that are produced, e.g. in collisions of nuclear progenitors in space. The latter, source particles, have recently been labelled 'primordial', and sometimes 'primary'. To avoid confusion between the 'source primaries' and the mixture that arrives above the Earth's atmosphere, it seems prudent to use the term 'arriving' to describe the latter.

It should be emphasized that the term 'galactic' as used in this paper, is not intended to exclude the possibility of extra-galactic origin for some of the particles, but only to differentiate them from *solar* energetic particles generated in flares, which are often called 'solar cosmic rays'.

Symbols have usually been defined where they first occur in this paper. For convenient reference, they are also collected in this appendix:

u atomic mass unit
A_t mass number of 'target' nucleus
E kinetic energy
L-nuclei: Li, Be, and B
M-nuclei: C, N, and O
N number of nuclei having path length λ
R rigidity (momentum/charge)
T dwell time of cosmic rays
Z atomic number
λ path length (usually in g cm^{-2})
$\bar{\lambda}$ mean path length
σ cross section (usually in millibarns, mb; 10^{-31} m^2)
γ Lorentz factor (total energy/rest mass)
τ half life of a radionuclide
τ_0 half life at rest

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Discussion

P. H. Fowler, F.R.S. (*University of Bristol*). It is of interest to point out that the ultra-heavy nuclei with $Z \geqslant 80$ can give us very direct and relevant information on the age of the cosmic rays, from the comparison of the abundances of $Z \geqslant 90$ to Pb and Bi nuclei, $Z = 82$ and 83 even at this stage where the charge resolution is so poor ($\Delta Z \approx 4$). The observed ratio is about 1.0 based on about 40 tracks from the Denver Conference, which favours a young age for these particles of about 10^6 years.

Another feature in which these clocks of $Z \geqslant 90$ differ from those singled out by Shapiro (^{10}Be, ^{26}Al, etc.) is that they are not galactic secondaries and so are not dependent on the presence of interstellar matter.

M. M. Shapiro. There is little doubt that the ultra-heavy nuclei are a potential gold mine of information about dwell time, as well as conditions at the source(s) and their evolution.

T. Gold (*Space Sciences Building, Cornell University, Ithaca, New York* 14850, *U.S.A.*). If the age of most of the cosmic rays is only of the order of one or a few million years, one will of course be most concerned to know the presence or absence of time variations on a longer time scale.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

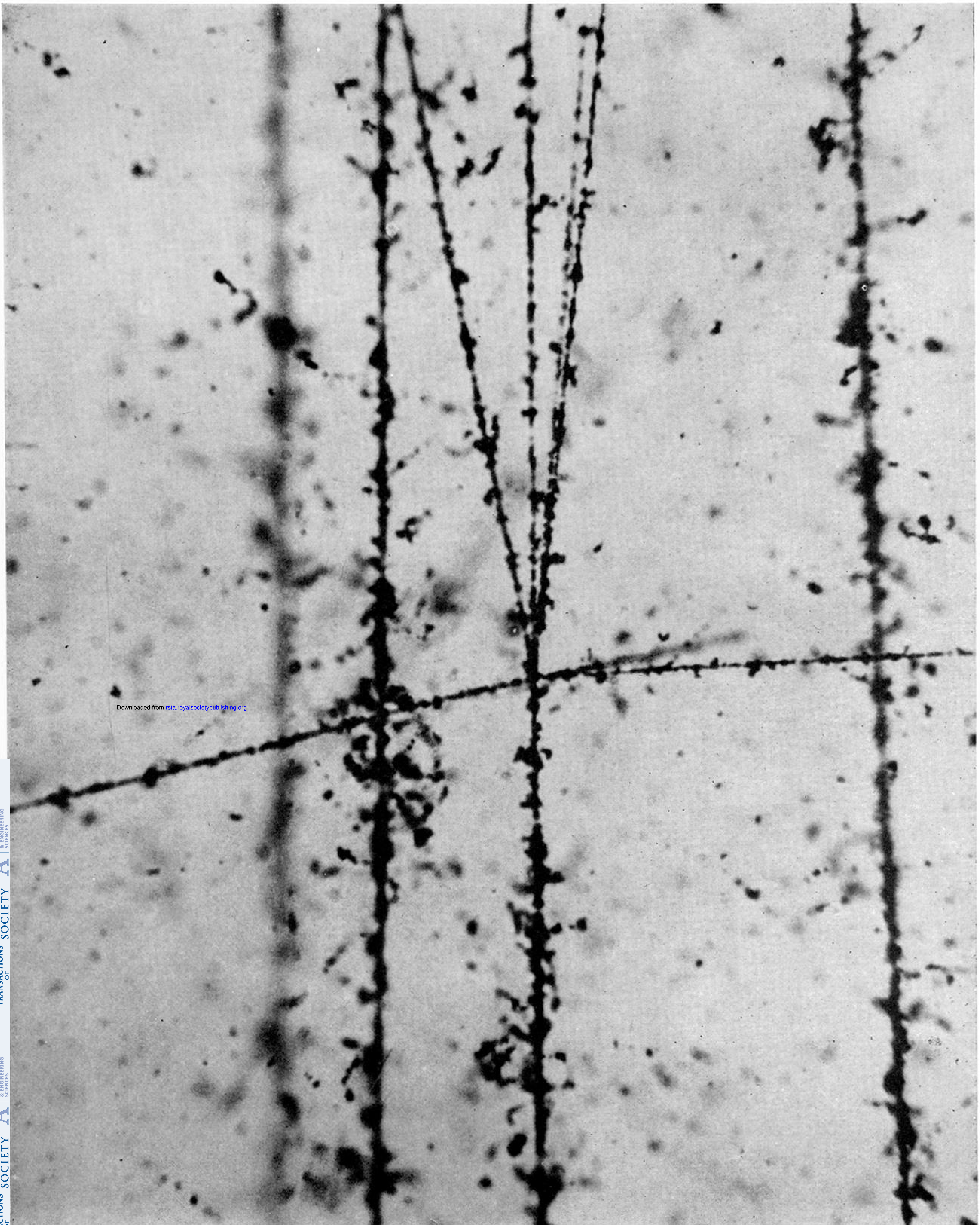
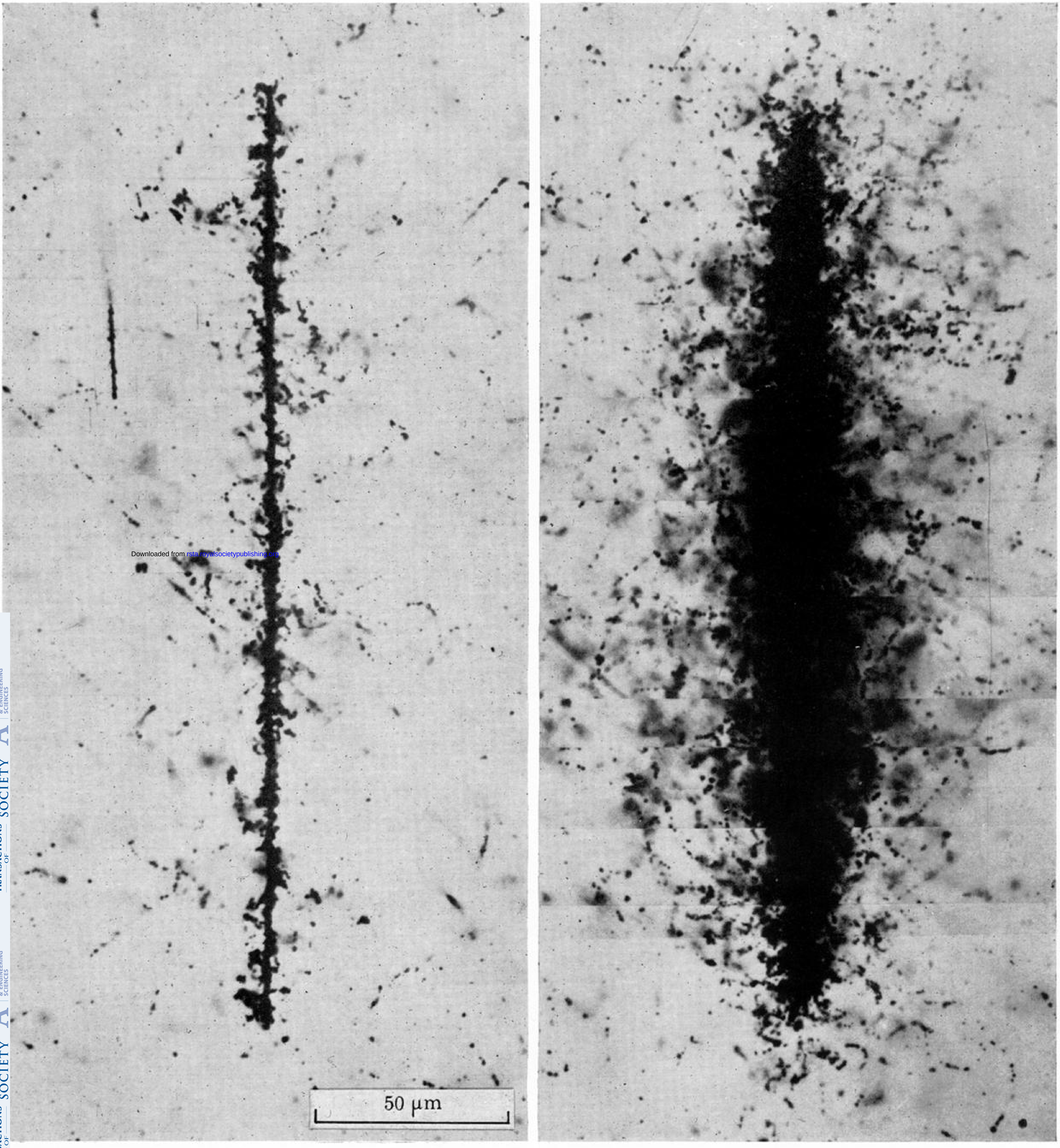


FIGURE 13. The breakup of a relativistic nitrogen ion from the Princeton Particle Accelerator upon collision with a nucleus in photographic emulsion; see text for particulars (Kidd, Shapiro & Wefel, N.R.L., unpublished).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



Fe $Z = 26$ $\qquad$ $Z \approx 90$

FIGURE 22. Cosmic-ray tracks recorded by a fast iron nucleus and by a nucleus of one of the actinide elements in a photographic emulsion (courtesy of P. Fowler). The scale of this photomicrograph appears at the bottom.