THE RUTHERFORD MEMORIAL LECTURE, 1971

Evolution of the elements

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I chose this title because, as your Chairman has emphasized, this is a historic occasion. More than 50 years ago Ernest Rutherford used this title when he returned to New Zealand in 1914 and lectured here, in Canterbury College. On that occasion he talked about the spontaneous disintegrations that radioactive nuclei undergo, with the emission of α, β and γ radiation; how one radioactive element changes into another and how uranium and thorium eventually transform to various isotopes of lead.

The understanding of the laws of radioactive change was the result of collaboration between Rutherford & Soddy in a long series of experiments at McGill; this was the first of three of Rutherford’s most important results—the other two were: ‘the discovery of the nucleus of the atom following experiments of Geiger & Marsden at Manchester’ and ‘the detection of nuclear interactions’.

Under the same title as used by Rutherford here in 1914 I want tonight to talk about how the chemical elements of which the Earth and Sun are made, may have evolved. As a start I would like to present to you in figure 1 some of the facts that need explaining—the relative abundance of the 300 or so naturally occurring types of atom—the isotopes of the various chemical elements. Their relative abundance tells us something about how the elements must have evolved. The graph displayed shows the results appropriate to the Solar System. One realizes that terrestrial or meteoritic abundances are seriously distorted by loss of volatile materials—but most of one’s data is collected from the Earth and meteorites, so we have to put up with it. The distribution, corrected as well as possible for the loss of volatile materials, is often called the ‘universal’ abundance for the elements, but this is overstating its significance.

A few features may be emphasized:

(a) Light elements H and He are by far the most abundant comprising about 98% of the total mass.

(b) Li, Be and B are very rare.

(c) The Fe group is prominent.

(d) Abundances are more nearly constant for Z > 40.
Returning to the structure of atoms, as I have just mentioned in the opening sentences, knowledge of their structure: their nuclei and their orbiting electrons sprung directly from the study of the α-radiation. We now know that nuclei themselves have a structure and are made of neutrons and protons, and that the complete atom which is electrically uncharged has a number of orbiting electrons equal to the number of protons present in the nucleus. The number of protons in the nucleus, and therefore the nuclear electric charge determines which chemical element the neutral atom is. The mass of any atom is principally determined by the mass of its components—protons, neutrons and electrons, but one must also take into account the large binding energy that holds the nucleus together—and of course the smaller figure for the binding energy of all the atomic electrons. The total binding energy shows itself in the mass of the combined atom \( M(A, Z) \) being smaller than the sum of the masses of the isolated constituents, e.g.

\[
M(A, Z) = Z(m_p + m_e) + Nm_n - B/c^2,
\]

where \( Z \) and \( N \) are the number of protons and neutrons in the atom, \( B \) is the total binding energy, and \( m_n, m_p \) and \( m_e \) are the rest masses of the neutron, proton and electron respectively, and \( c \) is the velocity of light.

**Figure 1.** Universal abundance of nuclides plotted against the mass number \( A \), normalized to 10^4 atoms of silicon. ○, odd \( A \); ●, even \( A \). The curve shows the prediction of an early model of element synthesis. (Adapted from Evans 1955.)
Careful mass measurements of numerous isotopes with mass spectrographs have yielded accurate data on the binding energies of nuclides, and the results are well known and are given in figure 2. We may draw attention to the binding energy per nucleon being zero of course for $^1$H, and rising rapidly at first to $^4$He (the α-particle) then more slowly—reaching a peak at $^{56}$Fe, and finally falling fairly steadily all the way to the heaviest elements.

![Figure 2](http://rspa.royalsocietypublishing.org/Downloaded from)

**Figure 2.** Average binding energy in MeV/nucleon plotted for naturally occurring nuclei (and $^6$Be) as a function of mass number $A$. Note the charge of $A$ scale at $A = 30$. (Adapted from Evans 1955.)

The lowest value of $B/A$ for the heaviest elements is responsible for their instability and observed radioactivity. The sum of all the reactions in the decay of the three naturally occurring thorium and uranium isotopes can be written

\[ ^{232}_{90}\text{Th} \rightarrow ^{208}_{82}\text{Pb} + 6^4\text{He} + 4e^- + 4\bar{\nu} + 42.8 \text{MeV}, \]
\[ ^{235}_{92}\text{U} \rightarrow ^{207}_{82}\text{Pb} + 7^4\text{He} + 4e^- + 4\bar{\nu} + 46.3 \text{MeV}, \]
and
\[ ^{238}_{92}\text{U} \rightarrow ^{206}_{82}\text{Pb} + 8^4\text{He} + 6e^- + 6\bar{\nu} + 51.6 \text{MeV}. \]

Since Rutherford's time we recognize the existence of neutrinos, $\nu$, and antineutrinos, $\bar{\nu}$, and so we write the full equations as above. Neutrinos were first postulated by Pauli (1934) and much later detected experimentally adjacent to a nuclear reactor by Reines & Cowan (1953).

In addition to the α, β and γ emission recognized by Rutherford as distinct radiations, three further significant modes of radioactive decay are now known: $\beta^+$ emission, electron capture and spontaneous fission. $\beta^+$ emission was discovered in France by Curie & Joliot (1934) and electron capture was first observed by
Alvarez in 1938 in U.S.A. Proton rich nuclei of all masses decay by one or both of these modes. The nuclei in the uranium and thorium decay chains are all neutron rich and so if they undergo $\beta$ decay they decay by $\beta^-$ emission only. Lastly, spontaneous fission was discovered in the Soviet Union by Flerov & Petrzhak (1940); this is a rare mode of decay for uranium, but is the principal mode of decay for transuranic nuclei with $Z \geq 100$.

As illustrated in figure 2, all nuclei heavier than $^{56}\text{Fe}$ are less tightly bound than $^{56}\text{Fe}$ itself, it is not just uranium and thorium that are less strongly bound. It is therefore energetically possible for almost all heavy nuclei to release energy spontaneously by $\alpha$-decay or by fission. The energy release in fission, $Q_f$, is given approximately by the expression

$$Q_f \simeq 0.22Z^2A^{-\frac{1}{3}} - 3.4A^{\frac{2}{3}} \text{ MeV},$$

and is positive for almost all isotopes with $Z \geq 40$. $Q_f$ is in fact in excess of 100 MeV for all nuclei $Z > 70$. However, no universal activity is observed, the reason being that the lifetimes for radioactive decay are too huge.

In the case of $\alpha$-decay there is a satisfactory theory due to Gamow and it may be simplified to give

$$\lg (T_{\alpha}) \simeq 1.7Q_{\alpha}^{-\frac{1}{3}} - 1.57Z^{\frac{1}{2}}A^{\frac{1}{4}} - 28.5,$$

where $A$ and $Z$ refer to the daughter nucleus and $Q_{\alpha}$ is the disintegration energy in MeV, and $a$ is the symbol for year.

The situation is more complex in the case of spontaneous fission as the shape and deformability of the nucleus become important and the fission lifetime is the result of a fine balance between the energy release and the Coulomb barrier between the two fragments. Empirically for $Z \geq 90$ we have

$$\lg (T_f) \simeq 160 - 4Z^3/A,$$

but we may use this expression as a guide to the lifetime for nuclei with $Z \geq 70$, where the fission energy release $Q_f$ is large.

When appropriate values are substituted into these two expressions for the lifetimes, $T$, in many cases the values obtained for $T$ are huge, frequently $> 10^{20}$ years. A lifetime of $10^{20}$ a for instance, implies that in the whole age of the Earth ($\approx 5 \times 10^9$ a) only $5 \times 10^{-11}$ of any sample with such a decay constant will have undergone transformation. The transformation rate is only ca. 1 atom per gram week, and is practically unobservable even in the case of spontaneous fission. The natural background disintegration rate for nuclei due to neutrons and other particles resulting from cosmic radiation and radioactivity is of this order at ground level.

Nuclei with half-lives in excess of $10^{20}$ a may therefore for practical purposes be considered stable. This includes not only rare and unimportant elements but some of significance for life, such as I, and Pb.

In addition to the three radioactive series that start with U and Th, several other activities are known, notably the activities of $^{40}\text{K}$ and $^{87}\text{Rb}$ which were discovered
as long ago as 1906 by Campbell & Wood. Both of these activities have been very valuable along with uranium and thorium decay chains in giving knowledge of the age of the minerals containing them, and the methods have been applied to meteorite crystals, and lunar material as well. Indeed radioactive dating pioneered by Rutherford and Boltwood has been one of the most significant ways in which understanding of radioactive processes has been applied. At the present moment we can expect exciting new data to come from recently collected lunar samples.

All naturally occurring radioactive nuclides are characterized either (a) by having a long lifetime themselves, a lifetime that is comparable to the age of the Earth \( \approx 5 \times 10^9 \) a, or (b) by themselves being the product of a longlived antecedent, e.g. radium, half-life \( \approx 1600 \) a, antecedent \( ^{238}\text{U} \) with a half-life of \( 4.2 \times 10^9 \) a. The naturally occurring radioactive nuclides are therefore the remains of the initial endowment that the Earth possessed at its formation. The overall effect of radioactive decay is thus to transform just a minute fraction of the Earth's material to its appropriate end product. There is thus little evolution of the elements taking place on Earth now. So we have to widen our view to locate where and when (and perhaps how) the elements on Earth evolved. We must appeal to astronomy.

The hierarchy in astronomy is well known:

The Earth is but one of a number of planets and smaller objects revolving round the Sun, forming the Solar System.

The Sun is but one typical member of stars of many different kinds forming the Milky Way, a huge family of about \( 10^{11} \) stars of mass comparable to the Sun.

The Milky Way is but one member of an enormous number of Galaxies; in all we believe there to be perhaps \( 10^{12} \) Galaxies in the observable Universe.

The elements we possess here on Earth could therefore have been fashioned (a) in the Sun, or perhaps in another planet, (b) elsewhere in the Milky Way, or (c) have an extra-galactic origin.

Other planets are believed to be similar to the Earth in that no nuclear processes other than radioactive decay go on there.

Next let us consider the Sun. Our knowledge of the Sun is unfortunately rudimentary, but from the use of the law of conservation of energy, first applied to the Sun by Lord Kelvin in the 1860s, we are forced to conclude that the Sun cannot have illuminated the Earth for more than \( 10^8 \) a at its present rate, unless, as put succinctly by Kelvin 'there exist sources of energy not yet known'. The same heat balance argument applied to the Earth gave the same result—that unless there were other sources of energy the Earth was \( \sim 10^8 \) a old. The equality of these two age estimates seemed very impressive. However, the discovery of radioactivity and measurement of the release of energy therein showed the existence of an internal source of heat for the Earth sufficient to invalidate Kelvin's result, as was recognized by Rutherford as early as 1904. At the same time direct radioactive dating provided clear cut evidence that some rocks are very old. Clearly the Earth cannot be older than the Sun. Therefore the Sun must also be old. Therefore there has to be another source of energy for...
the Sun, as its energy output is much higher per unit mass than the Earth, and as
the heavy elements are even less common than on Earth. However, nuclear reactions
are sufficient.

The Sun is 90% by mass composed of hydrogen. The nucleus of hydrogen consists
just of a proton, which has therefore no nuclear binding energy, so that the forma­
tion of any bound nucleus will result in a release of energy. Scientists are confident
that the sum of a long chain of reactions occurring in the Sun can be summed up as

\[ 4\text{H} + 2e^- \rightarrow 2\text{He} + 2\nu + 26.7 \text{MeV}. \]

Neutrinos have such a weak interaction with matter that even those generated in
the centre of the Sun are almost certain to escape, but on account of this weak
interaction they are exceedingly difficult to detect, as they are almost certain to
go right through your apparatus without effect. In spite of this the neutrinos from
the Sun have very recently been detected in the remarkable experiments of Davis
et al. (1971). Their energy is giving exciting information about the conditions and
the actual reactions going on in the Sun's centre.

But when we put all this element synthesis together we find that the Sun also
is doing very little to most of its nuclides. The elements we see with \( Z \geq 6 \) are
essentially an endowment from somewhere else—just as in the case of the Earth.
The Sun has however destroyed most of the light nuclei \( 3 \leq Z \leq 5 \).

So we turn to the next on the list of candidates—the Milky Way. Here we find
a different picture. Among its \( 10^{11} \) stars we do indeed find many vigorous examples
which certainly seem capable of both generating heavy elements and disseminating
them. This latter point is clearly important, for if the star just locked all its pro­
duction up, the Earth would not have benefitted. It does, however, seem likely that
there is insufficient helium produced and disseminated, and therefore that this
important component may have been assembled at the origin of the Universe.

The rate at which a star radiates light and hence uses its nuclear energy is pro­
portional to the fifth power of the star's mass. Thus heavy stars with mass greater
than about 10 times that of the Sun do not last long, and therefore are good candi­
dates. Indeed many stars explode, others appear to be losing mass in a steady
manner.

The study of the heavier elements, \( Z > 32 \), i.e. well above the Fe peak, has been
most fruitful in giving us understanding of where our endowment of elements here
on Earth may have come from. Three quarters of all the known naturally occurring
nuclides are in this group, but most of them are quite rare—and in total they
amount to \( 5 \times 10^{-4} \) of the Fe group or about \( 10^{-6} \) of the total mass.

Three processes seem to be responsible for the production of these nuclei—the
processes were thought about first by Burbidge, Burbidge, Fowler & Hoyle (1957),
they are:

- the 's' process, s for slow,
- the 'r' process, r for rapid,
- the 'p' process, p for proton.
Both the r and s processes involve successive neutron capture, r on a rapid time scale—as in a nuclear explosion, and s on a slow time scale, as in a nuclear reactor. In the core of a nuclear reactor conditions are such that a typical heavy nucleus may capture a neutron perhaps once a decade, but in the s process it seems that one capture per $10^5$ a is the appropriate rate. These two processes together are responsible for all the relatively abundant heavy nuclei—leaving only about 30 for the production exclusively by the p process.

I would now like to show you the nature of the evidence for these processes. The s process is the easiest to follow. It is believed to start from the Fe group and involve the successive capture by an individual nucleus of up to 200 neutrons, with intervening $\beta$ decays. Part of the neutron capture path is detailed in figure 3.
The cross-sections for capture of a neutron by a nucleus have been directly measured at a neutron energy of about 20 keV which is considered appropriate—it corresponds to a temperature of about $10^8$ K. The cross-sections generally increase with increasing mass, so that the small number of heavy nuclei are in fact reasonably efficient scavengers of the few available neutrons. Superimposed on this trend with mass one sees sharp variations associated with 'magic' nuclei, those with closed shells of neutrons in their structure. Such nuclei have measured cross-sections that are much smaller than their non-magic neighbours.

![Graph showing predicted and observed abundances of nuclei produced in the s process](http://rspa.royalsocietypublishing.org/)

**Figure 4.** Comparison of the predicted and observed abundances of nuclei produced in the s process (from Burbridge et al. 1957). ---, even $A$: ●, made only in slow chain; ○, probably made in slow chain. ——, odd $A$: ×, made only in slow chain; +, probably made in slow chain. ———, from $1/\sigma$ odd $A$.

In the approximation of steady flow, the probability of capture of a neutron is proportional to the cross-section for neutron capture, $\sigma$, therefore the lifetime of any nucleus in the neutron bath and thus the probability for it to be present when the neutron supply runs out should be proportional to $\sigma^{-1}$. The magic nuclei are thus selected strongly, especially

$^{88}$Sr, $^{90}$Zr, $^{138}$Ba and $^{208}$Pb.

It is worth emphasising that they are selected because of their low neutron capture cross-sections and not their undoubted greater binding energies. A comparison of the abundances of nuclei in the main s process stream with their measured cross-section $\sigma$ is given in figure 4. The general agreement is excellent.

The termination of the s process is important. It occurs just after Pb and Bi.
It is detailed in figure 5 where we see that it is complicated by branching due to the formation of two states of the nucleus $^{210}$Bi. Further neutron capture results in the emission of an $\alpha$-particle, thus the four nuclides $^{206,7,8,9}$Pb and $^{209,9}$Bi act as a sink. These nuclides can be thought of as acting like a catalyst for transforming sets of four neutrons into $\alpha$-particles. No heavier nuclides are made this way, because of the extremely short lifetime of the heavier nuclides for $\alpha$ decay.

![Diagram of neutron capture paths](image)

**Figure 5.** The capture paths at the termination of the $s$ process.

The $s$ process is on a very firm foundation. The cross-sections are directly measured. The production of the relative abundances of 150 nuclides are tied together with just three quantities, the rate of the process $\approx 10^5$ a/capture, the mean energy of the neutrons, and the mean number of neutrons captured—that is the temperature, concentration and duration of the neutron bath. Further, in the atmosphere of several classes of giant stars, large excesses have been observed of Zr, Ba and Rb, just those elements singled out by the $s$ process. In one class spectral lines of $^{43}$Tc are quite prominent. This element has no stable isotopes, and the appropriate isotope $^{43}$Tc has a half-life $\approx 2 \times 10^5$ a, showing the existence of nuclear synthesis in these stars at the present time. There is however a need to look for other processes that manufacture heavy elements.

The $s$ process makes just a single nuclide for each atomic mass. There are, however, often two or three naturally occurring nuclides on the same mass. Furthermore, sometimes the neutron rich nuclides bypassed by the $s$ process are the most abundant...
isotopes, as is the case for \(^{128,130}\text{Te}\) (illustrated in figure 9, plate 1) and \(^{196,198}\text{Os}\). But the most striking need for another process is the existence of \(^{92}\text{U}\) and \(^{90}\text{Th}\)—the radioactive nuclei. There is no route to them via the s process. What conditions for a neutron bath are required for their production?

![Diagram of nuclear decay paths](http://rspa.royalsocietypublishing.org/)

**Figure 6.** The capture paths in the r and s processes. (From Burbidge et al. 1957.)

In order to reach the Os and Te nuclei we have to bypass the \(\beta\) decays \(^{127,129}\text{Te}\), \(^{189,191}\text{Os}\) etc. and their lifetimes are minutes only. To reach U however from Pb—we have to get past \(^{212}\text{Po}\), lifetime \(\approx 10^{-7}\) s. So a radical change in conditions is required. It seems certain that the process is so rapid (it takes place in a time measured in seconds only, a time much smaller than the free fall time for the star) that the production must be explosive and not continuous. Its parallel on terrestrial affairs is the nuclear explosion—there a small fraction of nuclides do not undergo fission but capture considerable numbers of neutrons to become heavy U and Pu isotopes, which after the explosion undergo \(\beta\) decay to make many transuranic species.

In stellar conditions the necessary \(\beta\) decay has to take place in the explosive stage. One cannot add an indefinite number of neutrons to a nucleus, excess neutrons are weakly bound, and one will reach a state of equilibrium where

\[
(A, Z) + \frac{1}{2} \text{n} \rightarrow (A + 1, Z) + \gamma.
\]

Thus the path for rapid neutron capture shown in figure 6 is along very neutron rich species—and its rate is controlled by the slower \(\beta\) decays, which are those for which the energy release in \(\beta\) decay is the smallest. This enables one to get past the
Po isotopes quickly enough. It is now thought likely that the process builds up to nuclei with $A \approx 300$ before these monster nuclei undergo fission (Schramm & Fowler 1971). This provides two seed nuclei for further capture of neutrons and not the termination of the process. The process stops only when the neutron supply runs out—because of the expansion due to the explosion. In the stellar case it is thought to last about 10 s and such explosions are perhaps the supernovae explosions that astronomers have recognized. Supernova explosions are rare; there are only about one per century in the Galaxy, but the explosions are very, very energetic (liberating as much as $10^{44}$ J).

The explosion that produces the r nuclei provides a natural dissemination of the products to the surrounding medium, it throws out material weighing many solar masses. The total production of nuclei by the r process is very similar in quantity to the production by the s process. The distribution of nuclei produced in the r process is given in figure 7. There are peaks in the abundance distribution, but they are broader and less pronounced than for the s process. Many transuranic nuclei are expected to be produced in the conditions envisaged for the r process, and these during the existence of the Earth have decayed and we are left with just the three long-lived radioactive parents. ‘Fossil’ remains of tracks due to the spontaneous

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**Figure 7.** Comparison of the distribution of nuclides formed in the r process to their natural abundances (from Burbidge et al. 1957). Even $A$: •, made only in rapid chain; ○ ⊕, probably made in rapid chain. Odd $A$: ×, made only in rapid chain; + ⊕, probably made in rapid chain. ———, calculated.
fission of $^{244}$Pu have been found in meteorite crystals—indeed there should be about 1 kg left on Earth still, since its half-life is $8 \times 10^7$ a. Many scientists are looking for any remains of superheavy nuclei—that also seem likely to be made.

Before considering the production of the remaining neutron-poor nuclei that are bypassed by the s process, I wish to introduce the cosmic radiation to you—as a source of information. At the beginning of this lecture I introduced the relative abundances of the various elements and isotopes—and stated that it had been termed the ‘universal abundances’. It was felt until recently, that after making allowance for chemistry and volatility of various components that there was indeed something approximating to a universal abundance. It is now seen that this is an oversimplification, although of course such an abundance distribution forms a very valuable basis for comparison with any special distribution you may have, such as in this case the cosmic ray abundances.

Bombarding the top of the Earth’s atmosphere is a flux of particles of magnitude only about 1 cm$^{-2}$ s$^{-1}$. What chiefly distinguishes them from other particles is their immense energy and speed—most of them impinge on us with a velocity $>0.80$ of the velocity of light. It turns out that they are nuclei of various elements and the study of their relative abundances has been pursued with vigour over the years. The results are striking.

Figure 8 displays results representative of the best measurements that have been made where the resolution $\Delta Z$ is as low as 0.2 so that there is little overlap between neighbouring elements which are therefore clearly resolved. In table 1 the cosmic ray abundances are summarized and compared with the ‘universal’ abundances both being normalized to Fe. In two notable respects the cosmic rays stand out:

(a) The light elements Li, Be and B are of comparable abundance to the abundant elements C, N and O, in contrast to the figures for the universal abundance where the ratio is about $10^{-5}$. This feature also applies to the isotopes $^2\text{D}$ and $^3\text{He}$ which are quite abundant on the cosmic radiation, but very rare in the solar system.

(b) There are generally more heavy elements present in the cosmic rays.

We believe that the light elements are fragments from nuclear collisions suffered by the original primary in flying through interstellar space for several million years.

Space is nearly but not quite devoid of matter, and the path of a single nucleus of the cosmic radiation seems likely to be so huge—say $10^6$ to $10^7$ light years ($10^{22}$ to $10^{23}$ m), that an appreciable fraction of the original primaries must be expected to undergo nuclear collision. In such nuclear collisions between the cosmic ray nucleus and an interstellar proton for example a sizeable fragment of the original nucleus will often remain—and carry on with little deflexion or change in speed. In figure 9, plate 1, I show the effects of such a nuclear collision that occurred within our photographic emulsion detector.

If we accept this secondary origin for the light elements Li, Be and B and the isotopes $^2\text{D}$ and $^3\text{He}$ we can evaluate the distribution of elements at the source of the cosmic rays—this distribution is naturally still richer in heavy elements and is displayed in the last column of table 1.
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Figure 8. An example of the charge spectrum of the primary cosmic radiation. The data are from the experiments of Corydon-Petersen et al. (1970) of the Danish Space Research Institute. (Flight I, May 1969; residual atmosphere 350 Pa; geomagnetic cut off 4.5 GeV; 2489 events, z ≥ 6.)

Table 1. A comparison between the universal abundances and the cosmic rays as detected and estimated at the source.

For simplicity many of the elements have been grouped together.

<table>
<thead>
<tr>
<th>charge group</th>
<th>universal abundance</th>
<th>cosmic rays top of atmosphere</th>
<th>cosmic rays source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60000</td>
<td>3000</td>
<td>3040</td>
</tr>
<tr>
<td>2</td>
<td>3000</td>
<td>160</td>
<td>180</td>
</tr>
<tr>
<td>3-5</td>
<td>2 x 10^{-4}</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>6-9</td>
<td>50</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td>10-14</td>
<td>15</td>
<td>3.5</td>
<td>6.5</td>
</tr>
<tr>
<td>15-19</td>
<td>0.1</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>20-25</td>
<td>0.1</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>26</td>
<td>1</td>
<td>1</td>
<td>3.4</td>
</tr>
</tbody>
</table>

(normalized to 1.0)
Recently we have been studying still heavier elements in the cosmic rays, especially those with $Z \geq 50$. Such nuclei may leave very dramatic tracks in one's detector, and an example is given in figure 10, plate 2, which shows two segments of the track of a nucleus with $Z \simeq 92$ at different values of range and hence velocity.

**Table 2. The proportion of secondaries likely to have been detected in the ultra heavy experiments, and the possible source spectrum**

The figures in the second column refer to numbers of tracks collected in a total of approximately $90 \text{ m}^2 \text{ days}$ of exposure under $4 \text{ g/cm}^2 \text{ atmospheric depth}$.

<table>
<thead>
<tr>
<th>charge group</th>
<th>number at detector</th>
<th>number of air secondaries</th>
<th>number at top of atmosphere</th>
<th>number of interstellar secondaries</th>
<th>number at source</th>
</tr>
</thead>
<tbody>
<tr>
<td>24–28</td>
<td>ca. $6 \times 10^6$</td>
<td>—</td>
<td>$7 \times 10^6$</td>
<td>—</td>
<td>$2 \times 10^7$</td>
</tr>
<tr>
<td>36–43</td>
<td>ca. 300</td>
<td>70</td>
<td>350</td>
<td>200</td>
<td>700</td>
</tr>
<tr>
<td>44–51</td>
<td>ca. 150</td>
<td>40</td>
<td>180</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>52–59</td>
<td>66</td>
<td>20</td>
<td>80</td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>60–67</td>
<td>18</td>
<td>8</td>
<td>18</td>
<td>18</td>
<td>—</td>
</tr>
<tr>
<td>68–75</td>
<td>22</td>
<td>9</td>
<td>23</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>76–83</td>
<td>22</td>
<td>4</td>
<td>32</td>
<td>11</td>
<td>150</td>
</tr>
<tr>
<td>$\geq 84$</td>
<td>8</td>
<td>0</td>
<td>15</td>
<td>0</td>
<td>120</td>
</tr>
</tbody>
</table>

**Figure 11.** Charge spectrum for $Z \geq 50$ of the primary cosmic radiation at very high charges, summarized from a number of experiments in 1970, obtained principally from emulsion/plastic sandwich stacks from balloons over Texas.

The particle was detected in a multilayer detector of plastic and emulsion and penetrated 13 detector layers before coming to rest. The data available on these ultra-heavy cosmic rays at the present is still rudimentary, but the charge histogram as determined at detector level is given in figure 11, where peaks in the abundances seem evident as well as the presence of transbismuth ($Z > 83$) and possible transuranic elements ($Z > 92$). The abundance distribution is very reminiscent of that synthesized in the r process. We believe this to be significant and to support the
Figure 9. Nuclear disintegration caused by a nucleus of Fe of the cosmic rays. The speed of the incoming nucleus was about 0.5c, and it interacted within the photographic emulsion detector with a nucleus of Ag and Br. The track of the primary is at the top of the picture, the cosmic ray nucleus escaped complete disruption and about a half of it carried on with little deflexion. Numerous fragments of both the target nucleus and the cosmic ray nucleus produce the characteristic 'star'. Unlike figures 10 and 12, plate 2, this photograph was taken at a single depth of focus, and tracks not close to the plane of the emulsion pass out of sharp focus in a short distance. (From Powell, Fowler & Perkins 1959.)

(Facing p. 14)
Figure 10. Two segments of the track of a nucleus with \( Z \approx 92 \). Each segment shows the whole path of the particle that penetrated the 200 µm thickness of the film. The particle was slowing down, and the track density responds.

Figure 12. An example of the track of a cosmic ray nucleus that came to rest in the emulsion. Much of the internal extent of the track is produced by knock-on electrons with kinetic energies \( \approx 50\) keV. As the particle slows down, their production falls while the total energy loss rises. The characteristic tapering of the track is evident—the width being determined by the range of the knock-on electrons of the highest velocity that can be produced—which is approximately twice that of the velocity of the cosmic ray nucleus.
idea that the cosmic rays originate in supernovae explosions, which seem to be the source of the r nuclei.

But as with the light elements we must expect the primaries to be accompanied by an appreciable quantity of debris from nuclear collisions. Nuclear collisions do not usually result in the destruction of the nucleus, but just the removal of 10 or 20 neutrons and protons, leaving a neutron poor nucleus—as neutrons are the more easily lost. Many of these nuclei will eventually come to rest in the interstellar medium and become normal atoms. The rate at which they should be doing so can be evaluated from our experimental data. Making the assumption that the cosmic rays have had much the same intensity over the age of the universe one can calculate the build up of these fragments, and in our view this is the principal source of the p nuclei for Z > 50. These heavier p nuclei have therefore in our view been made by spallation—by reduction in mass, rather than by accretion. An example of the track of a cosmic ray nucleus with Z ∼ 44 coming to rest on the emulsion is given in figure 12, plate 2.

If I may now sum up this talk as follows: The elements we have on Earth are undergoing only a very small degree of change by radioactive decay—and of course it was the successive decay of uranium and thorium that formed the heart of Rutherford’s work. The elements evolved elsewhere—not even in the Sun. Nuclear reactions certainly occur in the Sun and indeed are responsible for the generation of the Sun’s energy—and therefore for having kept the Earth at an equable temperature and allowed the development of life on Earth. These reactions have however used only a very small part of the Sun’s store of hydrogen and have not touched any of the heavier elements.

Before the formation of the Solar System various active stars in our neighbourhood are presumed to have enriched the interstellar gas with their contribution of matter that had been through nuclear synthesis—including of course relatively small quantities of the heavy products that are synthesized by the r and s processes of successive neutron capture. These stars themselves are expected to emit mainly C, O, Si, Fe, etc. Their neutron baths will have irradiated only a small part of their material. The cosmic ray distribution gives a guide to the elements that a supernova might throw out into the interstellar gas. The solar system and other stars then are presumed to have formed as a result of the condensation of such a gas and dust cloud. We are now studying this matter which has had a complex evolution, some of it perhaps having been part of many stars before, and part, the H and He component perhaps, having yet to enter its first star.

The connexion of the subject-matter of this talk to Ernest Rutherford is clear; the work of Rutherford and his colleagues provided the key to the structure of the atom and the foundation of the science of nuclear physics. It is to the properties of the nucleus of the atom that we have to turn to find any explanation of the problem we have discussed tonight—namely the evolution of the atoms of which the Earth and we ourselves are made.
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