The Abundances of the Elements

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Introduction

On October 26, 1889, Frank Wigglesworth Clarke (1889)
read a paper before the Philosophical Society of Washington in
which he outlined a research program that covers the contents
of this paper. Clarke's paper was the first of numerous following
ones written by many different authors, and entitled, "The relative
abundance of the chemical elements". It contained the following
sentence: "An attempt was made in the course of this investigation
to represent the relative abundances of the elements by a curve,
taking their atomic weight for one set of ordinates. It was
hoped that some sort of periodicity might be evident but no such
regularity appeared."

During the following fifty years Clarke and his
co-worker, H. S. Washington, continued this line of research
at the U. S. Geological Survey. Their classical work is still
considered to be one of the most valuable sources of geochemical
knowledge. Since that time many scientists have attempted to
find explanations for the abundance distribution of the elements
or at least to find empirical rules which govern their main
features. Numerous suggestions have been made in that direction
most of which were too speculative to have influenced further
developments effectively. However, one observation based on the
work of Clarke and Washington proved to be of fundamental importance
in many fields of science. It was that expressed by Harkin's rule

which states that the elements with even atomic numbers are more abundant in nature than those with odd ones.

Clarke and Washington have based their work primarily on the composition of the earth's crust. As time passed it became more and more evident that meteorites were better objects for the study of the average abundance of the chemical elements in nature than terrestrial rocks. These studies culminated in Goldschmidt's (1937) classical paper which served as the basis of practically all the more recent work in this field.

When in 1889 Clarke was looking for periodicities in the relative abundance of the elements, he expected to find some connection with the periodic table. With an increasing knowledge of the abundances of the elements, the discovery of isotopes, and the determinations of the isotopic composition of the elements it was possible more than 40 years later to detect certain types of periodicities and it became obvious that these periods followed different laws than those of the atomic structure and had nothing to do with the periodic table. It seemed, that the abundances of the elements and their isotopes reflected nuclear properties and that the matter surrounding us bore signs of representing the ash of a cosmic nuclear fire in which it was created.

In 1948 one of us (H.E.S.) attempted to prove this conclusively. He showed that there was an empirical and quantitative correlation of the isotopic composition of an element with its cosmic abundance which could not be explained in any other way than by

assuming some kind of a correlation of nuclear properties with the distribution of the nuclear abundances. In the meantime considerable progress has been made both in the field of geochemistry and cosmochemistry as well as in our knowledge of nuclear structure so that a revision and extension of his earlier work is indicated.

The proper key for an understanding of the empirical and semiempirical features in the abundance distribution of the nuclear species in the universe would be a complete theory of the formation of the elements. Such theories have been formulated by various authors. Attempts were made to find an appropriate cosmogonic model which would lead in a reasonable way to an understanding of the formation of the nuclear species in ratios of their abundances in nature. These attempts have been successful insofar as they made it possible to understand in a qualitative way the existence of the heavier nuclei and their relative amounts. None of these theories, however, can account for the details in the abundance distribution and for the more quantitative features in the overall picture of nuclear abundances.

Independent of any theory of the origin of the universe, one may try to find indications for the nature of the last nuclear reaction that took place just before the present abundance distribution was finally established. Going backwards in time one may then try to find out how the conditions had developed under which these reactions took place. As the last and final step, a cosmogonic model may then be found for an explanation of the course of events. No attempt will be made to do this. However,

attention will be drawn to any evidence which might serve as a basis for future work along these lines and some tentative suggestions which may be helpful for further work will be included.

Rules for the Relative Abundance of Nuclides

All species of stable nuclei occur in nature. Their relative abundance, however, shows a variation by a factor of the order of 10^{15}. Harkins (1917) was the first to attempt a systematic classification of the stable nuclear species or nuclides based upon our knowledge of atomic number as a proper designation of an element and of the isotopes as the ultimate constituents of these elements, and Harkins' rules represent important regularities in the abundances of the nuclides. Mattauch introduced additional rules. Such rules are now in general understood in terms of binding energies, in particular from the point of view of the nuclear shell model as discovered and developed by Mayer (1948, 1949) and by Haxel, Jensen and Suess (1949).

In a previous paper (Suess, 1947) certain rules regarding the abundances of the stable nuclides were presented as follows:
(1) Odd mass number nuclides: The abundances of odd mass numbered nuclear species with $A > \sim 50$ change steadily with the mass number. When isobars occur, the sum of the abundances of the isobars must be used instead of the individual abundances.
(2) Even mass number nuclides: (a) In the region of the heavier

elements with A > 90, the sums of the abundances of the isobars
with even mass number change steadily with mass number. (b) In
the regions with A < 90, the abundances of the nuclear species with
equal numbers of excess neutrons change steadily with the mass
number.

(3) In the region of the lighter elements with A < 70, the isobar
with the higher excess of neutrons is the less abundant one at
each mass number. In the region of the heavier elements with A > 70,
the isobar with smallest excess of neutrons is the least
abundant one.

(4) Exceptions to these rules occur at mass numbers where the
numbers of ~~protons or of~~ neutrons have certain values, the so-called
magic numbers.

From the empirical side, the subject owes most to the
careful and extensive work of Goldschmidt and his coworkers.
Goldschmidt's classical work of 1937 is still a most valuable
source of information and those who have studied the subject
since lean heavily on his judgement in regard to relative
abundances of the elements. A posthumus book (1954) makes this
work more available. Ida and Walter Noddack (1930, 1931, 1934)
contributed additional data which is critically evaluated by
Goldschmidt. In using meteoritic abundances there is always the
problem of a proper average of the elements as they occur in the
stones and irons and in the silicate phases, the troilite phase
(FeS) and the metal phase. Goldschmidt weighted these phases in

the proportions 10:1:2. The Noddack's (1934) and Urey (1952a) used the chondritic stone meteorites as a proper average since these objects are so obviously a heterogeneous mixture of materials from many sources and hence may be a proper mixture in themselves. Brown (1949) used a much higher proportion of iron and his abundances deviate from the others generally in the sense of higher siderophile elements. Urey and Craig (1953) found two prominent groups of chondritic meteorites which are in fact two of Prior's groups (1916, 1920) derived by other criteria. Wiik (1955) has analysed a number of meteorites using the most modern methods of analysis and has confirmed the existence of these two groups. These two groups differ in the proportions of the metal and silicate phases.

Though we shall use these observational atomic abundances, we must recognize that there are no completely reliable samples

of cosmic matter available to us. It is obvious that the surface rocks of the earth do not constitute such a sample regardless of any method of averaging analyses of the many different varieties. The chondritic meteorites are evidently physical mixtures of constituents which have been markedly fractionated in previous melting processes and which may have been fractionated through other processes such as volatilization as well. We have found no evidence indicating the loss of elements from the earth or meteorites except in the case of elements which form compounds which are volatile at ordinary terrestrial temperatures. (See Urey 1954b) The achondrites and irons are samples of material which have been melted and separated from each other. We have no way of knowing whether these constituents which were once separated from each other have been put back together again in their proper cosmic proportions in chondrites or in any average of these with the achondrites and irons. In fact we have no sample of cosmic matter which is entirely reliable and probably will never have such a sample. Hence we must consider all atomic abundances derived from the analyses of meteorites as possibly not those characteristic of the primitive cosmic matter of the sun regardless of the precision of the analytical work.

That marked regularities in the cosmic abundances of elements exist has been evident for many years. The rare earths have very similar chemical properties so that separation of these elements approached in difficulty the separation of isotopes and

just in the case of these elements we find a marked regularity
of abundances. These show a regular alternation of abundances
between even and odd elements and the successive odd or even
elements change in abundances in a gradual and regular manner.
It was recognized by one of us (H. E. S.) that this meant that
the abundances of isotopes should similarly represent a definite
regularity and that elementary abundances should be such that
all nuclides should vary in some regular way. Accordingly it is
assumed in this paper that the relative abundances of all isotopic
species are meaningful and not the result of "chance" variations.
This assumption is shown to be valid in nearly all cases and of
course, we believe, that it is true in all cases even though quite
frankly we do not always see that this is the case. We
do not pretend to fully understand the regularities and irregularities
which we present. It might well be that the abundances of the nuclides
of odd mass for example follow a rough curve with the individual
nuclides falling above or below this curve in an irregular way.
For the most part we believe that this is not the case but that
surprisingly closely the isotopes of the elements determine the
slope of the curves uniquely and especially that of the odd mass
curve. Also the curves for the logarithms of the abundances of the
even and odd mass elements respectively follow curves which are
displaced over most of the mass range by nearly a constant amount
relative to each other when properly interpreted.

The following is a discussion of the elements with respect

to their abundance values and of adopted values of these abundances consistent with the above rules. The discussion is based essentially on Goldschmidt's empirical values together with new data which has appeared in the literature since then. In general Urey's recent abundance table, which uses analyses of the chondrites in preference to other averages, is used rather than other tables. Urey only showed that the chondrites did give a reasonable table of abundances. It is the object of this paper to estimate on the basis of observed regularities what the cosmic abundances are.

Empirical data on abundances

It would be expected that the sun's atmosphere contains all the elements in their primitive relative concentrations except insofar as nuclear reactions have altered these abundances. This has occurred in the case of H and He due to the slow conversion of hydrogen into helium and in the cases of deuterium and lithium which at the temperature of the sun's interior will be converted into helium. Deuterium has never been observed in the sun's atmosphere. Claas (1951) gives an upper limit for the H/D ratio in the sun of 6×10^7. Greenstein and Richardson (1951) find that the abundance of lithium in the sun is very low but not zero. It is difficult to secure precise and reliable values for the abundances of all elements in the sun because of the very involved dependence of the intensities of

spectral lines on the temperatures in various levels of the sun's atmosphere. The abundances of the elements in many of the stars are very similar to these values for the sun though important differences occur. Also the abundances in planetary nebulae are very similar to stellar values. Though for the most part we are really discussing solar quantities, it will be assumed that all sources are sufficiently similar so that numerical values can be compared.

The proportions of the elements in the earth's crust have obviously been modified in several ways. During the process of formation, the earth lost most of the most volatile elements, hydrogen, the inert gases, carbon as CH_4, nitrogen as NH_3 or N_2, oxygen as H_2O, and possibly some proportions of other elements though such loss is not evident (Urey, 1954 b). There has been a marked differentiation of the surface regions by partial melting and crystallization processes and a loss of the siderophile and chalcophile elements to the deep interior. Erosion by water has further differentiated the surface regions. It is exceedingly difficult to estimate in any reliable way what the mean composition of the surface region of the earth is, yet there are some data of use to the present study.

It is generally assumed that meteoritic matter, since the time it formed from solar material, has undergone less chemical fractionation than any terrestrial material found on the surface of the earth. The type of fractionation that is recognizable in

meteorites may be separated into three main phases: the metal
phase, the sulfide phase, and the silicate phases. Accordingly,
Goldschmidt divided all chemical elements into three groups: the
siderophile, the chalcophile, and the lithophile elements, depending
upon the meteoritic phase in which the elements were found to be
enriched. This classification, however, is not always a definite
one, as many elements are distributed among two of the three
phases in varying proportions. In this classification Goldschmidt
assumed that the elements were distributed in these three
phases in equilibrium proportions. If equilibrium was established
the proportions of the elements should be constant in all samples
of these phases and this is certainly not true. Craig (1953)
has presented reasons for believing that at high temperatures
the sulfide phase would dissolve completely in the silicate and
iron phases if they were completely melted. In this case the
elements would become distributed between these two phases.
Because of differences in densities they would separate even in weak
gravitational fields. Subsequent cooling would result in separation
of the sulfide phase from each of these and equilibrium might no
longer be established between the sulfide phases in the silicate
and the metallic fractions. Separation of nodules of iron
sulfide from the iron phase would occur as the temperature fell and
these would collect elements dissolved in the iron phase in
quantities quite different from those collected in the iron
sulfide which separated from the silicate phases. Mostly analysts

have studied the iron sulfide from iron meteorites and assumed
that the concentrations of elements in the iron sulfide enclosed
in the silicates were the same. There is no reason to believe
that this assumption is justified. In fact the amounts of the
elements in these troilite nodules in the iron meteorites can
probably be neglected in any average because they constitute
such a very small fraction of the iron meteorites and hence
of all meteoritic matter.

Another difficulty in computing the "average" composition
of the meteorites arises from our ignorance of the relative
amounts of the three meteoritic main phases. The meteorites
reaching the earth's surface cannot serve as a basis for an
estimate of these relative amounts because iron meteorites are
better preserved during their fall and on the surface of the
earth than are stony meteorites and pallasites. The assumptions
made by different invesigators are summarized in Table 1.

TABLE I

Assumptions made on the average composition of meteoritic matter
by various authors

Parts by Weight

Author	Metal	Sulfide	Silicate
Noddack and Noddack (1930)	68	9.8	100
Noddack and Noddack (1934)	14.6	6.7	100
Fersman (1934)	20	• 4	100
Goldschmidt (1937)	20	10	100
H. Brown (1949)	67	0	100
Urey (1952 a)	10.6	7	100

The values given by Harrison Brown and by Noddack and
Noddack (1930) are obtained from the ratio of the weights of
core to mantle of the earth assuming that the average composition
of the earth represents the average of solar nonvolatile matter.
A new value secured by Rabe (1950) for the mass of Mercury leads
to a density for Mercury of about 5 and this indicates that it
contains a higher proportion of metallic iron than the earth.
Urey (1951, 1952 c) shows that the planets generally vary in
density and estimates the proportions of metallic phase. He
concludes that some fractionation must, therefore, have occurred
during the formation of terrestrial planets, separating metal
from silicate in such a way that the silicate was lost preferentially.
Hence, the ratio of core to mantle of the earth cannot serve
as a basis for an estimate of the respective cosmic ratios.
Urey, from his considerations of the thermodynamics involved
in the chemical processes leading to the formation of the ter-
restrial planets, has concluded that the moon and also the chondrites
would best represent the average composition of the nonvolatile
part of solar matter. His value for the iron fraction is even
smaJ er than that of Goldschmidt.

His
assumption of the lower value for iron has been confirmed by a new
measurement of the f-value of iron obtained by a new and precise
method by Kopfermann and Wessel (1951), whose new value is about
one third of that previously accepted. Urey derived his values for

the proportion of the three phases from the composition of the chondrites as given by Prior (1933). The new silicate metal ratio of meteorites make a revision of all the abundance values necessary. The empirical data are given in Table 2.

Recently on the basis of arguments regarding the heat balances of the earth, the moon and Mars, Urey (1955) has suggested that the elements potassium, uranium and thorium have been concentrated in the chondritic meteorites over solar values by a factor of about 3.2. If these elements have been concentrated in the chondrites by the melting processes which obviously have occurred, then other elements must have been concentrated in some degree and still others must have been decreased in concentration. In this paper abundances of elements have been modified from the meteoritic analytical data in accordance with these ideas. In fact abundance curves seem to be more regular as a result of such procedures.

Our decision to use such data was strongly influenced by advice from Professors Goldberg and Aller in connection with their studies on solar and other stellar abundances. The application of these arguments to individual elements will be discussed under each element and the method will be discussed when the potassium abundance is considered in detail.

Limits of error

Goldberg and Brown (1950) have shown that rhenium is about 130 times more abundant and that lead is at least 50 times less abundant than was previously assumed. This has created some doubt as to the validity of the data published for the cosmic abundances of the minor constituents of the less abundant elements. Previous to Brown's investigation the values for rhenium and lead were based entirely on the work of I. and W. Noddack. A comparison of their work with that of others shows that, in general, data compiled by these authors should not be accepted uncritically. In many cases no other data are available and Goldschmidt has used their values considering, however, possible sources of error in their determinations.

As will be evident from the detailed discussion under individual elements, there are serious sources of error in all data available. The data published in the last twenty years and particularly since the war seem to be generally much more reliable than that published previously. Even certain data of such a reliable investigator as V. M. Goldschmidt have been shown to be seriously in error, as for example in the case of lead. Generally, the amounts reported for the rarer elements, particularly in the range of a few parts per million, have decreased with time. Hence in our choice of data we have tended to select lower values rather than higher ones. In some cases we have selected values definitely outside the reported analytical values. It is our expectation that many reported analytical data are in error

by more than a factor of 10, e.g. Sn, Ag and W. Only further careful analytical work can decide whether our rather arbitrary choices in some cases are justified. We can say categorically that if some of these choices are incorrect, then our fundamental assumption of considerable smoothness in the abundance curves as a function of mass number is incorrect also.

Discussion of elemental abundances

All atomic abundances are given relative to Si equal to 10^6. Goldschmidt used silicon equal to 100 and Brown changed this to 10000. We use 10^6 in order to get values for the rarer elements which can be written without negative exponentials, or awkward decimal fractions. Plots of logarithms of the abundances, H, against mass numbers, A, are given in Figure 1 and our selected values are given in Table 3.

The cosmic abundance ratio of hydrogen to helium has been studied by astronomers for many years. Unsöld in his classical study on the atmosphere of γ Scorpii found this ratio to be 7.2 and others following his method of calculation have reported similar values. [See Aller (1953) for a review of this data.] He assumed one value for the temperature and one value for the electron pressure throughout the atmosphere of the star. Recently Underhill (1951) has used a model atmosphere with varying temperature and pressure for the O 9.5 star 10 Lacertae and secured a larger value of 20 to 25 for this ratio. Neven and de Jager (1954)

have constructed model atmospheres for four B-type stars, Υ Sco, δ Cet, γ Peg and $\flat$ Her from their hydrogen spectra and give an average value of 17.7 for this ratio with little variation between their values for these stars. Aller (1953) reports that his most recent studies give a similar value. Traving (1955) has made a model atmosphere calculation for this ratio in Υ Scorpii and finds 5.9 for this ratio. We adopt 13 for the ratio of hydrogen to helium though it may well be that the true ratio deviates from this value appreciably.

For the ratio of hydrogen to the metals we take the geometric mean of Unsöld's (1948) and Claas' (1951) values normalized to magnesium equal to 6.15. We find better agreement between the astronomical values when normalized to our magnesium value than when normalized to silicon equal to 6.00. The astronomical values for silicon seem to be too low as compared to Na, Mg, Al, Ca and Fe. This gives 10.56 for log H_H as compared to 10.54 (Unsöld) and 10.58 (Claas) for this quantity. The abundance of deuterium relative to protium in meteorites has been found to be about the same as on earth by Boato (1954) and Edwards (1955a). Deuterium is much less abundant in the sun than on the earth. We shall use 7000 as the H/D ratio which is slightly larger than the terrestrial ratio of 6500. The isotopic abundance of He^3 in primitive solar matter is unknown.

Lithium, Beryllium and Boron

The abundance of these three elements seems to be about a

million times smaller than that of the group of the next heavier
elements in the cosmos, carbon, oxygen, and nitrogen. According
to Greenstein and Richardson (1951), Li in the sun seems to be
even less abundant by another factor of 100. The low abundance of
these three elements can easily be understood as a consequence
of their instability at high stellar temperatures and their
possible thermonuclear reactions with protons. Such reactions
may have occurred toward the end of the processes by which the
elements were made.

The analyses of igneous rocks and of meteorites for these
elements are summarized by Goldschmidt (1937). He gives for
the atomic ratios of Li and Be in the lithosphere and in silicate
meteorites relative to Si equal to 10^6:

	Li	Be
Lithosphere	900	67
Silicate meteorites	100	20

Both are concentrated to some extent by the fusion processes that
have concentrated elements in the earth's crust. For this
reason smaller values than those of the meteorites, just as in the
case of K, U, and Th, might be used in our estimate of cosmic
abundances. However, because of the uncertainty of analyses, no
corrections have been made. Goldschmidt estimates the atomic
abundance of boron as 28. Its abundance in the earth's surface
is complicated by its appreciable concentrations in the sediments
and ocean waters.

Carbon, Nitrogen, Oxygen, and Neon

Our knowledge of the abundance of these elements is based entirely on spectroanalytical astronomic observations mostly in other stars than the sun, and in planetary nebulae, since very high temperatures or high frequency light is required to excite them to higher energy levels of the neutral atoms or to ionize them. Bowen (1948) has studied one line of oxygen in the sun and secured a somewhat higher abundance relative to the best estimates for carbon and nitrogen, namely 7×10^{20} atoms cm^{-2} as compared with 0.3 and 1.0 $\times 10^{20}$ atoms cm^{-2} for carbon and nitrogen, respectively. Minnaert (1953) summarizes the work of Unsöld (1948), Claas (1951) and Hunnaerts (1950) on the sun and Aller (1953) gives a summary of all stellar data. We will select the Unsöld data for C and N in the sun and the geometric average of the Unsöld and Claas data for O in the sun, all normalized to log H_{Mg} equal to 6.15. Very good agreement between their data for Na, Mg, Al, Ca and Fe and our selected values for the elements is secured in this way.

Aller concludes that oxygen and neon have nearly the same abundance in the stars and planetary nebulae. Traving (1955) estimates the neon abundance as 1/2.5 that of oxygen. If oxygen and neon have nearly equal abundances, the logarithm of the abundances of Ne^{20}, Ne^{22}, Mg^{24}, and Mg^{26} fall on nearly a straight line. If neon is considerably less abundant than oxygen, it could be ascribed to a fall in abundances after the neutron number 8 of O^{16}

as occurs at other points in the abundance-mass number curves.
We are disposed to suggest that neon is considerably less
abundant than oxygen, and have taken its abundance as 0.4 that
of oxygen. A maximum in abundance at N^{15} with 8 neutrons is
indicated with a miniumum in the curve at F^{19}. Since the
abundance of fluorine is not well known, this minimum might be
at O^{17} instead.

Fluorine

The astronomical values for fluorine have always been very
uncertain, and we must depend on terrestrial and meteoritic
values. The only value for fluorine in meteorites, namely 30 ppm,
is that of Walter and Ida Noddack (1934). A recent detailed study
by Koritnig (1951) on the terrestrial distribution reports 100 ppm
in pyroxenes and peridotites and increasing amounts in the more
acidic rocks with an average in the lithosphere of 702 ppm. This
is not an extreme degree of differentiation as compared to some
other elements. We shall estimate the abundance of fluorine as
200 ppm relative to silicon as 0.185 by weight in primitive solar
nonvolatile material and thus take the atomic abundance as 1600.

Elements from sodium to iron

The analyses for the elements from sodium to iron both for
the earth's surface and for meteorites are numerous and appear
generally to be well done. Goldschmidt (1937) reviewed the older
analyses as did Brown and Patterson (1947) but the most recent
and extensive review of the older analyses have been made by Urey

and Craig (1953). The latter authors selected 94 superior analyses
of chondrites from 350 analyses and gave specific reasons for their
selection. The abundances so secured did not differ markedly
from the table of Goldschmidt. They showed that two rather well
defined groups of chondrites existed having different quantities
of total iron so that the iron silicon ratios in the two groups
averaged 6084 and 8494 to 10000 for silicon. They found that the
amounts of cobalt and nickel for the two groups differed even
more than those of iron. They argued that the lower iron abundance
was more probably correct on the grounds that the fractionation
of the silicate and iron phases, which has occurred among the
planets generally (Urey 1951), probably took place through the
loss of the silicate phase rather than the metallic phase, which
was the view expressed by Urey previously. This leads to a low
abundance of iron which is very much in accord with the most
recent astronomical data. We shall take the abundances of iron,
cobalt and nickel from Urey and Craig's low iron group of chondrites
for this work.

The analytical values for potassium given in the older
analyses are certainly too high. This was shown by Ahrens,
Pinson and Kearns (1952) who secured 0.09% as the correct
analytical value for potassium in chondritic meteorites. Edwards
and Urey (1955) by further improvement of analytical procedures
showed that the chondrites are remarkably constant in their
potassium and sodium contents. We take the abundance of K as

220 ppm relative to silicon equal to 18.5 percent by weight in primitive nonvolatile solar material. This is one fourth of its reported abundance. We use this somewhat larger factor because Urey's (1955) calculations indicate that his choice of radioactive elements is somewhat too high for reasons which he discusses. Also, the somewhat lower abundance gives a somewhat smoother abundance curve. This gives 854 for its atomic abundance. The use of this abundance leads to the similarity in shape of the even and odd mass curves in the minimum region between oxygen and iron.

As explained above, the choice of this lower value for potassium requires that other abundances by adjusted if we are to be consistent. It seems likely that the melting processes which produced the silicate minerals produced the fractionation of potassium, uranium and thorium, and in this case the abundances of all elements which are markedly concentrated by such processes must be appropriately adjusted as well. In order to judge the direction and amount of such adjustments we have studied the relative abundances of the elements in the earth's crust and in the meteorites. Potassium makes up 2.6 percent of the earth's surface rocks and only 0.09 percent of the meteorites. Also, analyses of ultramafic rocks show that potassium is very low in these rocks. Ross, Foster and Myers (1954) analysed olivine bombs from basaltic lava flows and found low values for sodium and potassium and Edwards (1955b) using an improved method of analysis

has found 0.018 and 0.22 percent for potassium and sodium respectively
in such material. Sodium, aluminum and calcium have been concentrated
at the earth's surface though less markedly than potassium, and
magnesium is depleted in concentration at the earth's surface.
Thus, we must expect that the analytical amounts of sodium,
aluminum and calcium in meteorites are also too high and that
magnesium is too low, though by smaller factors than is true of
potassium. Also titanium may be somewhat too high and chromium too
low. Our selected values for the abundances of the elements are
based on the meteoritic abundances adjusted somewhat in accord
with these arguments.

Some ratios of concentrations in the earth's crust and
meteorites are given in Table 4.

TABLE 4

Element	Ratio	$\triangle$
Na	2.83/0.7 = 4	-0.1
Mg	2.1/16 = 1/7.6	+0.183
Al	8.13/1.42 = 5.7	-0.12
Si	28.89/21.20 = 1.35	0.00
P	~1	0.00
S	?	
Cl	?	
K	2.6/0.09 = 29	-0.607
Ca	3.63/1.73 = 2.1	0.00
Sc	~1	+0.38*
Ti	0.44/0.076 = 5.8	-0.38*
V	~1	0.00
Cr	~400/3300 =1/8.2	+0.28
Mn	~1	0.00

* The unusual choice of these values is discussed in
   the text.

Column two gives the ratio of the terrestrial to meteoritic

abundances, R, and column three gives the amounts by which the logarithms of abundances have been adjusted, Δ. These adjustments are not always entirely consistent. Explanations for this are given later in this paper.

Magnesium is a particularly interesting element in this connection. It is a popular idea that the mantle of the earth is mostly dunite which consists mainly of magnesium and ferrous orthosilicates, Mg_2SiO_4 and Fe_2SiO_4. With an atomic abundance of magnesium only 0.9 that of silicon, as indicated by the analyses of the chondritic meteorites and the addition of some ferrous iron, the metasilicates of magnesium and ferrous iron should make up the earth's mantle. Our changed abundance of magnesium would permit the formation of much orthosilicate if the mantle consists of such material. Hess (1955), on the basis of the probable composition of the earth's mantle, suggests a ratio of magnesium to silicon of 4/3. We have used 1.4 for this ratio, which is about 1.5 times the observed ratio in meteorites.

Phosphorus, sulfur and chlorine

The analyses for phosphorus seem to be consistent and satisfactory. Phosphorus is not markedly concentrated in the earth's surface. We use the meteoritic value.

The silicon-sulfur ratio is an important datum, since the sulfur exists in a separate phase as iron sulfide and many elements dissolve in this phase. Goldschmidt's estimate for sulfur is much less than the astronomical values though the

astronomical values depend on data which are very difficult to interpret. Urey gives a smaller value than Goldschmidt. Such values are probably in error on the low side since iron sulfide would be reduced by hydrogen at moderate temperatures, i. e. the melting point of iron and lower, and hence sulfur was probably partly lost as hydrogen sulfide during the formation of the meteorites. Since sulfur exists in the carbon compounds of the carbonaceous chondritic meteorites, as shown by Mueller (1952) the element may have escaped in such compounds during the formation of the solar system. We have selected a value between the astronomical estimates and the meteorite value. A lower sulfur value would make it very difficult to select a satisfactory selenium value compared to other elements near it in the periodic table and at the same time not deviate unduly from the observed sulfur-selenium ratio.

Chlorine abundances have been extensively studied recently by Behne (1953) and Salpeter (1952). The former of these studied many terrestrial igneous and sedimentary rocks and a few meteorites and the latter analysed a considerable number of meteorites. The two sets of values are in disagreement generally. Behne secured some 100 ppm in two chondrites and the average of Salpeter's chondritic values is 840 ppm.

Selevanov (1940) reports 100 ppm for one chondrite. Urey (1952a) used the Noddack's value of 470 ppm. Some of the iron meteorites contain small amounts of chlorides. Mueller (1952) has shown that the organic compounds of the carbonaceous chondrites contain appreciable amounts of chlorine suggesting the possibility of loss of this element through volatile compounds as discussed by Urey (1954a). We have used the 660 ppm value as a compromise in view of the uncertainties of the situation.

The heavier rare gases.

The rare gases with the exception of helium are not observed in the sun because of its low temperature and their low abundance. Neon and argon have been observed in O type stars and planetary nebulae. The data are reviewed by Unsöld (1948) and by Aller (1953). Certainly the probable limits of error are very large because the observed lines are those of the ions and it is difficult to estimate the conditions of excitation with sufficient accuracy to secure the abundances within better than a factor of 10 with certainty.

The ratios of the rare gases in the atmosphere are well known. From these ratios one may derive some valuable conclusions independent from any theory on the formation of the atmosphere. In particular, it seems safe to postulate that the heavier rare gases have been enriched with respect to the lighter ones on the surface of the earth. This means, that the ratio of krypton to xenon must be equal or larger in solar matter than in the atmosphere. The same will be true for the ratio of argon to krypton or neon to argon, exclusive of the A^{40} isotope. This seems to be an absolutely safe statement as no chemical or physical process is known by which the heavier gas would escape more readily then the lighter one. Terrestrial helium and A^{40} must be radiogenic and hence cannot be included in any argument of this kind.

The astronomical values for the abundances of argon and chlorine in planetary nebulae are much higher than those expected from simple interpolation for argon and chlorine from the values for neighboring elements in the meteorites. If the astronomical values are used for the graphic presentation of nuclear abundances, one obtains a most remarkable feature, namely a sharp rise in the odd and even mass abundances curves at masses 35 and 36 followed by a precipitant fall to lower abundances through masses Cl^{37}, K^{39}, K^{41}, Ca^{43} in one curve and through A^{38},

Ca^{40}, Ca^{42} in the other curve. There seems to be no physical reason to expect such a behavior of these curves. Also it is difficult to understand such a very large loss of chlorine from the earth and meteorites on the basis of its chemical properties (Urey, 1952b). We conclude that this interpretation is incorrect and interpolate A^{36} and A^{40} smoothly between sulfur and calcium and use the chlorine value discussed above. This choice indicates our feeling of uncertainty in regard to astronomical values for other elements such as C, N, O, F, Ne, and S. The krypton - xenon ratio adopted is the atmospheric ratio of 12.5 in agreement with the postulate made above. The xenon value determines the uncertain tellurium abundance.

Calcium, scandium and titanium.

Calcium has been determined in the meteorites with high precision and is only moderately concentrated in the surface rocks of the earth. We use the Urey and Craig value of 53,600. The concentrations of scandium in the meteorites as determined by Pinson, Ahrens and Franck of 6 ppm is essentially the value given by Goldschmidt. This element is more concentrated in the more basic rocks. (See Rankama and Sahama (1950) p. 516 for a summary of the data.) Russell has called our attention to the fact that the lines of scandium are much more intense in the sun's spectrum than are those of gallium, in spite of the greater intrinsic intensity of the gallium lines. It is difficult to secure any marked difference in scadium and gallium abundances unless scadium has a higher abundance than that indicated by the analytical data on meteorites. We assume that scandium is depleted in the meteorites and take its abundance as 48 instead of 20 as the meteoritic data indicates.

Titanium has been determined with excellent precision for many years. Urey and Craig's average is 0.066%. Wiik (1955) has made very recent and carefully controlled analyses on a number of mostly carbonaceous chondrites and concludes that

the amount is very constant near 0.075%. The element is concentrated in the surface regions of the earth, and hence we have used a lower value for the solar abundance, namely 1020, instead of the Urey and Craig value of 2200 or the Wiik value of 2500. This lower titanium abundance is used after many attempts to adjust the zirconium and hafnium values to their neighboring elements and yet to maintain the observed ratios of these elements to each other and to titanium. The lower value of titanium seems to be the most plausible adjustment that we have been able to make. It may well be that some other choice will be more correct as better analyses become available.

Vanadium, chromium and manganese.

Analyses for these three elements seem to be good and hence the choice of abundances is not a problem. Chromium is depleted in the earth's surface regions by a factor of about 8.2 relative to the meteorites. Hence we use a slightly higher value for chromium than the meteoritic value, namely, 1.817 x 10^4 instead of 1.15 x 10^4. We use the meteoritic values for vanadium and manganese.

Important ratios of elemental abundances.

The titanium-zirconium-hafnium ratios appear to be well established. The evidence indicates that the ratios are nearly the same in meteorites and terrestrial sources. Goldschmidt gave about 20 for the Ti / Zr ratio and about 50 for the Zr / Hf ratio by weight in both sources. Pinson, Ahrens and Franck (1953) find 33 ppm for Zr in chondrites and Wiik (1955) finds 0.075% for Ti, i. e. a ratio of 22.7. We shall use this value and take the atomic Zr abundances as 1/43 of our titanium abundance.

The Zr / Hf ratio depends on the extensive investigation of Hevesy and Würstlin (1928, 1934) on the abundance of hafnium in zirconium from many sources. Their values for Zr in the Pultusk and Waconda meteorites differ

markedly from those of Pinson, Ahrens, and Franck (1953). There is some
considerable probable error in the data. Through the kindness of Dr. S. G.
English, we have learned of many recent analyses of zirconium minerals for
hafnium made by the U. S. Bureau of Mines. The average of sixty eight
analyses is 2.37 percent of hafnium relative to zirconium and hafnium. This
is a somewhat higher abundance of hafnium than Goldschmidt gave. It is not
possible to decide whether there is a definite concentration of hafnium
relative to zirconium in the process of formation of these minerals but
a few samples (which were not included in the average) do contain much higher
concentrations of hafnium. We use 55 for this weight ratio and 110 for the
ratio of atomic abundances.

Goldschmidt gave the terrestrial ratio of S / Se as 6000 and the meteoritic ratio
as 3300 by weight. Since then Byers (1938) has analysed a number of meteorites
including several chondrites. Two of these latter were Allegan and Tabory,
which are observed falls while the others which he used are finds. The selenium
was reported as 13 and 10 ppm in these two meteorites and less in other
chondrites. He also determined the sulfur - selenium ratio in troilite from
Canyon Diablo as 4215 by weight and thus intermediate between Goldschmidt's
values. If we use Goldschmidt's ratio and our sulfur value we secure 42.3
whereas Byer's data gives 24.2 for the atomic abundance. Because of the
differences in stabilities of H_2S and H_2Se and of the carbon compounds of the
two elements, it is not probable that selenium would be lost as readily as sulfur.
We have selected 37.7 as our abundance of selenium. More data on this ratio
are needed, but we conclude that the abundance of Se may be less, but hardly
more, than our value. The data on tellurium are most uncertain and we must
interpolate a value for this element.

The ratio of chlorine to bromine is probably more reliable than the bromine

values. This ratio is 300 by weight in sea water. Selivanov(1940) (See
Rankama and Sahama (1950 p. 760) reported values ranging from 100 to nearly
300 for the ratio in terrestrial rocks. Behne (1953) gives values for this
ratio which vary greatly in different igneous rocks. We weight the oceanic
value very heavily. Behne generally finds lower values for chlorine than we
have used. Our ratio of 500 for the atomic abundances equivalent to 220 for
the weight ratio is taken as a mean of the data on this ratio. The oceanic
value for iodine is valueless because iodine is used by living organisms and
hence is probably depleted in the sea as compared to the sediments.

The ratio of potassium to rubidium has been extensively investigated in
recent years. Ahrens, Pinson and Kearns (1952) found a ratio of 100 by weight.
Edwards and Urey (1955) secured a value of 180 on a few samples of meteorites.
Herzog and Pinson (1955) find that a revision of this ratio to about 200 seems
likely. The ratio is very comparable to the chlorine-bromine ratio. Using
our potassium abundance this gives 1.10 ppm. which is lower than the reported
values. If potassium has been increased in concentration in the meteorites, we
can expect the same is true of rubidium since the two elements follow each
other very closely in nature. We use the somewhat higher value of 1.22
ppm or an atomic abundance of 2.18.

However, we believe that there
is a minimum in the curve in this region on the low mass side of the neutron
number 50 just as there is on the low mass side of the region of neutron
number 82 and and our curve is similar to that previously given by Suess (1949).

Goldberg, Uchiyama and Brown (1951) have determined the amounts of Ni,
Co, Pd, Au, and Ga in 45 iron meteorites. As stated previously the content
of gallium varies markedly and there is some slight correlation with palladium
content. Their ratio of nickel to palladium is the most reliable value for this

ratio, namely 2.24×10^4 by weight. With our nickel value this gives
0.850 for the palladium abundance. Goldschmidt gave 2.5 for this value.
Goldschmidt's assumption of a higher proportion of metallic phase
increased his value. Using 10 per cent of the metallic phase and
neglecting the troilite phase, his value becomes 0.9 ppm which is
only slightly larger than our selected value. The Ni-Au ratio is
also given by the studies of Goldberg et al and this fixes the
position of gold relative to nickel. These two ratios are the most
reliable that we have for fixing the position of our curves over
the high mass range.

The atmospheric ratio of krypton to xenon by atoms is 12.5
and the solar ratio must be this value or higher since krypton may
have escaped more readily than xenon, as explained above. It has been
most interesting that throughout our attempts to secure the adjustment
of abundances consistent with all the evidence, we have never found
it desirable to increase this ratio above the value of 12.5. Our
abundances of krypton and xenon, 25.0 and 2.00 respectively are
consistent with this ratio.

Copper, Zinc, Gallium, Germanium, Arsenic, Krypton, Strontium, Ytterbium

Within reasonable estimates of the errors in the reported
abundances of elements from Fe to Zr, it is possible to secure a
smooth curve for the odd mass elements of this region. The pairs
of isotopes of Cu, Ga, and Br define the slope at three points. The
general position of the curve is fixed by the Br and Rb abundances.

The Cu content of meteorites varies within surprisingly large
limits. Goldschmidt after an extensive discussion of the
best data which vary by factors of more than 10, selected an atomic
abundance of 460. Preliminary unpublished data of Wiik indicate

greater constancy in the copper data for chondritic meteorites.
Our choice of 228 for the atomic abundance results from a consideration
of his data.

Zinc in meteorites is typically chalcophile and is concentrated
in the sulfide phase. Goldschmidt's selection of data would require
zinc to be less abundant than copper, which would be a surprising
result. Unsöld's value based on three lines in the solar spectrum
is more than ten times higher than Goldschmidt's estimate of 360
for the atomic abundance. We use 486 in order to secure smooth
abundance curves in this region. This value is surely within the
errors of the analytical data.

Gallium has been studied in the iron meteorites by Goldberg,
Uchiyama and Brown (1951) who found three groups of iron meteorites
having quite distinctly different contents of gallium, namely, 60, 20
and 2 ppm, respectively. No satisfactory explanation of this variation
has been given. These abundances are puzzling particularly since gallium
is a rather electropositive element and is concentrated to some extent
in the surface terrestrial rocks. It seems probable that gallium is
present partly in the silicate phases as well. We use 14.6 for this
abundance, equivalent/to 6.7 ppm, which makes scandium 3.3 times as abundant
as gallium, thus meeting to some extent the observations of Russell
regarding the relative abundances of these elements. It would be
difficult to be certain that gallium should not be lower or scandium
higher or both.

The careful studies of Goldschmidt and Peters (1933a) on the
germanium content of meteorites gave a mean of 79 ppm in their average
of the silicate, troilite and metallic phases. The germanium

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was found mostly in the metallic phase. We are assuming considerably

less iron in our average and less in the metallic phase than did

Goldschmidt. In order to place Ge^{73} on our smooth odd

mass curve we must assume about 25 ppm of germanium or an atomic abundance of 51 instead of Goldschmidt's 188 for this quantity. There is considerable reason to believe that the germanium, tin and lead values selected by Goldschmidt are all too high as will be evident when tin and lead are discussed.

A recent value of Sandell (1955) for arsenic of 2.2 ppm in chondritic meteorites or an atomic abundance of 4.0 seems to be very reliable. This is an average of 14 chondritic meteorites. The Noddack's (1934) values are much too high. Their value together with our values for selenium, bromine and rubidium will not give a smooth curve for the odd mass elements. Ge^{74} is more abundant than the neighboring even mass nuclides whose masses are divisible by four. All nuclides from O^{16} to mass 68 whose masses are divisible by four are either more abundant than their neighbors or the inflections of the curve indicate that they are preferred. It may be that this irregularity appears in the odd mass curve at As^{75}. We use an abundance of 3.2 instead of 4.0 and avoid the irregularity in the curve.

Pinson, Ahrens and Franck (1953) have recently determined strontium in meteorites by improved techniques and report an average of 11 ppm. This element is highly concentrated at the earth's surface, 100 to 460 ppm having been reported. (See Rankama and Sahama (1950) p. 453 for a summary of data.) Strontium is increased in the earth's crust to a smaller degree than barium and to a greater degree than calcium. We lower the observed value of strontium by a factor of 1.58 or 0.2 in the logarithm, and barium by 0.68 in order to correct for the concentration effect. This gives 12.1 for the atomic abundance of strontium. Our calcium value is the unchanged meteoritic abundance.

The abundances of yttrium and the rare earths are difficult to estimate. The concentrations of yttrium in acidic and basic rocks are much the same, and

also these are very similar to its reported concentrations in meteorites. Hence, we use Goldschmidt's value of 5 ppm in meteorites and an atomic abundance of 8.9 (See Rankama and Sahama (1950 pp. 510 and 516 for a review of the data).

The curves in this region indicate a slight maximum at bromine and a minimum before the magic number nuclides at N equal to 50. The minimum could be eliminated if the factors of 4 for the rubidium data and of 1.58 for the strontium data were not applied. However, as stated above, we believe the minumum is real and similar to that preceding the magic number nuclides at N equal to 82. We also believe that the gallium and selenium values might be lower but not higher and hence that the slight irregularity of the curve is justified on the basis of present evidence.

Zirconium through tin.

The fundamental nickel-palladium ratio previously discussed fixes the abundance of palladium. The value so determined fits smoothly with the determination of Kuroda and Sandell (1954) for molybdenum of a mean of 1.54 ppm in the chondrites and a corresponding atomic abundance of 2.42. This new analytical value is about half of the older value (Noddack & Noddack 1930, 1931). The decreasing abundances of the Zr isotopes shows that there is a rapid decrease in abundances after neutron number 50. The even mass nuclides of the even atomic number elements Ru, Pd, Cd and Sn can be fitted to a smooth curve of abundance versus mass number and at the same time a reasonably smooth curve for the odd mass nuclides can be constructed. The ratios of ruthenium, rhodium and palladium are not well known. Goldschmidt estimates the ratios as 10 : 5 : 9. We have adopted atomic abundances of 1.49, 0.214, and 0.850, making our ratios 10 : 1.44 : 5.7. These give a smooth curve and we believe our values are within present limits of error, though they differ considerably from Goldschmidt's ratios. For cadmium we use an atomic abundance of 1.36 as compared to the

Noddack's value of 1.86 for the chondritic meteorites. This makes our zinc to
cadmium atomic ratio equal to about 360 instead of Goldschmidt's estimate of
160. Better analytical data for this element is needed badly.

The meteorite analyses by Goldschmidt and Peters (1933b) and Goldschmidt (1937)
gave 100, 15 and 5 ppm of tin in the metal troilite and silicate phases. Using
metal : troilite : silicate in the ratio of 10 : 5 : 85 would give about 15 ppm
and an atomic abundance of 19. The Noddacks (1934) give 50 for the atomic
abundance. Instead of these we have used an abundance of 2.65. The use of
Goldschmidt's or the Noddacks' value would give an irregularity in the curve with
respect to all neighboring elements on the basis of present knowledge. We
conclude that the analytical data for this element are incorrect by a large
factor. Tin is an element which is extensively used in laboratory equipment as
solder, block tin stills for distilled water, etc. Dr. M. Fleischer advises
us that tin is often reported too high in silicate materials because of the use
of soldered sieves for separating crushed samples.

Niobium was determined by Rankama in chondritic meteorites as 0.5 ppm
equivalent to an atomic abundance of 0.81. This value is close to our adopted
value of 1.00. The silver value adopted here is much lower than indicated
by analytical data. Goldschmidt selected a value of 3.2 for the abundance
on the basis of his own and the Noddacks' data. We find that we must use 0.346,
if silver is to lie on our odd mass curve. Mr. Joensuu advises us that much
analytical data on small amounts of silver is incorrect because of the ease
of excitation of its resonance lines, and because of the presence of silver coins
in the pockets and hands of analysts. Also, this chalcophile element may be
reported too high partly because it is reported in high concentrations in

troilite nodules from iron meteorites. Its concentration in iron sulfide from silicate meteorites is reported as 5 ppm by the Noddacks' and as 38 ppm in the iron sulfide from iron meteorites.

The older data on indium indicates 0.15 to 0.20 ppm in meteorites, but recently Shaw (1952) has been unable to detect indium in two chondrites and one achondrite using a sensitivity believed to be able to detect about 0.02 ppm. Our interpolated value of 0.193 corresponds to 0.15 ppm in chondritic meteoritic matter. It is difficult to understand Shaw's very low values unless the large amount of iron in the meteorites interferes with his spectrographic analyses because of the high background produced by the many iron lines.

Maxima appear in both our curves at neutron number 58, which we are unable to eliminate by any reasonable adjustment of adopted abundances. At this neutron number the $g_{7/2}$ shell might be filled. Mayer and Jensen (1955) believe that the $d_{5/2}$ shell should be filled first at neutron number 56. We can see no irregularity in abundances at this neutron number.

It is evident that it would be highly desirable to secure more modern analytical data for the elements from zirconium to tin. Between mass numbers 99 and 123 inclusive five pairs of isotopes of odd mass numbers occur with a maximum abundance ratio of 1.34, i.e. Sb^{121} to Sb^{123}. Our values are selected on the assumption that the ratios of abundances of nuclides that are not isotopic pairs should have similar values.

Selenium, Tellurium, Iodine, Xenon, Cesium, and Barium

The analytical data on the first five of these elements is almost of no

value. Undoubtedly a marked decrease in the even mass
abundance curve occurs at mass 120 and a smaller decrease
at 119 or 121 in the odd mass curve. Goldschmidt states
that the selenium-tellurium ratio, based on data by the
Noddacks (1934), "may perhaps" give the right order of
magnitude, and he estimated it as 80. We use a value of
11.5 for the atomic ratio which may not be unreasonable.

The value for xenon is fixed relative to the krypton
value by reasoning presented above. The krypton-xenon
ratio is either 12.5 or greater, and we are assuming the
maximum possible value for xenon. The unusual abundances
of its odd mass isotopes and their relation to the even
mass abundances require maxima in both the odd and even
mass curves near mass number 130. A barium abundance
of 8 ppm in chondrites has been given recently by Pinson,
Ahrens, and Franck (1953). This gives an atomic abundance
of 8.8. Our selected value of 1.83 is thus much lower.
Barium is concentrated in the earth's surface regions to
as high or even a higher degree than potassium, and hence
the reduction in the observed abundance is justified to
some extent. We would prefer to use a higher abundance,
but, then if the smooth curve in the rare nuclides of Sn
to Ce (See Fig. 1) is to be preserved, a higher abundance
of xenon and tellurium would be required. This in turn

requires a higher abundance of krypton.

We have been unable to completely resolve our uncertainties on these points. It is impressive, however, that the uncertainties with respect to these relative abundances amount only to a factor of 1.25 or 1.5. Our strontium to barium ratio is 6.6.

The odd mass isotopes of these even atomic number elements outline the odd mass curve. Iodine and cesium at 0.40 and 0.228 fit nicely into the curve. The data on both these elements are very unsatisfactory. Van Fellenberg's (1927) data lead to an average of 1.25 ppm for iodine, while the Noddacks (1934) give 0.035 ppm. Our adopted value based entirely on interpolation is equivalent to 0.33 ppm and is close to van Fellenberg and Lunde's values (1926) for igneous rocks. In fact all our adapted halogen values are comparable to those for igneous rocks. Our interpolated cesium abundance is equivalent to 0.20 ppm, whereas the Noddack's (1930, 1934) have given two values, 0.01 and 1.1 ppm for this quantity.

Only a few data are given by the Noddacks (1931, 1934) for antimony in

meteorites. We have selected a value which fits on the odd mass curve with the break in the abundance curve occurring at mass 121. The value so secured, namely 0.493 and equivalent to 0.39 ppm, is near the Noddack value, providing the troilite data are ignored on the assumption that analyses on the troilite from the metallic meteorites give values which are much too high for the sulfide phases in average chondritic meteorites.

It is evident that the observational data for this range are very few in number and of doubtful quality. Our selected values may be extensively revised as new data becomes available, though we expect that the general shape of our curves are likely to remain.

The rare earth elements, hafnium, tantalum and wolfram.

As pointed out above, the relative abundances of the rare earth elements have been used as an argument for the existence of the given abundance rules. The rare earth elements have chemical properties so similar that any major separation of these elements from each other seems to be improbable in any kind of cosmochemical process. Hence, the analytical data for meteorites should give the relative abundances of these elements relative to each other with great reliability. Furthermore, it seems improbable that even on the surface of the earth these elements have been separated from one another by a large factor, except in certain types of minerals, and except that according to Goldschmidt and Bauer (Quoted by Goldschmidt (1937) europium has a tendency to separate from the other rare earth elements and to follow strontium and lead in its geochemical behavior. Minami (1935), in Goldschmidt's institute, carried out a complete analysis of terrestrial sediments for the rare earth elements. He found that in sediments europium does not show any abnormal abundance, and therefore, concluded that these sediments contained the rare earth elements in a ratio corresponding to that of the average at the earth's surface.

The analyses of meteorites carried out by Ida Noddack (1935)
lead to values considerably different from those given by Minami
for terrestrial sediments. The ratio of La to the heavier rare
earth elements, such as Er, Yb, etc., is about 8 times larger in
Minami's values for the sediments than in those of Noddack's for
the meteorites. It seems difficult to believe that a fractionation
of that order of magnitude could have occurred during the formation
of the earth, and it seems more probable that one of the series of
analytical data is considerably in error.

Minami's values for the abundances of the rare earth elements
relative to each other in terrestrial sediments have been tenta-
tively assumed here to give a closer approximation to the truth
than the value given by Noddack. Goldschmidt (1937), Brown (1949)
and Urey (1952) all used Noddack's values and hence considerable
differences between their tables and the present table occur.
The abundance of the group as a whole relative to silicon has
been chosen arbitrarily so as to secure what appears to the
writers to be a reasonable interpolation to the lower and higher
mean abundances. Our values certainly lie within reasonable
limits of error of the data.

Considerable concentration of the group has occurred in
the more acidic rocks and hence a somewhat lower value for
lanthanum

than that given by Noddack (1935) is justified. The abundances
are adjusted only slightly from Minami's values in order to
secure smoother curves. Table 5 compares the observed and
selected values both normalized to our lanthanum value.

TABLE 5

	La	Ce	Pr	Nd	Sm	Eu
Minami's abundances	1.00	2.46	0.295	1.25	0.215	0.052
Our abundances	1.00	1.13	0.20	0.72	0.324	0.093

	Gd	Tb	Dy	Ho	Er	Tm
Minami's abundances	0.31	0.043	0.21	0.052	0.11	0.0084
Our abundances	0.34	0.048	0.28	0.059	0.16	0.0159

	Yb	Lu
Minami's abundances	0.12	0.032
Our abundances	0.11	0.025

The most serious disagreement occurs in the case of cerium. The
discrepancies are surely within the observational errors, but
also the true curves may be less regular than we have drawn them.

The abundance of hafnium was taken as

$\sim$ 1/110 that of zirconium, as discussed

above. Rankama (1944, 1948) gives the maximum amount of tantalum in
meteorites as 0.38 ppm, equivalent to an atomic abundance of 0.32.
We have adopted the smaller value of 0.036 by interpolation.
We have discussed this with Dr. Rankama, who agrees that the lower
value is probable.

It seems certain that the earlier analytical data on wolfram

are much too high according to Sandell (1946) and Landergren (1948).
Results of the Noddacks (1930, 1931) and by Hevesey and Hobbie
(1933) on igneous rocks are higher than Sandell's by more than a
factor of 10. We conclude, therefore, that the data by the Noddack's
on meteorites are also in error, and that there is no analytical
datum for wolfram in meteorites. We have interpolated a value
of 0.35 corresponding to 0.42 ppm. This interpolated value is
about one third of Sandell's value for igneous rocks.

Rhenium, osmium, iridium, platinum, gold

Brown and Goldberg (1949) have determined rhenium in the
five iron meteorites by the neutron activation method and find
amounts varying from 0.25 to 1.45 ppm and an average of 0.62 ppm.
Assuming that mean meteoritic matter would contain some 10% of
metal phase this indicates about 0.062 ppm for this element. The
thermodynamic properties of rhenium and its compounds are nearly
unknown, but descriptive discussions of its chemical properties
would suggest the possibility of some chalcophile as well as
the proven siderophile character. Our selected atomic abundance
of 0.155 is 2.5 times the value estimated from the iron phase
alone.

Goldschmidt (1938) estimated osmium, iridium, and platinum
in ppm as follows:

	Metal	Troilite	Average	Atomic Abundance
Os	8	9	0.8	0.64
Ir	4	0.4	0.4	0.31
Pt	20	2	2.0	1.5

The average is secured by assuming 10% metal, neglecting the troilite phase, which was from iron meteorites, and assuming that these elements are not present in the silicate fraction and its troilite. Our adopted atomic abundances are 1.00, 0.82 and 1.62 for Os, Ir, and Pt, respectively. Goldschmidt's estimates are certainly approximate, and the agreement is satisfactory. Data on these elements, of the precision of the Goldberg, Uchiyama and Brown (1951) data for Pd and Au would be highly desirable. The even and odd mass curves, if they are smooth and if their slopes are given by the isotopic abundances of Re^{185} and Re^{187}, Os^{187} and Os^{189}, and Ir^{191} and Ir^{193} for the odd mass curve and mostly of the Os^{188} and Os^{190}, and Pt^{194}, Pt^{196} and Pt^{198} for the even mass curve, must lie close together and have maxima at masses 193 and 194. These maxima are similar to those in the neighborhood of mass number 130.

We use Goldberg, Uchiyama and Brown's (1951) data for the nickel-gold ratio in order to fix the atomic abundance of gold. These analytical data have a rather wide spread of values for this ratio with an average value of 5.8×10^{4} by weight. Their palladium-gold ratios are more nearly constant. With our nickel abundance this gives 0.145 for the atomic abundance.

Mercury, thallium, lead, bismuth, uranium and thorium

Mercury is a volatile element which may have been partly lost from the meteorites. Also it is so prevalent in all chemical laboratories that all analyses are suspect. The Noddacks (1934)

reported it in Canyon Diablo troilite. We interpolate our mercury value at an atomic abundance of 0.0318.

The Noddack's give 0.15 ppm for thallium in the silicate phase of meteorites, but Shaw (1952) was unable to detect its presence in two chondrites and one achondrite and this indicates an abundance of <0.01 ppm. Shaw's extensive studies establish the mean abundance of thallium in igneous rocks as 1.3 ppm. This element is greatly concentrated in the surface terrestrial rocks and hence is probably concentrated in the chondrites as well. This indicates a very low solar abundance. In order that Tl^{203} and Tl^{205} shall lie on a smooth curve with our Pb^{207} and Bi^{209}, we take the thallium atomic abundance as 0.0112 corresponding to 0.013 ppm. If we take the solar value for thallium in nonvolatile material as 1/100 of Shaw's terrestrial mean, as we have done for potassium, we secure this same value. Also, Ahrens (1947) found a ratio of rubidium to thallium of 230 in atomic abundance for pegmatitic minerals. Our adopted ratio is 250. We are unable to explain Shaw's very low observed values unless the high iron content interferes with his analyses. If thallium is much less abundant than we have assumed, all of the thallium of the entire mantle of the earth must be in the crust, which appears to be unlikely. Our assumed value mulliplied by the factor of about 4 should be the amount of thallium in the chondritic meteorites.

Fairly high values for lead in meteorites were reported by Goldschmidt and the Noddacks in all phases of meteorites. Today

these data all appear to be doubtful, because Brown and his co-workers have shown that lead is present in much smaller amounts in all phases. Lead is a very ubiquitous element, present in many reagents and in water in small amounts and, since the use of tetraethyl lead in motor fuel, in atmospheric dust as well. Because the troilite from metal meteorites probably does not contribute to the average to an important extent, even the very reliable lead determination of Patterson, Brown, and Tilton (1953) does not increase our knowledge of the natural lead abundance. We shall use other arguments in order to secure a value for lead.

Patterson et al (1955) have determined the isotopic composition of lead from Canyon Diablo and Henbury iron meteorites and found their lead compositions to be nearly identical, and to contain the lowest amounts of radiogenic leads, Pb^{206}, Pb^{207} and Pb^{208}, relative to Pb^{204} of any natural leads so far studied. They believe that this is primeval lead of 4.5×10^9 years ago. Patterson (1955) has isolated lead from terrestrial basalts and chondritic meteorites and has determined the isotopic composition. Subtracting the amounts of Pb^{206}, Pb^{207}, and Pb^{208} relative to Pb^{204}, taken as unity of the iron meteorites from the amounts of these isotopes in the basalts and chondrites, they secure the relative amounts of these isotopes which are the product of radioactive decomposition of U^{238}, U^{235} and Th^{232} respectively. Without knowing the amounts of uranium and thorium the age of the leads can be calculated from the Pb^{206} to Pb^{207} ratio.

The age so calculated is 4.5×10^9 years both for the basalts
and chondrites. Wasserburg and Hayden (1955) secure essentially
the same age for chondrites from the K^{40}-A^{40} ratio. The identity
of the ages for the basalts and chondrites has been puzzling,
since they have had very different histories. This identity must
mean that uranium and lead accompany each other rather closely in
differentiation processes and, specifically, since uranium and
thorium have been concentrated markedly in terrestrial surface
rocks, lead must be so concentrated as well. Also, if uranium
and thorium have been concentrated in the meteorites by a factor
of 3.2 as Urey has argued, then lead must have been concentrated
by the same factor also. This simple circumstance would explain
the identity of the ages of terrestrial and meteoritic material
as determined by the lead methods. Dr. H. D. Holland independently
came to this conclusion and brought it to our attention.
The age is the time since the Canyon Diablo and Henbury meteorites
became separated from uranium and thorium and no other age is
involved. Particularly, the data determines nothing about the
time of formation of the earth's core, for in order to determine
this a sample of the core lead would be needed.

Sandell and Goldrich (1943) have determined the amounts of
lead in basic and acidic rocks and found average values of 9
and 19 ppm, respectively. Sahama (1945) found from 9 to 27 ppm
in granites. These are modern analyses and we believe they are
reliable. Patterson's values for the chondrites of 0.4 to 0.9

ppm are not presented with great confidence by him, but they appear to be approximately correct. The ratio of these values is perhaps 25 as an average. The ratio of potassium in the earth's crust, i.e. 2.6%, to its amount in the chondrites, 0.09%, is about 29. Also, uranium and thorium are concentrated in the earth's surface relative to the chondrites by the same factor roughly. The evidence indicates that lead is concentrated along with potassium, uranium and thorium in melting processes, and is apparently lithophile in character and not chalcophile so far as these processes are concerned. Rankama and Sahama (1950, P. 97 ff) discuss this character of lead.

In view of the above argument we calculate the lead abundances as follows. We take Urey's (1955) estimate for the uranium abundance in solar matter at the present time as 0.0332 ppm of the nonvolatile fraction, which is 1/3.19 of Chackett's et al (1950) value for uranium in the Beddegelert meteorite. It is nearly all U^{238}. Since the half life of U^{238} is 4.51 x 10^9 years, the amount of U^{238} decomposed in 4.5 x 10^9 years is 0.0332 ppm. This produced 0.0287 ppm of Pb^{206}. Patterson's estimate of the amounts of radiogenic leads produced in 4.5 x 10^9 years relative to Pb^{204} are given in the first line of Table 6. This is the average of the Forest City and Modoc meteorites. The 9.87 of Pb^{206} is relative to Pb^{204} is equivalent to the 0.0287 ppm given above. In the second line are Patterson's values of Canyon Diablo lead which is presumed to be primeval lead. By simple proportion we calculate

the atomic abundances of the other lead isotopes assuming that the
Canyon Diablo lead has the primitive composition and list these
in the third and fourth lines of the table. The values secured
are more approximate than indicated.

TABLE 6

	Pb^{204}	Bb^{206}	Pb^{207}	Pb^{208}
Average radiogenic lead	(1)	9.87	5.50	9.14
Canyon Diablo lead	1	9.50	10.36	29.49
Solar abundances of primeval lead, ppm	0.00288	0.0276	0.0303	0.0867
Atomic abundances of primeval lead	0.00214	0.0203	0.0222	0.0631

If Patterson's lead isotope ratios for Nuovo Laredo had been
used instead of those of Modoc and Forest City our lead abundances
would be lower and there is no certainty that chondritic
meteorites will not be found with lead isotopic ratios giving
higher abundances of primeval lead. Urey's estimate for uranium
depends on the heat balance of the earth, moon and Mars and
cannot change much due to future uranium determinations unless
his arguments are shown to be incorrect.

The Noddacks give 0.144 for the atomic abundance of
bismuth. Its geochemical distribution has not been carefully
studied. We adopt the somewhat smaller value of 0.08, which with
Pb^{207} and our choice of thallium gives a smooth curve connecting
the odd mass nuclides. Mostly the older analytical values for
rare elements are too high and hence this lower value may be
justified.

We adopt values for U^{235}, U^{238} and Th^{232} by calculating the amounts of these nuclides at 4.5×10^9 years ago from Urey's (1955) estimate of their present concentrations. The values so secured are 0.0121, 0.0423 and 0.0858, respectively. These are minimum values for the abundances when the elements were first synthesized, since this time was probably more than 4.5×10^9 years ago.

If we do not decrease the observed uranium and thorium abundances by a factor of 3.2 as required by Urey's argument, the Pb, Tl, Bi and Hg abundances must all be raised by this factor. We believe that the observed data on Bi and Hg are not good enough to give any weight to any possible decision in regard to this question. Since thallium is concentrated at the earth's surface, its abundance in the chondritic meteorites gives no evidence in regard to this question.

The Age of the Elements

As is well known the elements cannot be older than the time required for the production of all Pb^{207} from U^{235}. The ratio of lead to uranium in a sample of material in which this ratio has not changed since the formation of the elements gives the necessary data for a valid calculation. By using the Patterson et al. (1955) data on Forest City, Modoc, Canyon Diablo and Henbury meteorites for the lead abundances, we have the necessary data. The time calculated from this data to produce the Pb^{207} of the iron meteorites is 1.07×10^9 years and this gives 5.57×10^9 as the

maximum age of the elements.

If some Pb^{207} was produced by the processes which produced the elements, the age is less than this. If the age is 5.2×10^9 years, that is one half life of U^{235} earlier than the age of the meteorites, the abundances of the lead isotopes become 0.0101, 0.0153, and 0.0600 for Pb ^{207}, Pb^{206}, and Pb^{208}, respectively. The logarithms of these are 0.004-2, 0.177-2 and 0.778-2. Taking the mean of the logarithms for Pb^{206} and Pb^{208} and subtracting that for Pb^{207} gives 0.47 as the difference between the odd and even mass curves. This difference as we have drawn the curves is 0.20 and hence it would be necessary to lower Bi^{209} and the thallium points by about 0.27 in order to secure a smooth curve. The data of these elements is hardly sufficiently certain to exclude this possibility. However, the difference of 0.47 between the two curves is larger than the separation of our even and odd mass curves at any point above mass 120. Since the odd and even mass curves become closer together at high mass numbers, it seems likely that the elements were synthesized more than 5.2×10^9 years ago. This estimate does not depend on the absolute values of the abundances of lead and uranium, but only on their ratios which are determined from the lead isotope ratios. If the Patterson data for Nuovo Laredo meteorite were used the calculated age of the elements would be less. On the other hand, from the absence of conspicuous amounts of Xe^{129} and the known half life of I^{129} in meteorites, Suess and Brown (1951) conclude that

the elements were formed at least 3×10^9 years before the meteorites. We conclude that the elements of our solar system originated $5.0 \pm 0.2 \times 10^9$ years ago.

Problems of interpreting the nuclear abundance distribution

Theories of the origin of the elements

The nuclear abundance distribution as derived from the discussion above, supplies a basis for comparison of empirical data with the various theories of the origin of the nuclear species. No such comparison will be given here, and the reader is referred to three excellent review articles by Alpher and Herman (1950/1953) on the theory of the origin and relative abundance distribution of the elements dealing with this subject, in which some 180 papers are critically discussed. It is shown there that none of the existing theories can account for all of the empirical facts, even in a crude way. Hence, it seems hopeless to attempt to explain the finer details presented here by any of these theories in their present form.

It seems possible, however, that a modification of one theory or the other, in particular through assumptions regarding secondary and subsequent reactions, may lead to a satisfactory agreement. We hope that the following discussion will be helpful for the study of the nature of such reactions.

The nuclear abundance values obtained in the way described above differ in some mass regions quite noticeably from previous estimates (Suess 1949). A comparison, however, of figure I with the corresponding figure published previously shows that the main features of the abundance distribution have been retained. These features are essentially independent of the choice of the element abundance and constitute well-defined problems, which will be discussed in the following. This discussion will not be a complete one, and it will be left to the reader to detect many more features in figure 1 which might serve as evidence for or against the prevailing of a certain mechanism of element formation.

An impressive difference exists between the character of the region of the lighter (A < 90) and heavier (A > 90) nuclei. In the lower A region the line

for the sum of isobaric abundances for the even A species has a zigzag-shaped irregular appearance and the abundance values depend strongly on the neutron excess number. At mass numbers where two stable isobars exist, the one with the smaller neutron excess has the higher nuclear abundance in the light mass region.

Going to higher mass numbers the curves for the sum of the isobaric abundances get more and more regular and the isobars with the higher neutron excess become the more abundant ones.

One may try to understand this difference by considering two types of nuclear reactions:

(1) A reaction leading to the formation of nuclear species on the neutron-rich side of the energy valley. This reaction predominated at higher mass numbers and yielded a "smoothed out" abundance distribution.

(2) A reaction leading to nuclei on the neutron-deficient side of the energy valley. This reaction predominated and led to the "fine structure" in the abundance distribution of the lower mass region.

It is feasible to assume that reaction (1) was a "neutron capture, build up", that is $(\eta \gamma)$ followed by β-decay, as postulated by the neutron capture theory. No theory has yet been proposed, that could account for a reaction of the type (2) but the empirical evidence indicates that a reaction of this kind is required, as will be shown later.

A steady change of the abundances with mass number has to be expected from any theory in which very high temperatures (kT $\gg$ 1 Mev) are postulated for the transmutation of nuclei of one given mass number into those of another mass number. In the case of a very high temperature, not only the ground state but also many excited states will be involved in the reactions so that the effect of an abrupt change of a property of the ground states (for instance at a magic number) will be

"smeared out" as a result of the participating excited states. The same will be true if the reactions leading to changes in mass number take place in the regions of the beta unstable nuclei on the slopes of the energy valley, as is assumed in the neutron capture theory of the formation of the elements (Alpher and Herman, 1950, 1951, 1953).

The sum rule of isobar abundances

In the A 100 region the isobar with the highest neutron excess, is almost always the most abundant one. The abundance of the isobar with the lower neutron excess, the so called "shielded" isobar is only of a comparable magnitude, if this isobar has a considerably greater binding energy than the unshielded one. In most of these cases the value for the sum of the abundance of the two isobars agrees with an interpolated value between the values of the unshielded isobar existing at the mass numbers $A - 2$ and $A + 2$.

The distribution gives the impression, as if, in this mass range, the shielded nuclei have formed from their shielding isobars after the mass distribution was established. It can be shown, however, that such transmutation can not have occurred by two subsequent β^- decays from a thermally excited level. One can show this by considering the isobaric pair $In^{115}-Sn^{115}$ for which the following information is available: Ratio of abundance $In^{115}/Sn^{115} = 10.5$. Excited level in In^{115} : 0.335 Mev $= E^*$. Half life on this state: 4.5 hours. Partial half life for the beta decay of this state 70 hours. Spins of In^{115} in the excited and normal states are $9/2$ and $\frac{1}{2}$. The number of In^{115} nuclei in the excited state, N^*, at a temperature T will be $N^* U = g/g^* N e^{-E^*/kT}$. From the above experimental data one finds that natural indium cannot have been at a temperature T for more than

$$50 \times e^{0.335/kT} \text{hours},$$

with kT expressed in Mev.

This means that the In^{115} in nature cannot have been subject to a higher temperature then about 0.3 Mev $= kT$ for more then a few days, or else a larger proportion of the nuclei of mass 115 would be present in the form of Sn^{115}. By comparing this result with available data on excited states one finds that it is not possible to account for the abundance of the shielded nuclear species by assuming beta decay from thermally excited levels higher than the ground state of the intermediate odd-odd isobar. According to the neutron capture theory, shielded nuclei will form in the later stage of the neutron build up when the rate of the neutron capture processes becomes smaller than the average rate of beta decay, so that the build up takes place in the stable nuclei region. They will then form from sufficiently long lived or stable odd A nuclei by $(\eta \gamma)$ and subsequent beta decay of the odd-odd nuclei. These abundances, however, cannot readily be expected to follow the pattern required by the sum rules.

Light isotopes in the higher mass region

The neutron capture theory does not account for the existence of the type of shielded nuclei that have a lower binding energy than their shielding isobars and are on the β^+ side of the energy valley. The abundance of these species is in general about ten times smaller than that of the energetically favoured type of shielded nuclides. Their abundance is not correlated with their relative binding energies. One can immediately see this from the fact that in a number of elements the abundance of the lightest isotope is higher than that of the second lightest. This is the case for Mo, Ru, Cd, Sn, Xe, and Ba. In the case of Ce and Dy the lightest isotope is only slightly less abundant than the second lightest. The lightest isotope, of course, always has a smaller

binding energy than the second lightest.

The most remarkable feature in the abundance distribution of these rarer nuclides is, that, for wide ranges of mass numbers, their abundance values as a function of A seem to follow a law of "smoothness" of their own. In particular the abundances of Sn^{112}, Sn^{114}, Te^{120}, Xe^{124}, Xe^{126}, Ba^{130}, etc., show this behavior in an impressive way. The conclusion seems inevitable that in these mass ranges a fraction of nuclear matter must have formed on the β^+ side of the energy valley in the region of the unstable neutron-deficient nuclear species, in a way that led to a "smoothed out" distribution of the stable species. Possibly, secondary spallation processes may have led to the formation of these nuclides in the required proportions.

Magic number effects in the higher mass region

Elsasser (1933, 1934) was the first physicist who noticed that the abundance of nuclear species containing certain numbers of neutrons or protons is exceptionally large. These numbers, the so called "magic numbers" are:

$$2, 8, 20, 28, 50, 82, 126 - - - - -$$

They belong to two different arithmetical series:

$$(1)\ 2, 8, 20, 40, 70, 112 - - - - -$$
$$(2)\ 2, 6, 14, 28, 50, 82, 126 - - - - -$$

The first series is significant at lower mass numbers, while the second series predominates at mass numbers greater than 40. Magic number effects are now well understood in terms of a shell structure of the nucleus. (Mayer and Jensen, 1955)

A magic number is signified by the sudden drop in the binding energy of the next nucleon. The binding energy of the next nucleon, however, is also a function

of the neutron excess number. In the higher mass number region there is no obvious correlation of abundances with neutron excess, and therefore no simple correlation of the abundance values with the drop of the binding energy of the last particle at a magic number can be expected.

Hughes and Sherman (1950) have shown that the neutron capture cross section of nuclei containing a magic number of neutrons is exceptionally small. This experimental result has been taken as strong evidence speaking in favor of the neutron capture theory of the origin of the elements, because in this theory the high cosmic abundances of the magic neutron nuclei follow from the low neutron capture cross sections in a very satisfactory way. A neutron build-up process taking place in the region of the stable nuclei leads, according to this theory, to a sharp rise at a neutron shell edge and a gradual smooth leveling off of the nuclear abundances when going to higher mass numbers. If the neutron build-up takes place in the region of the neutron-rich β^- unstable nuclei, the maximum to be expected will be flattened out and be displaced toward lower mass numbers. It is possible that the broad maxima in the abundance curves around mass number 130 and 194 are magic number effects of the shell closures at N equal to 82 and 126 from a neutron build-up in the N - Z equal to 34 and 54 regions. With decreasing neutron density the center of the build-up reaction will shift to lower neutron excess numbers, so that the sharp maxima at A equal to 138 and 208 may have piled up subsequent to the formation of the bulk of nuclei in this mass range.

It has not yet been possible to describe the kinetics of such reactions in a more rigorous quantitative way and to find out what assumptions are necessary to explain the sharp minima around A equal to 135 and 206 immediately proceeding the N equal to 82 and 126 shell closures.

In the corresponding region proceeding the shell closure at N equal to 50 no conclusive indications of a similar pattern are found.

The data, however, indicate a small maximum for nuclei containing 50 neutrons and a minimum preceeding that region. Our adopted values show this behaviour, although a more regular pattern may also be possible.

A break that cannot be smoothed out by any means, occurs in the abundance curves at A equal to 120 and 121. The break, associated with a change in the character of isotopic abundance distribution occurs at a point where the number of neutrons in the nuclei reaches 70. The break at this number is unexpected, but the conclusion seems inevitable that the high spin of the neutrons in the 6 $h_{11/2}$ shell must in some way be connected with this irregularity. At the corresponding place for 112 neutrons a slight change in the character of the abundance distribution might be discerned, but a break in the abundance curves, which might possibly exist at A equal to 186 and 187, can be smoothed out without difficulty. Probably the filling of the 7 i $_{13/2}$ neutron shell begins before the number of neutrons reaches 112.

Other irregularities in the higher mass range are less impressive and not as firmly established. Uncertainties in the relative abundances of the rare earth elements make it impossible to recognize in a quantitative way an irregularity which apparently exists in the A equal to 170 region, and to see what pattern may be correlated with the fact that the odd A hafnium isotopes do not show abun-

dance values fitting into the trend of the odd A abundance curve. It may be noted that the sum rule is not obeyed at mass number 176. It might be tempting to correlate the long half life of the naturally occurring Lu^{176} with this irregularity, but no plausible reason for such a connection can be suggested.

Contrary to current opinion no indications are found in the abundance distribution for effects, that can in an unmistakeable way be attributed to proton shell closures.

The $70 < A < 90$ mass region

From what was said in the preceeding paragraph one is led to the conclusion that in the $A > 90$ region most of the nuclear matter must have formed on the neutron-rich side of the energy valley and only a small fraction of about 1% on the neutron-deficient β^+ side. In the following section it will be shown that obviously the opposite is true for the region of the lighter elements with mass numbers $A < 70$ where the bulk of nuclear matter must have formed in the form of neutron-deficient β^+ active nuclides. From this it seems reasonable to suspect that an intermediate range of mass numbers will exist, where the nuclei have formed directly in the region of the stable nuclear species close to the bottom of the energy valley. If, for instance one assumes that the final abundance distribution was determined by the two opposite reactions discussed above, in such a way that in a later stage of the development the one reaction ("neutron build up") predominated in the higher mass region and the reverse reaction in the lower mass region, then the abundance in an intermediate mass range should reflect equilibrium conditions to a greater degree than those of any other mass range. This, indeed, seems to be indicated by the empirical abundance data. The odd A abundances in the region from A equal to 57 to 87 fit into a smooth curve. The even A abundances, however, show a strangely irregular behavior

and the sum rule of isobaric abundances is certainly not obeyed. Another kind
of regularity, however, becomes apparent at once, if one connects the values for
nuclei with the same neutron excess in figure 1. In this case smooth lines are
obtained. In regions between shell closure the binding energy will be a smooth
function of the mass number for species with the same neutron excess and therefore
the smoothness of this pattern can be taken as an indication of an intrinsic
relationship of the binding energy and cosmic abundance of the nuclei in this
mass range. An estimate of the apparent temperature governing such relationship
gives values for kT of the order of 1 Mev.

The fact that the odd A abundance curve does not clearly show any correlation
of abundances with neutron excess is not surprising because the contribution
of the β unstable isobars to the final abundances of the stable species will
be much larger for odd mass numbers than for even. Besides this, minor irregularities
in the odd A abundance curve may have been "smoothed out" when estimating the
abundance values for the elements.

The iron peak and the lower mass region

The new value for the Fe to Si ratio, which is about one third of that
previously assumed, still leaves the abundance of Fe^{56} larger than the sum of
abundance of all other nuclear species with mass numbers greater than 40. No
property of the Fe^{56} nucleus is known that could possibly explain its predominance
in nature. Fe^{56}, however, is an isobar of the "double magic" unstable Ni^{56},
which contains 28 protons and 28 neutrons. The expectation of a correlation of
abundances with nuclear properties leads inevitably to the conclusion that Ni^{56}
was the primeval nucleus from which Fe^{56} has formed[1] and, hence, that the nuclei
of this mass region had formed on the neutron deficient side of the energy valley.

[1] This idea was first suggested by O. Hexel in 1946 to one of us, quoted as a
private communication in Suess (1948)

The half life of Ni^{56}, which decays by K-capture into Co^{56} (80d) has recently been found to be 6.5 days (Sheline and Stoughton (1952) and Worthington (1952)). Hence the process leading to the excessive abundance of mass 56 cannot have taken longer than a few days.

Together with Fe, the elements Cr, Ti, and Ca show an excessively high abundance of their isotopes with the neutron excess of I equal to 4. This may be taken as an indication, that in this whole mass range nuclei with zero neutron excess, i. e. (N = Z), had formed first and thereafter decayed into their I equal to 4 isobars. In general nuclei with N = Z seem to show higher binding energies than would correspond to a perfectly parabolic energy valley and this makes the high original abundance appear plausible.[2] That the abundance distribution was actually established within less than a day is indicated by the half life of Fe^{52} of 7.8 hours, which decays into Cr^{52}.

Undoubtedly, magic number effects exist at N = 8, 14 and 20, although the uncertainties in the abundance values and the rapid change of abundances with mass number in this region makes the character of these effects somewhat obscure. The enhanced abundance of the nuclei Mg^{30} and A^{38} with I equal to 2 indicates effects from the shell closure at N equal to 14 and 20, respectively.

Harkin's rule and the abundances of odd A nuclei

According to Mattauch's law, there is only one isobar stable at each odd mass number. There exists, however, for each odd mass number greater than 32, also at least one unstable isobar with a half life of more than a day, that is a half life long compared to the time in which the mass distribution was established. Obviously, at an odd mass number unstable isobars must have on the average contributed relatively more to the abundance of the stable species than

[2] See Blatt and Weisskopf, Theor. Nuc. Phys. P. 241 ff. Theoretically the "symetry" energy leads to two parabulae crossing at N = Z.

at an even mass number.   From this, one can understand the fact that the odd A abundance curve is much more smoothed out than that for the even A species. Otherwise the difference in the abundances of the even and odd nuclear species may be only a qualitative nature.

As expressed by Harkin's rule, there is always one even A isobar at each mass number with an abundance greater than the geometric mean of the respective odd A neighbors.   The difference in the even and odd abundances, i. e., the even odd effect of the abundances, decreases with increasing mass numbers and disappears for several mass numbers around A = 170 and 190.

The even odd effect of the abundances, as expressed by Harkin's rule can not be a simple consequence of the difference in the binding energies between the even and odd A nuclei, as was assumed for many years.   The effect does not follow from the neutron capture theory of the formation of the elements, but a number of refinements and additional assumptions are possible which could explain the effect within the frame of this theory in a satisfactory way.   For example, the rate of the processes in a beta decay series is on the average somewhat greater for odd than for even mass numbers so that odd A species formed on the neutron-rich slope of the energy valley will decay into species with a lower neutron excess somewhat faster than even species.   The neutron capture cross section will depend on the neutron excess and will at a given mass number be larger if the neutron excess is smaller so that odd A species will be transformed by neutron capture into even species of the next higher mass number at a somewhat greater rate than even species into odd ones.

The discussion of the general picture of the abundance distribution could be continued at much greater length.   However, it is hope that the points mentioned here will eventually lead to improvements of the theoretical basis and of the cosmalogic model which in turn will facilitate an interpretation of empirical features in the distribution of cosmic nuclear abundance.

TABLE II

Atomic Abundances of the Elements.[*] Silicon $= 1 \times 10^6$

		Goldschmidt	Brown	Urey (revised)	This paper
1	H		3.5×10^{10}	3.5×10^{10}	3.62×10^{10}
2	He		3.5×10^{9}	3.5×10^{9}	2.8×10^{9}
3	Li	100		100	100
4	Be	20		16	20
5	B	24		20	24
6	C		8.0×10^{6}	8.0×10^{6}	6.75×10^{6}
7	N		1.6×10^{7}	1.6×10^{7}	1.41×10^{7}
8	O		2.2×10^{7}	2.2×10^{7}	2.5×10^{7}
9	F	1500	9000	300	1600
10	Ne		9.0×10^{5}-- 2.4×10^{7}		1.0×10^{7}
11	Na	4.42×10^{4}	4.62×10^{4}	5.10×10^{4}	4.00×10^{4}
12	Mg	8.7×10^{5}	8.87×10^{5}	9.3×10^{5}	1.41×10^{6}
13	Al	8.8×10^{4}	8.82×10^{4}	8.2×10^{4}	6.31×10^{4}
14	Si	1.0×10^{6}	1.0×10^{6}	1.0×10^{6}	1.00×10^{6}
15	P	5.8×10^{3}	1.3×10^{4}	7.5×10^{3}	7.06×10^{3}
16	S	1.14×10^{5}	3.5×10^{5}	9.8×10^{4}	2.50×10^{5}
17	Cl	4000--6000	17,000	2100	2800
18	A		1.3×10^{4}-- 2.2×10^{5}		1.12×10^{5}
19	K	6900	6930	3400	854
20	Ca	5.71×10^{4}	6.7×10^{4}	5.6×10^{4}	5.36×10^{4}

TABLE II
continued 2

21	Sc	15	18	17	48
22	Ti	4700	2600	1800	1020
23	V	130	250	150	380
24	Cr	1.13×10^4	9.5×10^3	8.2×10^3	1.82×10^4
25	Mn	6600	7700	6800	7900
26	Fe	8.9×10^5	1.83×10^6	7.091×10^5	6.084×10^5
27	Co	3500	9900	2300	1730
28	Ni	4.6×10^4	1.34×10^5	3.6×10^4	2.74×10^4
29	Cu	460	460	420	228
30	Zn	360	160	180	486
31	Ga	19	65	10	14.5
32	Ge	190	250	110	50.5
33	As	18	480	4.0	3.2
34	Se	15	25	13	37.7
35	Br	43	42	49 ?	5.76
36	Kr				25.0
37	Rb	6.8	7.1	6.7	2.18
38	Sr	40	41	20	12.1
39	Y	9.7	10	9.7	8.9
40	Zr	140	150	55	23.9
41	Nb	6.9	0.9	0.7	1.00
42	Mo	9.5	19	2.4	2.42
44	Ru	3.6	9.3	2.1	1.49

TABLE II
continued 3

45	Rh	1.3	3.5	0.71	0.214
46	Pd	1.8	3.2	1.3	0.850
47	Ag	3.2	2.7	0.35	0.346
48	Cd	2.6	2.6	2.2	1.36
49	In	0.23	1.0	0.27	0.193
50	Sn	29	62	18	2.65
51	Sb	0.72	1.7	0.79	0.493
52	Te	0.2		0.16	3.26
53	I	1.4	1.8	1.5	0.40
54	Xe				2.0
55	Cs	0.1	0.1	1.3	0.228
56	Ba	8.3	3.9	8.8	1.83
57	La	2.1	2.1	2.1	1.00
58	Ce	5.2	2.3	2.3	1.13
59	Pr	0.96	0.96	0.96	0.20
60	Nd	3.3	3.3	3.3	0.72
62	Sm	1.15	1.2	1.1	0.332
63	Eu	0.28	0.28	0.28	0.0935
64	Gd	1.65	1.7	1.6	0.342
65	Tb	0.52	0.52	0.52	0.0478
66	Dy	2.0	2.0	2.0	0.278
67	Ho	0.57	0.57	0.57	0.059
68	Er	1.6	1.6	1.6	0.158
69	Tm	0.29	0.29	0.29	0.0159

TABLE II
continued 4

70	Yb	1.5	1.5	1.5	0.110
71	Lu	0.48	0.48	0.48	0.0251
72	Hf	1.5	0.7	0.55	0.219
73	Ta	0.40	0.31	0.26	0.0363
74	W	14.5	17.0	13.0 ?	0.352
75	Re	0.12	0.41	0.07	0.135
76	Os	1.7	3.5	0.97	1.00
77	Ir	0.58	1.4	0.31	0.821
78	Pt	2.9	8.7	1.5	1.625
79	Au	0.27	0.82	0.21	0.116
80	Hg	0.33		<0.006	0.0318
81	Tl	0.17		0.11	0.0112
82	Pb	9.1	<2.0	0.52	0.108
83	Bi	0.31	0.21	0.14	0.0794
90	Th	0.59		0.22	0.0856
92	U	0.23	0.02	0.067	0.0542

* Goldschmidt's values as given in the table have been modified
slightly by Suess and by Urey in accordance with data which is
now five years old. Urey's values are empirical data for the
chondritic meteorites modified in accordance with new analytical
data discussed in the text but without adjustment by factors
of about 3 or 4 for fractionation as applied to the data in the
last column. The lead, thorium, and uranium values given
under Urey (revised) are for the present time while those in
the last column are for a time 4.5×10^9 years ago.

TABLE III

	Element	A	N	I	Log H	H
1	H				10.56	3.62×10^{10}
		1	0	-1	10.56	3.62×10^{10}
		2	1	0	6.72	5.2×10^{6}
2	He				9.45	2.8×10^{9}
		3	1	-1	?	?
		4	2	0	9.45	2.8×10^{9}
3	Li				2.00	100
		6	3	0	0.87	7.4
		7	4	1	1.97	92.6
4	Be	9	5	1	1.30	20
5	B				1.38	24
		10	5	0	0.65	4.5
		11	6	1	1.29	19.5
6	C				6.83	6.75×10^{6}
		12	6	0	6.82	6.67×10^{6}
		13	7	1	4.87	7.4×10^{4}
7	N				7.15	1.41×10^{7}
		14	7	0	7.15	1.41×10^{7}
		15	8	1	4.71	5.1×10^{4}
8	O				7.40	2.5×10^{7}
		16	8	0	7.40	2.5×10^{7}
		17	9	1	3.97	9.3×10^{3}
		18	10	2	4.71	5.1×10^{4}
9	F	19	10	1	3.20	1600
10	Ne				7.00	1.0×10^{7}
		20	10	0	6.95	9.0×10^{6}
		21	11	1	4.48	3.0×10^{4}
		22	12	2	5.99	9.7×10^{5}

TABLE III
Continued 2

11	Na	23	12	1	4.60	4.0×10^4
12	Mg				6.15	1.41×10^6
		24	12	0	6.04	1.11×10^6
		25	13	1	5.15	1.41×10^5
		26	14	$\frac{1}{2}$	5.19	1.55×10^5
13	Al	27	14	1	4.80	6.3×10^4
14	S1				6.00	1.0×10^6
		28	14	0	5.96	9.2×10^5
		29	15	1	4.67	4.7×10^4
		30	16	$\frac{1}{2}$	4.49	3.1×10^4
15	P	31	16	1	3.85	7060
16	S				5.40	2.5×10^5
		32	16	0	5.38	2.38×10^5
		33	17	1	3.27	1860
		34	18	$\frac{1}{2}$	4.02	10600
		36	20	4	1.60	40
17	Cl				3.46	2300
		35	18	1	3.32	2100
		37	20	3	2.84	700
18	A				5.05	1.12×10^5
		36	18	0	4.97	9.4×10^4
		38	20	2	4.25	1.8×10^4
		40	22	4	?	?
19	K				2.93	854
		39	20	1	2.90	795
		40	21	$\frac{1}{2}$	0.01-1	0.102
		41	22	3	1.77	59
20	Ca				4.73	53600
		40	20	0	4.72	51900
		42	22	2	2.54	343
		43	23	3	1.84	69.7
		44	24	4	3.06	1140
		46	26	6	0.23	1.7
		48	28	8	1.98	96

TABLE III
Continued 3

21	Sc	45	24	3	1.68	48
22	Ti				3.01	1020
		46	24	2	1.91	81
		47	25	3	1.90	79
		48	26	4	2.87	749
		49	27	5	1.75	56.2
		50	28	6	1.74	54.5
23	V				2.58	380
		50	27	4	0.00	1
		51	28	5	2.58	379
24	Cr				4.26	18170
		50	26	2	2.90	800
		52	28	4	4.18	15200
		53	29	5	3.24	1730
		54	30	6	2.68	474
25	Mn	55	30	5	3.90	7900
26	Fe				5.78	6.084×10^5
		54	28	2	4.55	3.59×10^4
		56	30	4	5.75	5.57×10^5
		57	31	5	4.14	1.34×10^4
		58	32	6	3.30	2000
27	Co	59	32	5	3.24	1730
28	Ni				4.44	27400
		58	30	2	4.27	18570
		60	32	4	3.87	7170
		61	33	5	2.53	340
		62	34	6	3.00	1000
		64	36	8	2.50	318
29	Cu				2.36	228
		63	34	5	2.20	157.5
		65	36	7	1.85	70.5

TABLE III
Continued 4

30	Zn				2.69	486
		64	34	4	2.38	238
		66	36	6	2.13	134
		67	37	7	1.30	20.0
		68	38	8	1.96	90.9
		70	40	10	0.53	3.4

31	Ga				1.16	14.5
		69	38	7	0.94	8.73
		71	40	9	0.76	5.77

32	Ge				1.70	50.5
		70	38	6	1.02	10.4
		72	40	8	1.14	13.8
		73	41	9	0.58	3.84
		74	42	10	1.27	18.65
		76	44	12	0.59	3.87

33	As	75	42	9	0.50	3.2

34	Se				1.57	37.7
		74	40	6	0.56-1	0.36
		76	42	8	0.54	3.44
		77	43	9	0.45	2.83
		78	44	10	0.95	8.90
		80	46	12	1.27	18.83
		82	48	14	0.52	3.33

35	Br				0.76	5.76
		79	44	9	0.46	2.91
		81	46	11	0.45	2.85

36	Kr				1.40	25.0
		78	42	6	0.93-2	0.085
		80	44	8	0.75-1	0.557
		82	46	10	0.46	2.88
		83	47	11	0.46	2.37
		84	48	12	0.15	14.26
		86	50	14	0.64	4.36

TABLE III
Continued 5

37	Rb				0.34	2.18
		85	48	11	0.20	1.59
		87	50	13	0.77-1	0.59
38	Sr				1.08	12.1
		84	46	8	0.83-2	0.067
		86	48	10	0.08	1.193
		87	49	11	0.93-1	0.849
		88	50	12	1.00	9.99
39	Y	89	50	11.	0.95	8.9
40	Zr				1.38	23.9
		90	50	10	1.09	12.3
		91	51	11	0.43	2.68
		92	52	12	0.61	4.09
		94	54	14	0.62	4.16
		96	56	16	0.83-1	0.67
41	Nb	93	52	11	0.00	1.00
42	Mo				0.38	2.42
		92	50	8	0.56-1	0.364
		94	52	10	0.35-1	0.226
		95	53	11	0.58-1	0.382
		96	54	12	0.60-1	0.401
		97	55	13	0.37-1	0.232
		98	56	14	0.76-1	0.581
		100	58	16	0.37-1	0.234
44	Ru				0.17	1.49
		96	52	8	0.93-2	0.0846
		98	54	10	0.52-2	0.0331
		99	55	11	0.28-1	0.191
		100	56	12	0.28-1	0.189
		101	57	13	0.40-1	0.253
		102	58	14	0.68-1	0.467
		104	60	16	0.43-1	0.272
45	Rh	103	58	15	0.33-1	0.214

TABLE III
Continued 6

46	Pd				0.93-1	0.850
		102	56	10	0.83-3	0.0068
		104	58	12	0.90-2	0.079
		105	59	13	0.28-1	0.192
		106	60	14	0.35-1	0.230
		108	62	16	0.36-1	0.227
		110	64	18	0.06-1	0.115

47	Ag				0.54-1	0.346
		107	60	13	0.25-1	0.178
		109	62	15	0.23-1	0.168

48	Cd				0.13	1.36
		106	58	10	0.22-2	0.0166
		108	60	12	0.08-2	0.0121
		110	62	14	0.23-1	0.169
		111	63	15	0.24-1	0.175
		112	64	16	0.51-1	0.324
		113	65	17	0.23-1	0.168
		114	66	18	0.59-1	0.392
		116	68	20	0.02-1	0.104

49	In				0.28-1	0.193
		113	64	15	0.90-3	0.0080
		115	66	17	0.27-1	0.185

50	Sn				0.42	2.65
		112	62	12	0.43-2	0.0268
		114	64	14	0.26-2	0.0180
		115	65	15	0.97-3	0.0093
		116	66	16	0.58-1	0.378
		117	67	17	0.31-1	0.203
		118	68	18	0.80-1	0.632
		119	69	19	0.36-1	0.230
		120	70	20	0.94-1	0.867
		122	72	22	0.10-1	0.126
		124	74	24	0.20-1	0.159

51	Sb				0.69-1	0.493
		121	70	19	0.45-1	0.282
		123	72	21	0.32-1	0.211

TABLE III
Continued 7

52	Te				0.51	3.26
		120	68	16	0.46-3	0.0029
		122	70	18	0.91-2	0.0805
		123	71	19	0.46-2	0.0290
		124	72	20	0.19-1	0.155
		125	73	21	0.36-1	0.229
		126	74	22	0.79-1	0.610
		128	76	24	0.02	1.035
		130	78	26	0.05	1.117
53	I	127	74	21	0.60-1	0.40
54	Xe				0.30	2.00
		124	70	16	0.28-3	0.00190
		126	72	18	0.25-3	0.00176
		128	74	20	0.58-2	0.0382
		129	75	21	0.72-1	0.525
		130	76	22	0.91-2	0.0811
		131	77	23	0.63-1	0.425
		132	78	24	0.75-1	0.539
		134	80	26	0.32-1	0.210
		136	82	28	0.25-1	0.179
55	Cs	133	78	23	0.36-1	0.228
56	Ba				0.26	1.83
		130	74	18	0.27-3	0.00185
		132	76	20	0.25-3	0.00178
		134	78	22	0.65-2	0.0443
		135	79	23	0.08-1	0.1206
		136	80	24	0.15-1	0.1429
		137	81	25	0.32-1	0.2072
		138	82	26	0.12	1.311
57	La				0.00	1.00
		138	81	24	0.95-4	0.0009
		139	82	25	0.00	1.00
58	Ce				0.05	1.13
		136	78	20	0.34-3	0.00220
		138	80	22	0.45-3	0.00283
		140	82	24	0.00	1.00
		142	84	26	0.10-1	0.125

TABLE III
Continued 8

59	Pr	141	82	23	0.30-1	0.20
60	Nd				0.86-1	0.72
		142	82	22	0.29-1	0.195
		443	83	23	0.94-2	0.0878
		144	84	24	0.24-1	0.172
		145	85	25	0.78-2	0.0598
		146	86	26	0.09-1	0.124
		148	88	28	0.61-2	0.0412
		150	90	30	0.61-2	0.0403
62	Sm				0.52-1	0.332
		144	82	20	0.02-2	0.0104
		147	85	23	0.70-2	0.0500
		148	86	24	0.57-2	0.0374
		149	87	25	0.66-2	0.0460
		150	88	26	0.39-2	0.0246
		152	90	28	0.95-2	0.0884
		154	92	30	0.87-2	0.0748
63	Eu				0.97-2	0.0935
		151	88	25	0.65-2	0.0446
		153	90	27	0.69-2	0.0488
64	Gd				0.53-1	0.342
		152	88	24	0.84-4	0.000687
		154	90	26	0.87-3	0.00738
		155	91	27	0.70-2	0.0505
		156	92	28	0.85-2	0.0704
		157	93	29	0.73-2	0.0537
		158	94	30	0.93-2	0.0847
		160	96	32	0.87-2	0.0746
65	Tb	159	94	29	0.68-2	0.0478
66	Dy				0.44-1	0.278
		156	90	24	0.16-4	0.000145
		158	92	26	0.40-4	0.000251
		160	94	28	0.80-3	0.00637
		161	95	29	0.72-2	0.0525
		162	96	30	0.85-2	0.0709
		163	97	31	0.84-2	0.0694
		164	98	32	0.89-2	0.0783

TABLE III
Continued 9

67	Ho	165	98	33	0.77-2		0.059
68	Er				0.20-1		0.158
		162	94	26	0.20-4		0.000158
		164	96	28	0.37-3		0.00237
		166	98	30	0.72-2		0.0520
		167	99	31	0.58-2		0.0385
		168	100	32	0.63-2		0.0425
		170	102	34	0.35-2		0.0224
69	Tm	169	100	31	0.20-2		0.0159
70	Yb				0.04-1		0.110
		168	98	28	0.18-4		0.00015
		170	100	30	0.52-3		0.00333
		171	101	31	0.20-2		0.0158
		172	102	32	0.38-2		0.0240
		173	103	33	0.25-2		0.0178
		174	104	34	0.54-2		0.0349
		176	106	36	0.14-2		0.0139
71	Lu				0.40-2		0.0251
		175	104	33	0.39-2		0.0244
		176	105	34	0.81-4		0.00065
72	Hf				0.34-1		0.219
		174	102	30	0.60-4		0.00039
		176	104	32	0.05-2		0.0113
		177	105	33	0.61-2		0.0403
		178	106	34	0.77-2		0.0593
		179	107	35	0.48-2		0.0302
		180	108	36	0.89-2		0.0776
73	Ta	181	108	35	0.56-2		0.0363
74	W				0.55-1		0.352
		180	106	32	0.64-4		0.00044
		182	108	34	0.97-2		0.0926
		183	109	35	0.70-2		0.0503
		184	110	36	0.03-1		0.108
		186	112	38	0.00-1		0.101

TABLE III
Continued 10

75	Re				0.13-1	0.135
		185	110	35	0.70-2	0.050₁
		187	112	37	0.93-2	0.0851
76	Os				0.00	1.00
		184	108	32	0.26-4	0.00018
		186	110	34	0.20-2	0.0159
		187	111	35	0.22-2	0.0164
		188	112	36	0.12-1	0.133
		189	113	37	0.21-1	0.161
		190	114	38	0.42-1	0.264
		192	116	40	0.61-1	0.410
77	Ir				0.91-1	0.821
		191	114	37	0.50-1	0.316
		193	116	39	0.70-1	0.505
78	Pt				0.21	1.625
		190	112	34	0.00-4	0.0001
		192	114	36	0.10-2	0.0127
		194	116	38	0.73-1	0.533
		195	117	39	0.74-1	0.548
		196	118	40	0.62-1	0.413
		198	120	42	0.07-1	0.117
79	Au	197	118	39	0.16-1	0.145
80	Hg				0.50-2	0.0318
		196	116	36	0.71-5	0.000051
		198	118	38	0.50-3	0.00319
		199	119	39	0.73-2	0.00539
		200	120	40	0.87-3	0.00735
		201	121	41	0.62-3	0.00421
		202	122	42	0.98-3	0.00946
		204	124	44	0.34-3	0.00218
81	Tl				0.05-2	0.01125
		203	122	41	0.52-3	0.00332
		205	124	43	0.90-3	0.00793

TABLE III
Continued 11

82	Pb				0.03-1	0.108
		204	122	40	0.33-3	0.00214
		206	124	42	0.31-2	0.0203
		207	125	43	0.35-2	0.0222
		208	126	44	0.80-2	0.0631
83	Bi	209	126	43	0.90-2	0.0794
90	Th	232	142	52	0.93-2	0.0856
92	U				0.73-2	0.0542
		235	143	51	0.08-2	0.0120
		238	146	54	0.63-2	0.0422

FIGURE I   A
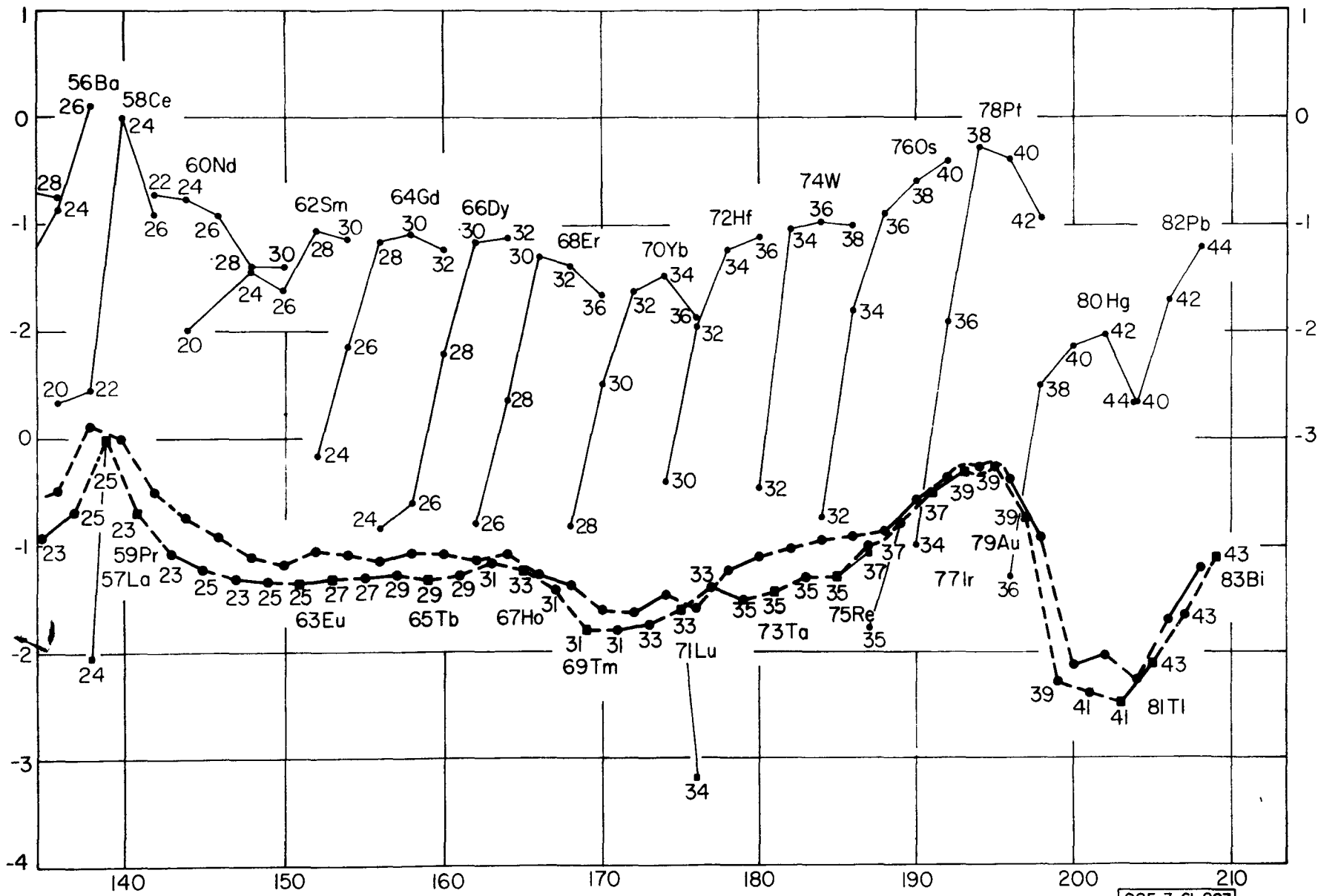
925-1·61-281

FIGURE I   B

925-2 61-282

FIGURE I   C

925-3 61-283
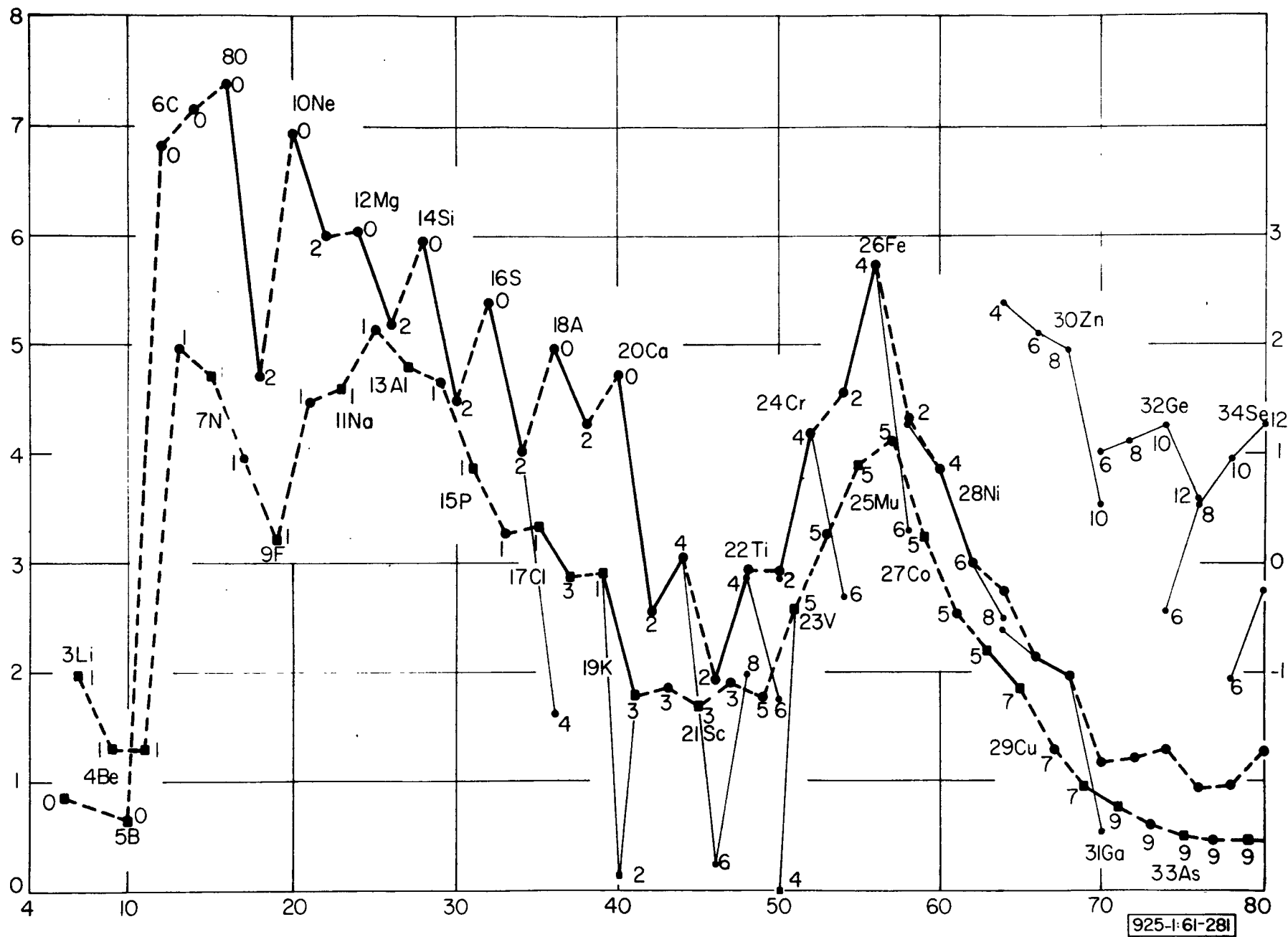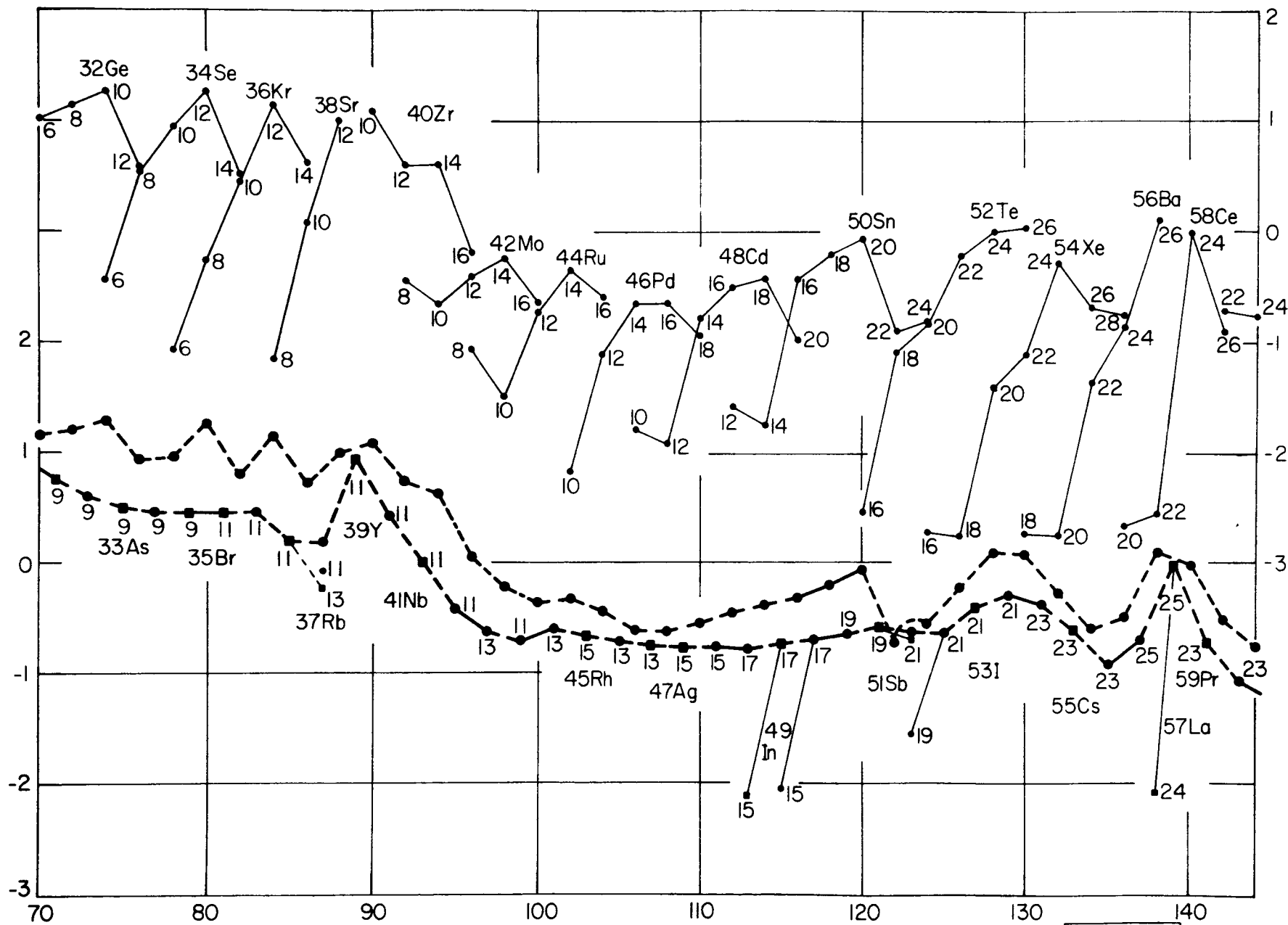
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