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Abundances of the Elements*

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AND

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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 entitled, "The Relative Abundance of the Chemical Elements," was the first of a number of papers by many different authors. 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 coworker, 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 them too speculative to effectively influence further developments. 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 classical paper (1937) which served as the basis of practically all the more recent work in this field.

When in 1889 Clarke was looking for periodicties 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 from 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 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. Since then considerable progress has been made in the field of geochemistry and cosmochemistry and 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 emperical and semiemperical 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 over-all 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 developed under which these reactions took place. As the last and final step, a cosmogonic model may then be found as an explanation of the course of events. No attempt is made to do this here. However, attention is drawn to evidence which might serve as a basis for future work along these lines and some tentative suggestions which may be helpful for further work are included.

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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 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 co-workers. Goldschmidt's classical work of 1937 is still a most valuable source of information and those who have studied the subject since then lean heavily on his judgment in regard to relative abundances of the elements. A posthumous book (1954) makes this work more available. Ida and Walter Noddack (1930, 1931, 1934) contributed additional data which are 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 meteorites in the silicate phase, the troilite phase (FeS), and the metal phase. Goldschmidt weighted these phases in the proportions 10: (silicate): 1 (sulfide): 2 (metal). 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 values for 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 (1956) has analyzed 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.

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 in these rare earth 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 must be true. We do not pretend to understand fully 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 the isotopic abundances of the elements determine the slope of the curves surprisingly closely and especially the slope of the odd mass curve. Also the curves for the logarithms of the abundances of the even and odd mass elements 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 have 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.

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 and mixing of the surface and interior has occurred. This has occurred in the case of H and He because of 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 been reported in the sun's atmosphere (DeJager, 1952) but the identification depends only on the D_α line and hence is doubtful. Greenstein and Richardson (1951) find that the abundance of lithium in the sun is very low but not zero. The presence of deuterium would indicate that there is no convection in the outer layers of the sun, but the opposite conclusion is indicated by the lithium observations. 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, and several sources of line broadening, e.g., Doppler effect, collisional broadening, turbulence, and natural damping. 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. It is necessary to be cautious however because real differences in composition occur among stars of different kinds.

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, probably some sulfur as H_2S, halogens in carbon compounds, and possibly some proportions of other elements though such loss is not evident (Urey, 1954b). 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 phase. 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 were 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 meteroites and pallasites. The assumptions made by different investigators are summarized in Table I.

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

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

Author	Parts by weight 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 (1952a)	10.6	7	100

TABLE II. Atomic abundances of the elements.[a] Silicon $=1\times10^6$.

	Goldschmidt	Brown	Urey (revised)	Aller (Astronomical)	This paper
1 H		3.5×10^{10}		2.94×10^{10}	4.00×10^{10}
2 He		3.5×10^{9}		4.05×10^{9}	3.08×10^{9}
3 Li	100		100	0.6	100
4 Be	20		16	1.0	20
5 B	24		20	1580	24
6 C		8.0×10^{6}		2.7×10^{6}	3.5×10^{6}
7 N		1.6×10^{7}		4.9×10^{6}	6.6×10^{6}
8 O		2.2×10^{7}		1.58×10^{7}	2.15×10^{7}
9 F	1500	9000	300		1600
10 Ne		9.0×10^{5}– 2.4×10^{7}		1.73×10^{7}	8.6×10^{6}
11 Na	4.42×10^{4}	4.62×10^{4}	4.38×10^{4}	7.7×10^{4}	4.38×10^{4}
12 Mg	8.7×10^{5}	8.87×10^{5}	9.12×10^{5}	1.78×10^{6}	9.12×10^{5}
13 Al	8.8×10^{4}	8.82×10^{4}	9.48×10^{4}	7.4×10^{4}	9.48×10^{4}
14 Si	1.0×10^{6}	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}	5.0×10^{3}	1.9×10^{4}	1.00×10^{4}
16 S	1.14×10^{5}	3.5×10^{5}	9.8×10^{4}	5.2×10^{5}	3.75×10^{5}
17 Cl	4000–6000	17 000	2100	300 000	8850
18 A		1.3×10^{4}– 2.2×10^{5}		1.0×10^{6}	1.5×10^{5}
19 K	6900	6930	3160	3900	3160
20 Ca	5.71×10^{4}	6.7×10^{4}	4.90×10^{4}	8.3×10^{4}	4.90×10^{4}
21 Sc	15	18	28	42	28
22 Ti	4700	2600	2440	1800	2440
23 V	130	250	220	300	220
24 Cr	1.13×10^{4}	9.5×10^{3}	7800	1.9×10^{3}	7800
25 Mn	6600	7700	6850	5600	6850
26 Fe	8.9×10^{5}	1.83×10^{6}	6.00×10^{5}	4.8×10^{5}	6.00×10^{5}
27 Co	3500	9900	1800	2200	1800
28 Ni	4.6×10^{4}	1.34×10^{5}	2.74×10^{4}	4.4×10^{4}	2.74×10^{4}
29 Cu	460	460	212	932	212
30 Zn	360	160	180	2880	486
31 Ga	19	65	11.4	2.5	11.4
32 Ge	190	250	65	25	50.5
33 As	18	480	4.0		4.0
34 Se	15	25	24		67.6
35 Br	43	42	49?		13.4
36 Kr					51.3
37 Rb	6.8	7.1	6.5	1	6.5
38 Sr	40	41	18.9		18.9
39 Y	9.7	10	8.9		8.9
40 Zr	140	150	54.5		54.5
41 Nb	6.9	0.9	0.8		1.00
42 Mo	9.5	19	2.42		2.42
44 Ru	3.6	9.3	2.1		1.49
45 Rh	1.3	3.5	0.71		0.214
46 Pd	1.8	3.2	1.3		0.675
47 Ag	3.2	2.7	0.35		0.26
48 Cd	2.6	2.6	1.9		0.89
49 In	0.23	1.0	0.26		0.11
50 Sn	29	62	1.33		1.33
51 Sb	0.72	1.7	0.12		0.246
52 Te	0.2		0.16		4.67
53 I	1.4	1.8	1.5		0.80
54 Xe					4.0
55 Cs	0.1	0.1	1.3		0.456
56 Ba	8.3	3.9	8.8		3.66
57 La	2.1	2.1	2.1		2.00
58 Ce	5.2	2.3	2.3		2.26
59 Pr	0.96	0.96	0.96		0.40
60 Nd	3.3	3.3	3.3		1.44
62 Sm	1.15	1.2	1.1		0.664
63 Eu	0.28	0.28	0.28		0.187
64 Gd	1.65	1.7	1.6		0.684
65 Tb	0.52	0.52	0.52		0.0956
66 Dy	2.0	2.0	2.0		0.556
67 Ho	0.57	0.57	0.57		0.118
68 Er	1.6	1.6	1.6		0.316
69 Tm	0.29	0.29	0.29		0.0318
70 Yb	1.5	1.5	1.5		0.220
71 Lu	0.48	0.48	0.48		0.050
72 Hf	1.5	0.7	0.55		0.438
73 Ta	0.40	0.31	0.32		0.065
74 W	14.5	17.0	13.0?		0.49
75 Re	0.12	0.41	0.05		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	0.140		0.145
80 Hg	0.33		<0.006		0.284
81 Tl	0.17		0.11		0.108
82 Pb	9.1	<2.0	0.47		0.47
83 Bi	0.11	0.21	0.144		0.144
90 Th	0.59				
92 U	0.23	0.02			

[a] Goldschmidt's values as given in the table have been modified slightly by Suess and by Urey in accordance with data which are 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. Most of the values have been changed. The rare earths differ from our adopted values for reasons explained in the text.

(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, 1952c) 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 terrestrial 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 iron is even smaller than that of Goldschmidt and is in closer agreement with the solar abundance determined by the use of more recent oscillator strengths 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. Edwards, Johnston, and Ditmars (1951) confirm their lower values for the vapor pressure of iron. 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 makes a revision of all the abundance values necessary. The empirical data are given in Table II.

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 Noddack and 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 those published previously. Even certain data of such a reliable investigator as Goldschmidt have been shown to be seriously in error, as for example in the case of tin and 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 some reported analytical data are in error by more than a factor of 10, e.g., *W*. Only further careful analytical work can decide whether our rather arbitrary choices in some cases are justified. It is difficult to estimate the accuracy of the astrophysical data. Mostly probable errors are probably not better than about a factor of 1.5 and particularly in the case of rare elements they may be in error by larger factors.

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 10 000. 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 Fig. 1 and our selected values are given in Table III.

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 τ 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 the data]. He assumed *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 an O 9.5 star 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, τ Sco, δ Cet, γ Peg, and ι 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 believes that the ratio is strongly dependent on the exact model of the stellar atmosphere used. Traving (1955) has made a model atmosphere calculation for this ratio in τ Scorpii and finds 5.9 for this ratio. In private communications Aller suggests that 10 would be a better ratio and Unsöld maintains that 6 or 7 is the correct ratio and that as yet unpublished data on the solar prominences confirm this value for the sun. 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 Claas' (1951) and Unsöld's (1948) values as modified by Claas normalized to a mean of magnesium and silicon. This gives 10.60 for $\log H_H$. 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 (1955). DeJager (1952) reports that the abundance of deuterium in the sun's atmosphere is approximately the same as that in terrestrial hydrogen, though this depends only on the D_α line intensity. 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 10^5 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 the following 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

We adopt the meteoritic values. Goldschmidt estimates the atomic abundance of boron as 21. 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 1.0×10^{20} atoms cm^{-2} for carbon and nitrogen, respectively. Minnaert (1953) summarizes the work of Unsöld (1948), Class (1951), and Hunnaerts (1950) on the sun and Aller (1953) gives a summary of stellar data. We will select Aller's estimate for the C, N, and O data normalized to a hydrogen value for $\log H$ equal to 10.60. The values so secured do not differ in an important amount from values reported by other authors.

Aller (1953) concludes that oxygen and neon have nearly the same abundance in the stars and planetary nebulae. Aller (1954) finds 0.28 for the neon to oxygen ratio in the planetary nebula *NGC* 7027. Traving (1955) estimates the neon abundance as 0.4 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}. We have taken neon as 0.4 of the oxygen abundance.

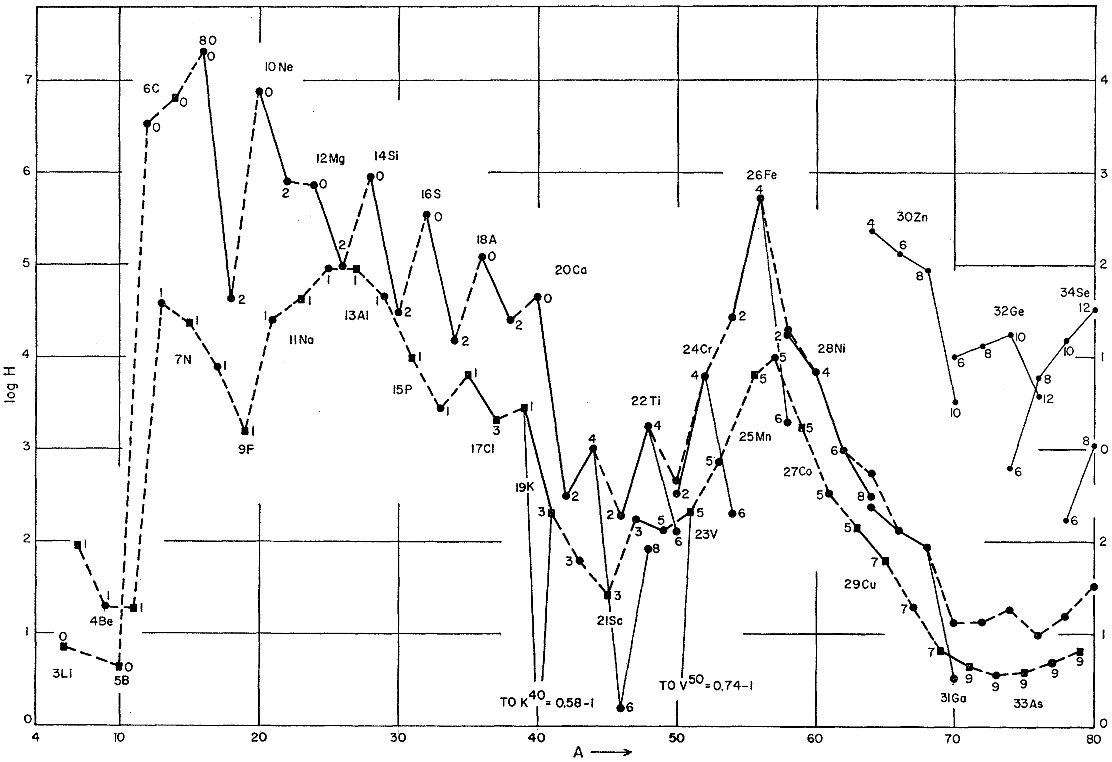

FIG. 1(a)

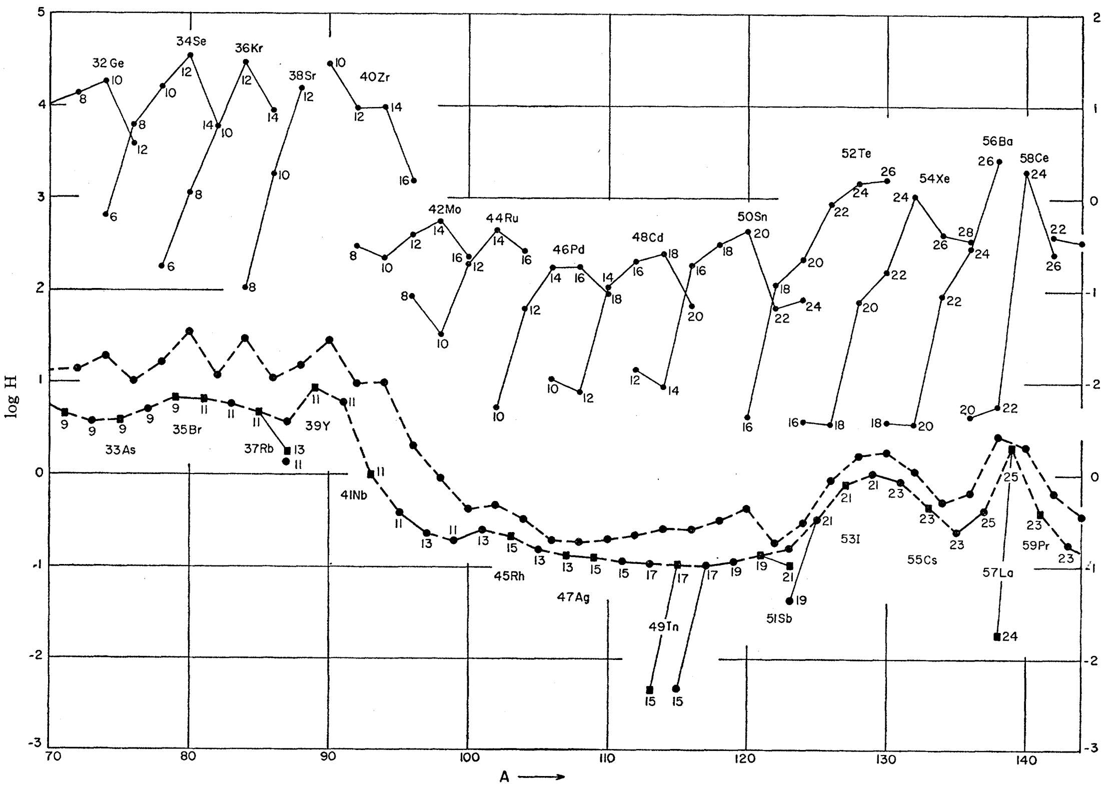

FIG. 1(b)

FIGS. 1(a)–1(c). Logarithm of abundance (silicon = 6) plotted against mass number (A). The even and odd mass numbers are on separate curves. The neutron excess numbers (I) are shown at each point. The curve without I indicated, shows the sum of the isobaric abundances for the even A series. Note that the right-hand scale is for the curve representing the even A series (light lines) beginning with $A = 64$ (Zn). [Part (c) on opposite page.]

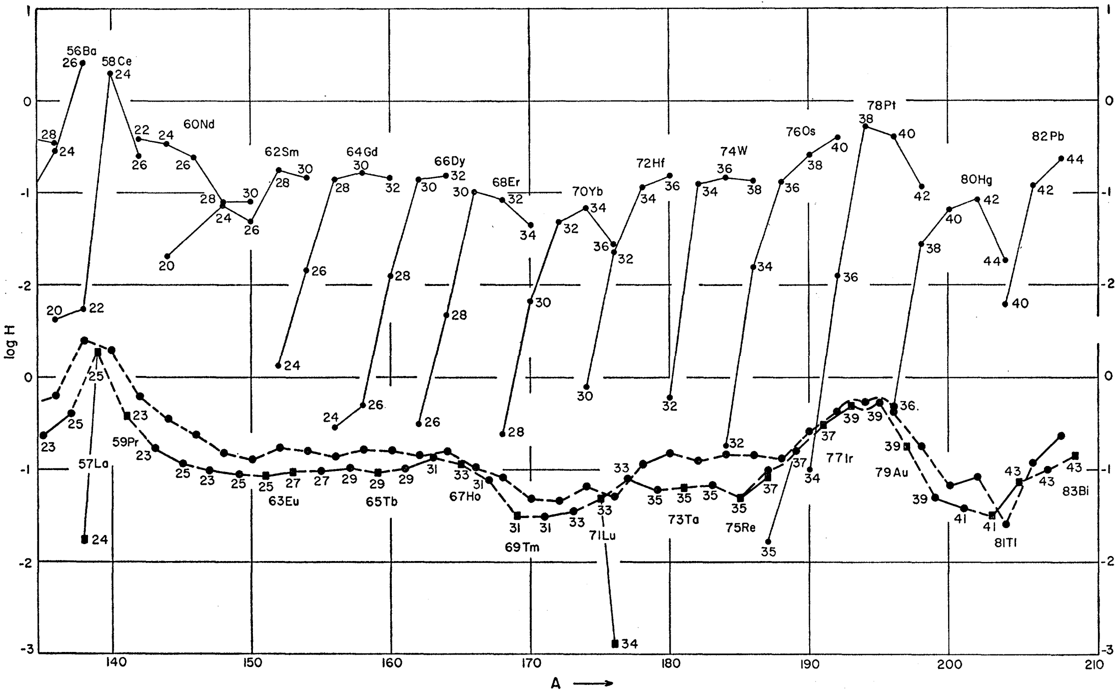

FIG. 1(c). (Caption on opposite page.)

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 Noddack and 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 700 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, taken 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 atomic ratios in the two groups averaged 6084 and 8494 to 10 000 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. Wiik (1956) has checked the existence of these two groups and finds slightly less iron in the low iron group and checks the nickel abundance. We use a round value of 6×10^5 for the iron abundance and the Urey and Craig values for nickel and cobalt. This low abundance of iron is very much in accord with the most recent astronomical data.

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 820 ppm relative to silicon equal to 18.5% by weight in primitive nonvolatile solar matter which is the average of analyses of many chondrites by Edwards (1956). We do not follow the lower value of this abundance as suggested by Urey (1955) since preliminary results of a recalculation of solar abundances by Goldberg and Aller

TABLE III.

Element	A	N	I	Log$H$	H
1 H				10.60	4.00×10^{10}
	1	*0*	*−1*	*10.60*	4.00×10^{10}
	2	1	0	6.75	$5.7\ \times10^{6}$
2 He					
	3	*1*	*−1*	...	...
	4	2	0	9.49	3.08×10^{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				6.56	3.54×10^{6}
	12	6	0	6.54	3.50×10^{6}
	13	*7*	*1*	*4.59*	3.92×10^{4}
7 N				6.82	6.60×10^{6}
	14	7	0	6.82	6.58×10^{6}
	15	*8*	*1*	*4.38*	2.41×10^{4}
8 O				7.33	2.14×10^{7}
	16	8	0	7.33	2.13×10^{7}
	17	*9*	*1*	*3.90*	8.00×10^{3}
	18	10	2	4.64	4.36×10^{4}
9 F	*19*	*10*	*1*	*3.20*	*1600*
10 Ne				6.93	$8.6\ \times10^{6}$
	20	10	0	6.89	7.74×10^{6}
	21	*11*	*1*	*4.41*	2.58×10^{4}
	22	12	2	5.92	8.36×10^{5}
11 Na	*23*	*12*	*1*	*4.64*	4.38×10^{4}
12 Mg				5.96	9.12×10^{5}
	24	12	0	5.86	7.21×10^{5}
	25	*13*	*1*	*4.96*	9.17×10^{4}
	26	14	2	5.00	1.00×10^{5}
13 Al	*27*	*14*	*1*	*4.98*	9.48×10^{4}
14 Si				6.00	1.00×10^{6}
	28	14	0	5.96	9.22×10^{5}
	29	*15*	*1*	*4.67*	4.70×10^{4}
	30	16	2	4.49	3.12×10^{4}
15 P	*31*	*16*	*1*	*4.00*	1.00×10^{4}
16 S				5.57	3.75×10^{5}
	32	16	0	5.55	3.56×10^{5}
	33	*17*	*1*	*3.44*	2.77×10^{3}
	34	18	2	4.19	1.57×10^{4}
	36	20	4	1.71	51
17 Cl				3.95	8850
	35	*18*	*1*	*3.82*	*6670*
	37	*20*	*3*	*3.34*	*2180*
18 A				5.18	1.50×10^{5}
	36	18	0	5.10	1.26×10^{5}
	38	20	2	4.38	$2.4\ \times10^{4}$
	40	22	4		
19 K				3.50	3160
	39	*20*	*1*	*3.47*	*2940*
	40	21	2	0.58 −1	0.38
	41	*22*	*3*	*2.34*	*219*
20 Ca				4.69	4.90×10^{4}
	40	20	0	4.68	4.75×10^{4}
	42	22	2	2.50	314
	43	*23*	*3*	*1.80*	*64*
	44	24	4	3.02	1040
	46	26	6	0.20	1.6
	48	28	8	1.94	87.7
21 Sc	*45*	*24*	*3*	*0.43*	*2.8*
22 Ti				3.39	2440
	46	24	2	2.29	194
	47	*25*	*3*	*2.28*	*189*
	48	26	4	3.25	1790
	49	*27*	*5*	*2.13*	*134*
	50	28	6	2.11	130
23 V				2.34	220
	50	27	4	0.74 −1	0.55
	51	*28*	*5*	*2.34*	*220*
24 Cr				3.89	7800
	50	26	2	2.54	344
	52	28	4	3.81	6510
	53	*29*	*5*	*2.87*	*744*
	54	30	6	2.31	204
25 Mn	*55*	*30*	*5*	*3.84*	*6850*
26 Fe				5.78	6.00×10^{5}
	54	28	2	4.55	3.54×10^{4}
	56	30	4	5.77	5.49×10^{5}
	57	*31*	*5*	*4.13*	1.35×10^{4}
	58	32	6	3.30	1980
27 Co	*59*	*32*	*5*	*3.25*	*1800*
28 Ni				4.44	2.74×10^{4}
	58	30	2	4.27	1.86×10^{4}
	60	32	4	3.86	7170
	61	*33*	*5*	*2.53*	*342*
	62	34	6	3.00	1000
	64	36	8	2.50	318
29 Cu				2.33	212
	63	*34*	*5*	*2.16*	*146*
	65	*36*	*7*	*1.82*	*66*
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	0.52	3.35
31 Ga				1.06	11.4
	69	*38*	*7*	*0.84*	*6.86*
	71	*40*	*9*	*0.66*	*4.54*
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*	*0.60*	*4.0*
34 Se				1.83	67.6
	74	40	6	0.81	0.649
	76	42	8	0.80	6.16
	77	*43*	*9*	*0.70*	*5.07*
	78	44	10	1.20	16.0
	80	46	12	1.53	33.8
	82	48	14	0.78	5.98

TABLE III—*Continued.*

Element	A	N	I	Log*H*	*H*
35 Br				1.13	13.4
	79	*44*	*9*	*0.83*	*6.78*
	81	*46*	*11*	*0.82*	*6.62*
36 Kr				1.71	51.3
	78	42	6	0.24 -1	0.175
	80	44	8	0.06	1.14
	82	46	10	0.77	5.90
	83	*47*	*11*	*0.76*	*5.89*
	84	48	12	1.47	29.3
	86	50	14	0.95	8.94
37 Rb				0.81	6.5
	85	*48*	*11*	*0.67*	*4.73*
	87	*50*	*13*	*0.25*	*1.77*
38 Sr				1.28	18.9
	84	46	8	0.03	0.106
	86	48	10	0.26	1.86
	87	*49*	*11*	*0.12*	*1.33*
	88	50	12	1.19	15.6
39 Y	*89*	*50*	*11*	*0.95*	*8.9*
40 Zr				1.74	54.5
	90	50	10	1.45	28.0
	91	*51*	*11*	*0.79*	*6.12*
	92	52	12	0.97	9.32
	94	54	14	0.98	9.48
	96	56	16	0.18	1.53
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	0.67 -1	0.467
	104	60	16	0.43 -1	0.272
45 Rh	*103*	*58*	*15*	*0.33 -1*	*0.214*
46 Pd				0.83 -1	0.675
	102	56	10	0.73 -3	0.0054
	104	58	12	0.80 -2	0.0628
	105	*59*	*13*	*0.18 -1*	*0.1536*
	106	60	14	0.26 -1	0.1839
	108	62	16	0.26 -1	0.180
	110	64	18	0.96 -2	0.0911
47 Ag				0.41 -1	0.26
	107	*60*	*13*	*0.13 -1*	*0.134*
	109	*62*	*15*	*0.10 -1*	*0.126*
48 Cd				0.95 -1	0.89
	106	58	10	0.04 -2	0.0109
	108	60	12	0.90 -3	0.0079
	110	62	14	0.04 -1	0.111
	111	*63*	*15*	*0.06 -1*	*0.114*
	112	64	16	0.33 -1	0.212
	113	*65*	*17*	*0.04 -1*	*0.110*
	114	66	18	0.41 -1	0.256
	116	68	20	0.83 -2	0.068
49 In				0.04 -1	0.11
	113	*64*	*15*	*0.66 -3*	*0.0046*
	115	*66*	*17*	*0.02 -1*	*0.105*
50 Sn				0.12	1.33
	112	62	12	0.13 -2	0.0134
	114	64	14	0.96 -3	0.0090
	115	*65*	*15*	*0.67 -3*	*0.00465*
	116	66	16	0.28 -1	0.189
	117	*67*	*17*	*0.01 -1*	*0.102*
	118	68	18	0.50 -1	0.316
	119	*69*	*19*	*0.06 -1*	*0.115*
	120	70	20	0.64 -1	0.433
	122	72	22	0.80 -2	0.063
	124	74	24	0.90 -2	0.079
51 Sb				0.39 -1	0.246
	121	*70*	*19*	*0.15 -1*	*0.141*
	123	*72*	*21*	*0.02 -1*	*0.105*
52 Te				0.67	4.67
	120	68	16	0.62 -3	0.00420
	122	70	18	0.06 -1	0.115
	123	*71*	*19*	*0.62 -2*	*0.0416*
	124	72	20	0.34 -1	0.221
	125	*73*	*21*	*0.52 -1*	*0.328*
	126	74	22	0.94 -1	0.874
	128	76	24	0.17	1.48
	130	78	26	0.20	1.60
52 I	*127*	*74*	*21*	*0.90 -1*	*0.80*
54 Xe				0.60	4.0
	124	70	16	0.58 -3	0.00380
	126	72	18	0.55 -3	0.00352
	128	74	20	0.88 -2	0.0764
	129	*75*	*21*	*0.02*	*1.050*
	130	76	22	0.21 -1	0.162
	131	*77*	*23*	*0.93 -1*	*0.850*
	132	78	24	0.03	1.078
	134	80	26	0.62 -1	0.420
	136	82	28	0.55 -1	0.358
55 Cs	*133*	*78*	*23*	*0.66 -1*	*0.456*
56 Ba				0.56	3.66
	130	74	18	0.57 -3	0.00370
	132	76	20	0.55 -3	0.00356
	134	78	22	0.95 -2	0.0886
	135	*79*	*23*	*0.38 -1*	*0.241*
	136	80	24	0.45 -1	0.286
	137	*81*	*25*	*0.62 -1*	*0.414*
	138	82	26	0.42	2.622
57 La				0.30	2.00
	138	81	24	0.25 -3	0.0018
	139	*82*	*25*	*0.30*	*2.00*
58 Ce				0.35	2.26
	136	78	20	0.64 -3	0.0044
	138	80	22	0.75 -3	0.00566
	140	82	24	0.30	2.00
	142	84	26	0.40 -1	0.250
59 Pr	*141*	*82*	*23*	*0.60 -1*	*0.40*
60 Nd				0.16	1.44
	142	82	22	0.59 -1	0.39
	143	*83*	*23*	*0.24 -1*	*0.175*
	144	84	24	0.54 -1	0.344
	145	*85*	*25*	*0.08 -1*	*0.119*
	146	86	26	0.39 -1	0.248
	148	88	28	0.91 -2	0.0824
	150	90	30	0.91 -2	0.0806

TABLE III—*Continued.*

Element	*A*	*N*	*I*	Log*H*	*H*
62 Sm				0.82 −1	0.664
	144	82	20	0.32 −2	0.0108
	147	*85*	*23*	*0.00 −1*	*0.100*
	148	86	24	0.87 −2	0.0748
	149	*87*	*25*	*0.96 −2*	*0.0920*
	150	88	26	0.69 −2	0.0492
	152	90	28	0.25 −1	0.176
	154	92	30	0.17 −2	0.150
63 Eu				0.27 −1	0.187
	151	*88*	*25*	*0.95 −2*	*0.0892*
	153	*90*	*27*	*0.99 −2*	*0.0976*
64 Gd				0.83 −1	0.684
	152	88	24	0.14 −3	0.00137
	154	90	26	0.17 −2	0.0147
	155	*91*	*27*	*0.00 −1*	*0.101*
	156	92	28	0.15 −1	0.141
	157	*93*	*29*	*0.03 −1*	*0.107*
	158	94	30	0.23 −1	0.169
	160	96	32	0.17 −1	0.149
65 Tb	*159*	*94*	*29*	*0.98 −2*	*0.0956*
66 Dy				0.74 −1	0.556
	156	90	24	0.46 −4	0.00029
	158	92	26	0.70 −4	0.000502
	160	94	28	0.10 −2	0.0127
	161	*95*	*29*	*0.02 −1*	*0.105*
	162	96	30	0.15 −1	0.142
	163	*97*	*31*	*0.14 −1*	*0.139*
	164	98	32	0.19 −1	0.157
67 Ho	*165*	*98*	*33*	*0.07 −1*	*0.118*
68 Er				0.50 −1	0.316
	162	94	26	0.50 −4	0.000316
	164	96	28	0.67 −3	0.00474
	166	98	30	0.02 −1	0.104
	167	*99*	*31*	*0.88 −2*	*0.770*
	168	100	32	0.93 −2	0.0850
	170	102	34	0.65 −2	0.0228
69 Tm	*169*	*100*	*31*	*0.50 −2*	*0.0318*
70 Yb				0.34 −1	0.220
	168	98	28	0.48 −4	0.00030
	170	100	30	0.82 −3	0.00666
	171	*101*	*31*	*0.50 −2*	*0.0316*
	172	102	32	0.68 −2	0.0480
	173	*103*	*33*	*0.55 −2*	*0.0356*
	174	104	34	0.84 −2	0.0678
	176	106	36	0.44 −2	0.0278
71 Lu				0.70 −2	0.050
	175	*104*	*33*	*0.69 −2*	*0.0488*
	176	105	34	0.11 −3	0.0013
72 Hf				0.68 −1	0.438
	174	102	30	0.90 −4	0.00078
	176	104	32	0.35 −2	0.0226
	177	*105*	*33*	*0.91 −2*	*0.0806*
	178	106	34	0.07 −1	0.119
	179	*107*	*35*	*0.78 −2*	*0.0604*
	180	108	36	0.19 −1	0.155
73 Ta	*181*	*108*	*35*	*0.81 −2*	*0.065*
74 W				0.69 −1	0.49
	180	106	32	0.78 −4	0.0006
	182	108	34	0.11 −1	0.13
	183	*109*	*35*	*0.84 −2*	*0.070*
	184	110	36	0.17 −1	0.15
	186	112	38	0.14 −1	0.14
75 Re				0.13 −1	0.135
	185	*110*	*35*	*0.70 −2*	*0.0500*
	187	*112*	*37*	*0.93 −2*	*0.0850*
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				0.45 −1	0.284
	196	116	36	0.65 −4	0.00045
	198	118	38	0.45 −2	0.0285
	199	*119*	*39*	*0.68 −2*	*0.0481*
	200	120	40	0.82 −2	0.0656
	201	*121*	*41*	*0.57 −2*	*0.0375*
	202	122	42	0.93 −2	0.0844
	204	124	44	0.29 −2	0.0194
81 Tl				0.03 −1	0.108
	203	*122*	*41*	*0.50 −2*	*0.0319*
	205	*124*	*43*	*0.88 −2*	*0.0761*
82 Pb				0.67 −1	0.47
	204	122	40	0.80 −3	0.0063
	206	124	42	0.09 −1	0.122
	207	*125*	*43*	*0.00 −2*	*0.0995*
	208	126	44	0.39 −1	0.243
83 Bi	*209*	*126*	*43*	*0.16 −1*	*0.144*
90 Th	232	142	52		
92 U	*235*	*143*	*51*		
	238	146	54		

do not check Urey's predicted value. This gives 3160 for its atomic abundance.§

We have adopted the abundances of Na, Mg, Al, and Si, from recent work by Wiik (1956) on the meteorites,

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§ Urey's suggestion is that the radioactive elements potassium, uranium, and thorium have been increased in concentration in the meteorites by a factor of about three or four and that other elements markedly concentrated at the earth's surface have similarly been concentrated in the meteorites. We have discussed the advisability of adopting this view many times. In general, postulates of this kind should be allowed to stand some test of time before additional papers are based upon them. After consultation with since these analyses have been made by the best modern techniques. The values secured are not markedly different from those secured by other analysts except that Al is somewhat higher. Wiik found that the iron precipitates contained some aluminum and the correction for this error raised his values.

Phosphorus, Sulfur, and Chlorine

The astronomical data for these elements are consistently higher than would be indicated by the analyses of meteorites. The analytical data for phosphorus indicates very variable amounts, even in the case of the recent data of Wiik (1956). Because of this we have selected an approximate astronomical value of 10^4. Wiik's analytical data indicate a meteoritic value of about 4000. It is possible that phosphorus escaped in carbon compounds during the formation of the meteorites [Urey (1954a)].

The silicon-sulfur ratio is an important datum, because 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, namely 3.75×10^5. A sulfur value as low as that indicated by meteorite analyses 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. Our choice has been influenced strongly by the high astronomical values.

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 analyzed 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. Selivanov (1940) reports 100 ppm for one chondrite. Urey (1952a) used the Noddacks' 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). The astronomical data indicate an abundance about 100 times as great as these meteoretic values. We cannot fit such a high abundance into our curves without producing great irregularities. We have selected as high a value for chlorine as possible and yet retain a reasonable separation of the odd and even mass curves.

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 *B*-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 of 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

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Professor Goldberg and Professor Aller, we concluded at first that the low value of potassium proposed by Urey would probably be confirmed by their solar studies. At present it appears that this is not the case.

We have constructed abundance curves of the elements on both assumptions. If the higher meteoritic abundances are used as presented in this paper we secure smooth curves by taking higher values of chlorine and sulfur and hence also of bromine and selenium and the observed meteoritic rubidium and strontium data fit the curve. This permits a higher choice for krypton and hence of xenon and this in turn accommodates the higher value for barium. There are other differences in the two curves, but these are the most important ones.

It is difficult to find any advantage in one curve over the other so far as nuclear regularities are concerned. However, if we had used Urey's lower values for potassium and other elements which are concentrated by melting processes, better agreement between the solar ratios of scandium to gallium and of copper to gallium could have been secured though the differences would still be large. As it is, we have no explanation for the very large differences in these ratios and definitely do not believe that they are due to errors in the analyses of the meteorites.

through A^{38}, Ca^{42} in the other curve. There seems to be no physical reason to expect such a behavior of these curves. 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. 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 through Nickel

Calcium has been determined in the meteorites with high precision. The Urey and Craig (1953) value is 53 600. Wiik's more recent analyses gives 49 000. The concentrations of scandium in the meteorites as determined by Pinson, Ahrens, and Franck (1953) of 6 ppm is essentially the value given by Goldschmidt. Wiik has secured 8 ppm in chondrites. 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. We select the highest observed value for scandium in meteorites for this reason.

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 chondrites and concludes that the amount is very constant near 0.079%, which gives 2440 for the atomic abundance as compared with the Urey and Craig average of 2100.

Recent analyses of Wiik for chromium and manganese agree well with the older data summarized by Urey and Craig (1953). We use these data for these three elements.

The iron, cobalt, and nickel abundances are taken from the data summarized by Urey and Craig (1953) for their low iron group of chondrites. These data are well confirmed by Wiik who secures a slightly lower iron value. Greenstein's astronomical estimate for iron is considerably smaller than our selected abundance and this would not be contrary to Urey and Craig's argument. We use their values in order to secure consistent iron and nickel relative abundances.

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 (1956) finds 0.079% for Ti, i.e., a ratio of 24. We shall use this value and take the atomic Zr abundance as 1/45 of our titanium abundance.

The Zr/Hf ratio depends on the extensive investigation of Hevesy and Würstlin [(1928) and (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 Frank (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 68 analyses is 2.37% of hafnium relative to zirconium plus 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 analyzed a number of meteorites including several chondrites. Two of these latter were Allegan and Tabory, which are observed falls while the others that 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 meteoritic ratio and our sulfur value we secure 47 whereas Byers' data give 24.2 for the atomic abundance. Because of the difference 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 from the meteorites as readily as sulfur. We have selected 67.6 as our abundance of selenium. More data on this ratio are needed. 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 292 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 use the oceanic ratio and our chlorine value to secure 13.4 for the bromine abundance. 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. The observed abundance by weight gives 3.8 ppm equivalent to an atomic abundance of 6.65 for rubidium.

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 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. 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 0.675 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% 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, 51.3 and 4.0, 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 with a maximum at bromine due to our choice of the chlorine and sulfur abundances. The pairs of isotopes of Cu, Ga, and Br define the slope at three points.

The Cu content of meteorites has been reported to vary 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. Unpublished data of Wiik and Sandell indicate greater constancy in the copper data for chondritic meteorites. Our choice of 212 for the atomic abundance is in agreement with the data of these two analysts.

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 on meteorites.

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. Sandell has made his most recent data on gallium available to us. These agree closely with Goldschmidt's and Noddacks' data. We use 11.4 for the atomic abundance equivalent to Sandell's 5.3 ppm in chondrites. Our ratio of scandium to gallium is 2.5 and this appears to be in disagreement with astronomical values for the sun as pointed out to us by Professor Russell. Aller (1953) gives 15 for the ratio of scandium to gallium in the sun and more recent data indicate an even higher ratio. Aller gives nearly 400 for the ratio of copper to gallium whereas the meteoritic data give about 20. The meteoritic data cannot reasonably be assumed to be sufficiently in error to account for these differences. If the solar data is reliable, a real difference in composition exists between the sun and the meteorites.

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 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 24 ppm of germanium or an atomic abundance of 50.5 instead of Goldschmidt's 188 for this quantity. There is considerable reason to believe that the germanium as well as the 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 Noddacks' (1934) values are much too high.

Our copper, gallium, and arsenic abundances taken from excellent and recent analytical data lie on a smooth curve. The astronomical value for copper is higher and that for gallium, lower than these data indicate.

As mentioned previously, no fractionation of elements less volatile than mercury has occurred by evaporation during the formation of the meteorites. Copper and gallium form very nonvolatile compounds while all compounds of arsenic are fairly volatile. Yet these three elements lie exactly on a smooth curve. Zinc is fairly volatile also. Our value is interpolated but it does *not* deviate much from the approximate analytical data on meteorites.

Pinson, Ahrens, and Frank (1953) have recently determined strontium in meteorites by improved techniques and report an average of 11 ppm. Schumacher, using an isotopic dilution technique secured 12 ppm in the Forest City chondrite. Our curves would look better to us, if strontium were somewhat higher but the data do not seem to justify such an assumption.

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 maximum at bromine and a minimum before the magic number nuclides at N equal to 50. We believe the minimum is real and similar to that preceding the magic number nuclides at N equal to 82. We also believe that the minimum at germanium is real and that the curves in this region preceding $N=50$ are similar to the curves in the region preceding N equal to 82.

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, namely 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 and Noddack (1930) and (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 0.89 as compared to the Noddack's value of 1.86 for the chondritic meteorites. Better analytical data for this element are 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 of tin. 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, 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. Recently, Sandell (private communication) has found that the mean concentration of tin in chondrites is 1 ppm equivalent to an abundance of 1.33. This has been used as a fixed value in constructing the curve in this region.

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 0.26 if silver is to lie on our odd mass curve. Mr. Joensuu advises us that many analytical data on small amounts of silver are 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. If we neglect the troilite phase of the iron meteorites and weight the troilite phase of the silicates as 0.05, the Noddacks' data approximate our adopted value for silver.

The older data on indium indicate 0.15 to 0.20 ppm in meteorites, but recently Shaw (1952b) has been unable to detect indium in two chondrites and one achondrite using a sensitivity believed to be able to detect detect about 0.02 ppm. Our interpolated value of 0.11 corresponds to 0.085 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.

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

The analytical data on the first five of these elements are of little value. Undoubtedly a marked decrease in the even mass abundance curve occurs at mass 120. 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 14.5 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 3.66 is thus much lower. 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 resolve completely 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 0.80 and 0.456 fit nicely into the curve. The data on both these elements are very unsatisfactory. Von Fellenberg's data (1927) 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 0.66 ppm. Our interpolated cesium abundance is equivalent to 0.40 ppm, whereas the Noddacks [(1930) and (1934)] have given two values, 0.01 and 1.1 ppm for this quantity.

Only a few data are given by the Noddacks [(1931) and (1934)] for antimony in meteorites. We have selected a value which fits on the odd mass curve namely 0.246 and equivalent to 0.2 ppm. This is 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. Sandell (private communication) reports that his approximate analyses lie in the range of 0.05 to 0.2 ppm.

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 become available, though we expect that the general shape of our curves are likely to remain.

The Rare Earth Elements and Hafnium, Tantalum, and Tungsten

As pointed out above, the relative abundances of the 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 tentatively assumed here to give a closer approximation to the truth than the values 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 abundances of the lower and higher mass elements. Our values certainly lie within reasonable limits of error of the data.

The abundances are adjusted only slightly from Minami's values in order to secure smoother curves. Table IV compares the observed and selected values both normalized to lanthanum as unity. 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 ~1/110 that of zirconium, as discussed above. Rankama [(1944) and (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 0.065 by interpolation. We have

TABLE IV.

	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	0.332	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				

discussed this with Dr. Rankama, who agrees that the lower value is probable.

It seems certain that the earlier analytical data on tungsten are much too high according to Sandell (1946) and Landergren (1948). Results of the Noddacks [(1930) and (1931)] and of 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 Noddacks on meteorites are also in error, and that there is no analytical datum for tungsten in meteorites. We have interpolated a value of 0.49 corresponding to 0.59 ppm. This interpolated value is about one-third of Sandell's value for igneous rocks.

Rhenium, Osmium, Iridium, Platinum, and 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 data (1951) 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 0.140 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 the mercury abundance as 0.284. It may well be higher or lower since our estimates for the higher mass nuclides are very uncertain and also because we have no even approximate theory for the trend of the abundance curve.

The Noddacks (1934) give 0.108 as the atomic abundance of thallium or 0.15 ppm in chondrites. Shaw (1952a) was unable to detect its presence in two chondrites and one achondrite and reports <0.01 ppm. Shaw's extensive studies establish the mean abundance in igneous rocks as 1.3 ppm. We shall adopt the Noddacks' datum, but cannot explain Shaw's observation unless the large amount of iron in meteorites interfered with his analysis.

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, Tilton, and Inghram (1953) does not increase our knowledge of the natural lead abundance.

Patterson *et al.* (1953) have determined the amounts and isotopic composition of lead from the metal phase of the Canyon Diablo and from the troilite phase of the Henbury and Canyon Diablo meteorites. These leads contain the least amounts of the radiogenic leads of any known sample of elemental lead. They have assumed that this is primeval lead. Patterson *et al.* [(1953) and (1955)], Tilton *et al.* (1954), and Patterson (1955) have isolated lead from terrestrial basalts, the Forest City and Modoc chondrites and the achondrite Nuevo

Table V.

					Required	
	Pb ppm	$\frac{Pb^{206}}{Pb^{204}}$	$\frac{Pb^{207}}{Pb^{204}}$	$\frac{Pb^{208}}{Pb^{204}}$	U^{238} ppm	Th^{232} ppm
(1) Canyon Diablo (Troilite)	18	9.41	10.27	29.16		
(2) Henbury (Troilite)	5	9.50	10.30	29.26		
(3) Av. Irons		9.455	10.285	29.21		
(4) Forest City	0.4	19.27	15.95	39.05		
(5) Modoc	0.9	19.48	15.76	38.21		
(6) Av. chondrites	0.65	19.375	15.855	38.63	0.0995	0.366
(7) Radiogenic lead (6)–(3)		9.920	5.570	9.42		
(8) Nuevo Laredo	0.7	50.28	34.86	67.97	0.214	0.817
Radiogenic (8)–(3)		40.825	24.575	38.76		

Laredo. Subtracting the amounts of Pb^{206}, Pb^{207}, and Pb^{208} relative to Pb^{204} taken as unity, in the iron meteorites from the amounts of these isotopes in basalts and stone meteorites they secure the amounts of these isotopes which presumably are the products of radioactive decay of U^{238}, U^{235} and Th^{232}. Without knowing the amounts of uranium and thorium, the age can be calculated from the ratio of Pb^{206} to Pb^{207}. The age so calculated is $\sim 4.5\times 10^9$ years. The calculation rests upon the assumptions that the stone meteorites initially contained lead of the composition of the lead from the iron meteorites, that no chemical processing has occurred since and that the stones contain the required amounts of uranium and thorium to produce the radiogenic leads as observed. This age is confirmed by Wasserburg and Hayden (1955) using the $K^{40}-A^{40}$ method on three chondrites. This dating method depends on the composition of each meteorite only and is the time since argon gas was lost from the meteorite. Schumacher (1956) has confirmed the age approximately using the $Rb^{87}-Sr^{87}$ method. All three methods have been used on the Forest City meteorite.

Table V summarizes data on these abundances of lead and its isotopes and the U^{238} and Th^{232} which must now be present in the meteorites in order to have produced the required radiogenic lead.

The amounts of uranium and thorium required in the chondrites is closely the same as that found by Chackett, Golden, Mercer, Paneth, and Reasbeck (1950) in the Beddgelert chondrite, namely 0.106 and 0.335 ppm for uranium and thorium respectively. However, Davis (1950), de Jager (1953), and Patterson *et al.* (1955) have reported much smaller amounts namely, 0.01 to 0.03 ppm of uranium. Urey (1955) has shown that the large amounts of uranium and thorium given by Chackett *et al.* together with the observed amounts of potassium in meteorites led to great difficulties in understanding the heat balance of the earth, the moon and Mars providing the amounts of these elements in the planets and meteorites are the same. We do not accept Urey's sugsuggested abundances, but the serious difficulties encountered in these problems are real. If the smaller abundances of uranium and thorium are correct, then we must assume two primordial leads, i.e., those of the irons and Nuevo Laredo, since the chondritic leads could be a mixture of these two in the proportions of 3 to 1.

We have not been able to resolve this problem. Since throughout this paper, the abundances of elements in chondritic meteorites have been used and found generally to be acceptable, we shall use the mean of the data on Forest City and Modoc for the lead abundances.

The Noddacks give 0.144 for the atomic abundance of bismuth and we adopt this value.

The data discussed above indicate that the abundance of uranium is between 0.01 and 0.1 ppm in the meteorites, i.e., its atomic abundance is between 0.0063 and 0.063. The same uncertainty exists in the case of thorium, but its abundance is about 3 or 3.5 times that of uranium.

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), (1951), and (1953)] on the theory of the origin and relative abundance distribution of the elements. 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 Fig. 1 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 Fig. 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 stables isobars exist, the one with the smaller neutron excess has the higher nuclear abundance in the light mass region.

At higher mass numbers the curves for the sum of the isobaric abundances become 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, buildup," 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 abundance with mass number has to be expected from any theory in which very high temperatures ($kT>1$ 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 $A>70$ 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, that 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 cannot have occurred by two subsequent β^- decays from a thermally excited level. One can show this by considering the isobaric pair $\mathrm{In}^{115}-\mathrm{Sn}^{115}$ for which the following information is available: Ratio of abundance $\mathrm{In}^{115}/\mathrm{Sn}^{115}=23$. Excited level in In^{115}: $0.335\ \mathrm{Mev}=E^*$. 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 $N^*=(g^*/g)N\exp(-E^*/kT)$. From the above experimental data one finds that natural indium cannot have been at a temperature T for more than

$$1\times e^{0.335/kT}\ \text{hours},$$

with kT expressed in Mev.

This means that the In^{115} in nature cannot have been subject to a higher temperature then about $0.3\ \mathrm{Mev}=kT$ for more than a few hours, 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 buildup 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 rule.

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 favored 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) and (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:

$$2, 8, 20, 28, 50, 82, 126\cdots.$$

They belong to two different arithmetical series:

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

The first series is significant at lower mass numbers, whereas 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 buildup 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 buildup 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 preceding the N equal to 82 and 126 shell closures.

In the corresponding region preceding the shell closure at N equal to 50 there are indications of a similar pattern are found, though it cannot be regarded as so certainly established as that preceding N equal to 82 and 126. 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 abundance 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 unmistakable way be attributed to proton shell closures.

The $70 < A < 90$ Mass Region

From what was said in the preceding 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 buildup") 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 Fig. 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[||] and, hence, that the nuclei of this mass region had formed on the neutron deficient side of the energy valley. 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 $(=2N-A)$ 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.[¶] 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 Abundance 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 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 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

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

[¶] See Blatt and Weisskopf, *Theoretical Nuclear Physics*, p. 241 ff. Theoretically the "symmetry" energy leads to two parabolas crossing at $N=Z$.

adundances, 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 cannot 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 hoped that the points mentioned here will eventually lead to improvements of the theoretical basis and of the cosmologic model which in turn will facilitate an interpretation of empirical features in the distribution of cosmic nuclear abundance.

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