ABUNDANCES OF THE ELEMENTS IN THE SOLAR SYSTEM*

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Abstract. The present status of abundance information for elements in meteorites and in the Sun is reviewed, and a new table of abundances of the elements, which should be characteristic of the primitive solar nebula, is compiled and presented. Special attention is called to the elemental abundances in the silicon-to-calcium region, where many of the abundances are rather poorly determined, and where these abundances have an impact on theories of nucleosynthesis of the elements. To each elemental isotope is assigned a mechanism of nucleosynthesis which may have been responsible for production of most of that isotope, and brief comments are made concerning the present status of understanding of the different mechanisms of nucleosynthesis.

1. Introduction

Knowledge of the relative abundances of the elements in the primitive solar nebula, from which the solar system developed, is of considerable interest both in theoretical studies of cosmochemistry and for the development of theories of nucleosynthesis of the elements in stars. In the field of cosmochemistry, these abundances determine the mineral phases which will condense from the primitive solar nebula under different conditions of temperature and density, so that by examining the bulk compositions and individual mineral phases of planetary and smaller bodies in the solar system, much can be deduced about the conditions in the original primitive solar nebula. As our knowledge of the abundances improves, more stringent boundary conditions can be placed on the mechanisms of nucleosynthesis which produced these elements in stars, particularly in short-lived phases such as supernova explosions, thus allowing better tests of theoretical astrophysical calculations in this field.

Most stars have elemental compositions which are very similar to that of the Sun. Indeed, it was not recognized until about 20 yr ago that there were significant abundance differences between different types of stars. Before that time, it was generally believed that the abundances of the elements were essentially uniform throughout the universe, and that the planetary bodies in the solar system simply represented the non-volatile fraction of that universal abundance distribution. This general distribution was sometimes called a universal or 'cosmic' abundance distribution of the elements. The term 'cosmic' was first used by Noddack and Noddack (1930), and has frequently been used since then. However, since it is now realized that there are not only sometimes strikingly large abundance differences between different stars, but that the general abundance distribution has evolved with time during the evolution of our Galaxy, we shall refer in this paper simply to solar system abundances, and all abundance data used in compiling the abundance tables presented herein are derived from solar system sources.

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The modern approach to compilation of abundance tables started with Suess (1947, 1949), who noted the smooth variation of abundances of nuclides throughout the region of the rare earths, particularly the nuclides of odd mass number, and who proposed that such regularities must be a general feature of the abundance table, so that considerations of nuclear regularities could be used to select from among various uncertain abundance determinations. This principle was utilized by Suess and Urey (1956) to compile an abundance table based largely upon abundances in ordinary chondritic meteorites. This paper was of central importance in the development of theories of nucleosynthesis in stars (Burbidge *et al.*, 1957; Cameron 1957) in that it provided a firm basis for the classification of element production by different mechanisms of nucleosynthesis. Urey has subsequently discussed the abundances of the elements in a number of publications, and attention is drawn in particular to Urey (1964, 1972).

Meteorites provide abundance data only for nonvolatile elements. For the more volatile elements, the only source of data which can be used arises from spectroscopic analyses of the solar spectrum. Important reviews of the evidence concerning the abundances of the elements in the Sun have been provided by Aller (1961, 1965), and among more recent compilations of solar abundance data may be mentioned those of Hauge and Engvold (1970) and Withbroe (1971). The latter abundance compilation has been used extensively in the preparation of this report.

The present writer has prepared several compilations of the abundances of the elements during the last two decades. The first of these (Cameron, 1959) was an attempt to invert the procedure used by Suess and Urey in their compilation; it was pointed out that several abundances in the Suess-Urey table appeared to be inconsistent with the processes of nucleosynthesis as understanding of them had, by then, emerged. The more significant modifications which were made to the Suess-Urey abundance table were the use of meteoritic data rather than terrestrial data for determining the relative abundances of the rare earths, and the choice of a large abundance for lead. These revisions were subsequently verified when better meteoritic data became available. The abundance table was later revised by giving greater emphasis to abundances of elements measured in Type-I carbonaceous chondrites (C1 meteorites) (Cameron, 1963). This table appeared only in a set of mimeographed lecture notes, but abundances given in it were frequently quoted in the literature, and hence these abundance figures were again given in a later compilation (Cameron, 1968) in which still greater reliance was placed upon newly-measured abundances in C1 meteorites. The present paper continues this trend; a complete re-evaluation of elemental abundance data in C1 meteorites has been used in the table given herein; this evaluation has drawn very heavily upon the abundance data evaluated in different chapters contained in Mason's *Handbook of Elemental Abundances in Meteorites* (Mason, 1971).

There has been considerable discussion concerning the choice of C1 meteorites as a standard for abundances of the non-volatile elements. Elements of intermediate volatility are systematically depleted in going from C1 to C3 meteorites; the average depletion factor in C2 meteorites relative to C1 meteorites is 0.55, whereas for C3 meteorites the depletion factor is approximately 0.33. This runs parallel to the trend in the chondrule component of these meteorites; C1 meteorites are essentially free of chondrules with the chondrule content increasing with increasing number of the classification. This led Larimer and Anders (1967) to suggest that original unequilibrated chondrules in meteorites contain only the highly nonvolatile elements, whereas the intervening matrix material contains elements of intermediate volatility as well. On this basis the C1 meteorites should be the best available samples of both highly nonvolatile and intermediate volatile elements, since they essentially consist just of matrix material. To argue that one of the other classes of meteorites, such as C2 meteorites, is the best representative sample of nonvolatile elements in the solar system would require the postulate that the elements of intermediate volatility had been uniformly enriched in C1 meteorites. This view has its proponents (Schmitt *et al.*, 1966; Goles, 1969). Anders (1971) discussed five lines of evidence bearing on the choice of the meteorite class to be chosen for abundance data, and came to a strong conclusion that C1 meteorites should be chosen for this purpose. In a later section of this paper an additional line of evidence, involving the element sulfur, is presented which also is strongly indicative that C1 meteorites should be chosen. Urey (1972) has also examined this question, and expressed a weak preference for the C1 meteorites.

2. The Abundance Tables

Table I gives the abundances of the elements in the solar system as given by Suess and Urey (1956), by Cameron (1968), and as obtained in the current study. The manner in which each abundance number has been selected is indicated in the Notes to Table I. The general rule has been to take the abundances of elements in C1 meteorites, providing suitable data are available, and providing there is no reason to believe that there is significant depletion of the element in C1 meteorites because of its volatility. The volatile elements must be assigned abundance values from solar and solar cosmic ray data.

The *Handbook of Elemental Abundances in Meteorites* (Mason, 1971) has been of immense value to the writer in the revision of the abundance table. Most of the elements are individually treated in separate chapters in this book, and most of the authors have made their own assessments of the average abundances of the elements relative to silicon in the C1 meteorites, as well as in other meteorite classes. It has been conventional in tables of the abundances of the elements, starting with the Suess-Urey table, to list abundances relative to silicon $= 10^6$ taken as a normalizing standard. This convention has been retained here. Other valuable sources for abundance data in C1 meteorites, which have been utilized, are Krähenbühl *et al.* (1972), and Schmitt *et al.*, (1972). Attention should also be drawn to the recent paper by Case *et al.* (1973), which came to the attention of the author too late to be included in the averaging process utilized in construction of Table I. The abundance values given in this latter paper are generally consistent with those adopted in Table I, but there are some differences, and these values should be utilized in future averages used in revising the abundance table.

TABLE I

Compilations of abundances normalized to $\mathrm{Si} = 10^6$
(Notes refer to sources used for the present compilation)

Element	Suess Urey	Cameron (1968)	This Work	Notes
1 H	4.00×10^{10}	2.6×10^{10}	3.18×10^{10}	1
2 He	3.08×10^{9}	2.1×10^{9}	2.21×10^{9}	2
3 Li	100	45	49.5	3
4 Be	20	0.69	0.81	25
5 B	24	6.2	350	25
6 C	3.5×10^{6}	1.35×10^{7}	1.18×10^{7}	1, 4
7 N	6.6×10^{6}	2.44×10^{6}	3.74×10^{6}	1, 4
8 O	2.15×10^{7}	2.36×10^{7}	2.15×10^{7}	1, 4
9 F	1600	3630	2450	3
10 Ne	8.6×10^{6}	2.36×10^{6}	3.44×10^{6}	2
11 Na	4.38×10^{4}	6.32×10^{4}	6.0×10^{4}	3
12 Mg	9.12×10^{5}	1.050×10^{6}	1.061×10^{6}	3
13 Al	9.48×10^{4}	8.51×10^{4}	8.5×10^{4}	3
14 Si	1.00×10^{6}	1.00×10^{6}	1.00×10^{6}	3
15 P	1.00×10^{4}	1.27×10^{4}	9600	3
16 S	3.75×10^{5}	5.06×10^{5}	5.0×10^{5}	3, 5
17 Cl	8850	1970	5700	3, 5
18 Ar	1.4×10^{5}	2.28×10^{5}	1.172×10^{5}	5
19 K	3160	3240	4200	3, 5
20 Ca	4.90×10^{4}	7.36×10^{4}	7.21×10^{4}	3
21 Sc	28	33	35	6
22 Ti	2240	2300	2775	7
23 V	220	900	262	7
24 Cr	7800	1.24×10^{4}	1.27×10^{4}	3
25 Mn	6850	8800	9300	23
26 Fe	6.00×10^{5}	8.90×10^{5}	8.3×10^{5}	23
27 Co	1800	2300	2210	23
28 Ni	2.74×10^{4}	4.57×10^{4}	4.80×10^{4}	3
29 Cu	212	919	540	3
30 Zn	486	1500	1244	18
31 Ga	11.4	45.5	48	3
32 Ge	50.4	126	115	18
33 As	4.0	7.2	6.6	3
34 Se	67.6	70.1	67.2	18, 24
35 Br	13.4	20.6	13.5	24
36 Kr	51.3	64.4	46.8	8
37 Rb	6.5	5.95	5.88	9, 18
38 Sr	18.9	58.4	26.9	3, 10
39 Y	8.9	4.6	4.8	3
40 Zr	54.5	30	28	3
41 Nb	1.00	1.15	1.4	11
42 Mo	2.42	2.52	4.0	3
44 Ru	1.49	1.6	1.9	3
45 Rh	0.214	0.33	0.4	12
46 Pd	0.675	1.5	1.3	3
47 Ag	0.26	0.5	0.45	18
48 Cd	0.89	2.12	1.48	18
49 In	0.11	0.217	0.189	18
50 Sn	1.33	4.22	3.6	3

Table I (Continued)

Element	Suess Urey	Cameron (1968)	This Work	Notes
51 Sb	0.246	0.381	0.316	18
52 Te	4.67	6.76	6.42	18
53 I	0.80	1.41	1.09	3
54 Xe	4.0	7.10	5.38	13
55 Cs	0.456	0.367	0.387	18
56 Ba	3.66	4.7	4.8	3
57 La	2.00	0.36	0.445	14
58 Ce	2.26	1.17	1.18	14
59 Pr	0.40	0.17	0.149	14
60 Nd	1.44	0.77	0.78	14
62 Sm	0.664	0.23	0.226	14
63 Eu	0.187	0.091	0.085	14
64 Gd	0.684	0.34	0.297	14
65 Tb	0.0956	0.052	0.055	14
66 Dy	0.556	0.36	0.36	14
67 Ho	0.118	0.090	0.079	14
68 Er	0.316	0.22	0.225	14
69 Tm	0.0318	0.035	0.034	14
70 Yb	0.220	0.21	0.216	14
71 Lu	0.050	0.035	0.036	14
72 Hf	0.438	0.16	0.21	22
73 Ta	0.065	0.022	0.021	15
74 W	0.49	0.16	0.16	16
75 Re	0.135	0.055	0.053	17, 18
76 Os	1.00	0.71	0.75	6
77 Ir	0.821	0.43	0.717	18
78 Pt	1.625	1.13	1.4	6
79 Au	0.145	0.20	0.202	18
80 Hg	0.284	0.75	0.4	19
81 Tl	0.108	0.182	0.192	18
82 Pb	0.47	2.90	4	3
83 Bi	0.144	0.164	0.143	18
90 Th	-	0.034	0.058	6, 20
92 U	-	0.0234	0.0262	18, 21

Notes to Table I

1. Normalized to abundances in type-I carbonaceous chondrites by multiplying the solar abundance scale, $H = 10^{12}$, by 0.03175, which is an average of the ratios of the solar scale and meteoritic scale ($Si = 10^6$) for the elements Mg, Al, Si, P, S, Ca, Fe, and Ni.
2. Based upon solar flare cosmic rays (Bertsch *et al.*, 1972), for which $He/O = 103 \pm 10$ and $Ne/O = 0.16 \pm 0.03$.
3. Type-I carbonaceous chondrites (Mason, 1971).
4. Solar photospheric composition adopted by Withbroe (1971).
5. Choice of abundance influenced by semi-equilibrium interpolation between ^{28}Si and ^{40}Ca. See text.
6. Weighted mean of carbonaceous chondrites (Mason, 1971).
7. Weighted mean of type-I and -II carbonaceous chondrites (Mason, 1971).
8. Average of the geometric interpolations of ^{84}Kr between ^{80}Se and ^{88}Sr and of ^{83}Kr between ^{81}Br and ^{85}Rb.
9. Present abundance 5.77. Adopted value includes correction for ^{87}Rb decay since solar system formation.

10. Present abundance 27. Adopted value allows for growth of ^{87}Sr since solar system formation.
11. Very little meteorite data: 0.3 in L6, 1.6 in LL6 chondrites (Mason, 1971). Value is an interpolation between ^{91}Zr and ^{95}Mo.
12. Very little meteorite data: 0.4 in H5, 0.31 in L6, 0.70 in LL6, and 0.36 in E4 chondrites (Mason, 1971).
13. Fitted to Te and I to form a continuous abundance peak with the same odd-even abundance ratios centered at mass numbers 127 and 129. Carbonaceous chondrite isotope ratios used.
14. There is little variation in rare earth abundances among meteorite classes, but type-I carbonaceous chondrite measurements are not as good as those in ordinary chondrites. Hence the latter values were chosen (Mason, 1971) but multiplied by 1.20 to normalize to Orgueil and Ivuna type-I carbonaceous chondrites (Urey, 1964).
15. No data on C1 meteorites. Value chosen is average of H-group meteorites (Mason, 1971) and is possibly low.
16. Average of C2 and C3 meteorites (Mason, 1971) omitting higher values of Rieder and Wanke (1968).
17. Present value 0.050 has been corrected for decay of ^{187}Re since formation of solar system.
18. Measurements in C1 chondrites (Krahenbuhl *et al.*, 1973).
19. Mercury has enormous variations in meteorites, and the carbonaceous chondrite values are one to two orders of magnitude too high for nuclear systematics. The value chosen is a representative value for enstatites (Mason, 1971). See text.
20. Present value 0.046, corrected for decay since formation of solar system.
21. Present value 0.0098, corrected for decay since formation of solar system.
22. The C1 values of Ehmann and Rebagay (1970) are surprisingly high, since there is no indication that there should be fractionation of Zr or Hf among carbonaceous chondrites. The adopted value was obtained by dividing the C1 Zr abundance of Ehmann and Rebagay by the average chondritic Zr/Hf ratio.
23. Average C1 values of Schmitt *et al.* (1972).
24. Average C1 value of Goles *et al.* (1967).
25. See Cameron *et al.* (1973).

The current status of information concerning photospheric and coronal abundances of the elements in the Sun has been reviewed by Withbroe (1971). Withbroe made a selection of photospheric abundances from the literature which he considered more reliable, and published a table of solar abundances based upon these. Only the major volatile elements of low atomic number are needed for the purposes of Table I, but the remaining parts of Withbroe's table have been utilized in two ways. The first way is to establish a normalizing factor between the solar and meteoritic abundance scales. Solar abundances are traditionally given relative to hydrogen, which is taken to be 10^{12}. The eight elements listed in footnote (1) to Table I were used to normalize Withbroe's table of solar abundances to the C1 meteorite scale of abundances in which silicon $= 10^6$. This produced the factor 0.03175 by which the solar abundance scale should be multiplied to obtain the meteoritic abundance scale. After this work was relatively far along, receipt of the reprint of the paper by Schmitt *et al.* (1972) led to a slightly lower adopted value for the C1 abundance of iron, but the conversion factor was not modified since it should be regarded as accurate only to two significant figures.

All abundances listed in this paper are by relative numbers of atoms, except where parts per million by weight are mentioned.

The second way in which Withbroe's solar abundances have been utilized is for comparison with the abundances of nonvolatile elements in C1 meteorites. This comparison is shown graphically in Figure 1, in which are plotted the solar-to-C1 meteoritic abundance ratios. The elements used for normalizing the abundance scales are shown as dark circles in this figure, and remaining elements are plotted as crosses.

Figure 1 appears to present essentially a random scatter diagram. Most solar abundances are within a factor 3 of C1 meteoritic abundances, and this factor is comparable to the probable errors of most solar abundance determinations. Thus it can be said that there is a substantial systematic agreement between the abundances of nonvolatile elements in C1 meteorites and those in the solar photosphere.

Actually, in plotting Figure 1, newer values of solar abundances for four elements were substituted for those selected by Withbroe. The new values are for rubidium (Hauge, 1972a), strontium (Hauge, 1972b), silver (Ross and Aller, 1972a), and gold (Ross and Aller, 1972b). These newer values give an improved agreement for these elements with the normalized line in Figure 1.

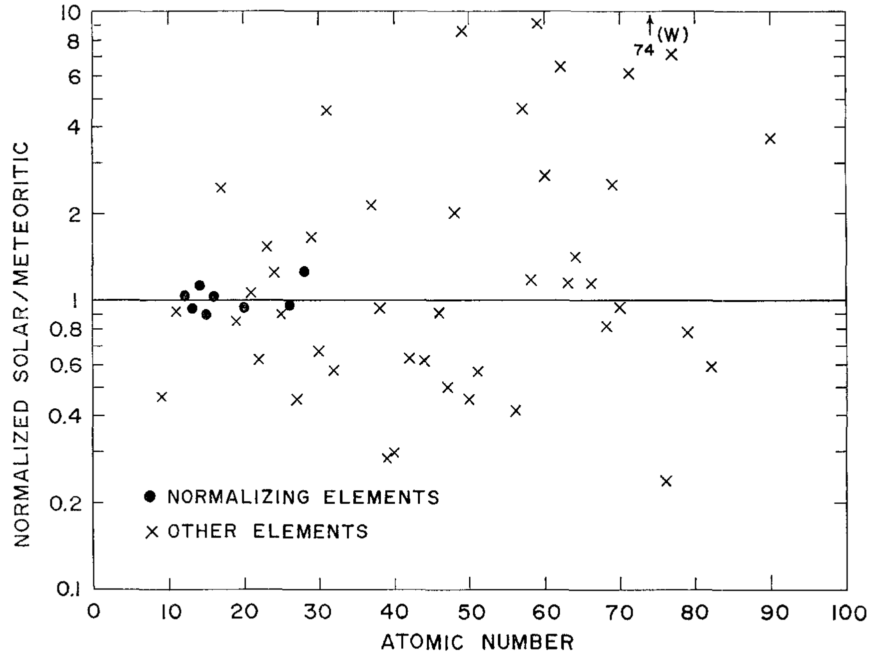

Fig. 1. Comparisons of nonvolatile elemental abundances in C1 meteorites with those measured in the solar photosphere.

There are no abundance determinations of the noble gases in the solar photosphere, and the values for the solar chromosphere are not of sufficient precision for use in this abundance table. Accordingly, it has been necessary to estimate the abundances of these elements in a variety of ways.

The abundances of helium and neon were taken from measurements of energetic cosmic rays following solar flares, averaged over many events by Bertsch *et al.* (1972). The abundances of carbon, nitrogen, oxygen, and magnesium in these solar cosmic rays run parallel to those in the solar spectrum, so that this procedure seems relatively safe. Helium and neon were thus assigned values from solar cosmic ray data in Table I normalized relative to oxygen. Above magnesium, the abundances of solar cosmic rays decline much more rapidly than those in the solar spectrum, a trend also noted by Crawford *et al.* (1972). Therefore this method would not be trustworthy for determining an abundance for argon.

Argon, krypton, and xenon were determined by interpolation relative to their neighbors using nuclear properties. The abundance determination of argon is described in the next section. The resulting ratio of ^{20}Ne to ^{36}Ar is consistent with the abundance ratio in 'solar' gases in meteorites, and in lunar fines and solar wind measurements, as summarized by Marti *et al.* (1972). These latter data have too much scatter to be used with confidence in determining an argon abundance.

The abundances of krypton and xenon were determined by fitting them to their neighboring elements in order to get a smooth variation of the appropriate nuclear isotopic abundances, as described in the footnotes to Table I. These interpellation procedures are the same as those used in Cameron (1968), and will not be described in detail here. Cameron (1968) contains several diagrams showing in detail the abundance variations of those heavy elements made by the s- and r-processes of nucleosynthesis. The general features shown in those diagrams are relatively little affected by the current revision of abundances, and hence these figures are not repeated here. Because of the scarcity of meteoritic data, it was also necessary to interpolate the abundance of niobium relative to its neighbors; this interpolation is particularly insecure and must be regarded as unreliable.

The above describes the general methods by which the abundance values given in Table I were assembled. Some additional comments on these abundances follow.

It may be noticed that the abundance given for boron in Table I is very much higher than previous values. It was noticed in the course of revising this abundance table that recent measurements of boron in carbonaceous chondrites gave values very much higher than in ordinary chondrites. A straight average of the abundances over all classes of carbonaceous chondrites would yield an abundance of 140. Cameron *et al.* (1973) have argued from a systematic examination of these abundances that the existing measurements of the boron abundance in C1 meteorites probably give too low values, and the value of 350 given in Table I is extrapolated from measurements in C2, C3, and C4 meteorites. New measurements of the boron abundance in C1 meteorites are needed because of the importance of this element in a number of cosmochemical, astrophysical, and cosmological contexts as discussed by Cameron, Colgate, and Grossman.

It may be noted that the abundances of vanadium, copper, and strontium have been significantly lowered as a result of more data for consideration.

The abundance of iridium has been significantly revised upwards, as a result of new data. This revision essentially eliminates the odd-even effect in the nuclide abundance pattern in the region of one of the r-process peaks.

Footnote (14) to Table I should be noted. The abundances of the rare earth elements are much better determined in ordinary chondrites than in C1 meteorites, so these abundances have been adopted as given by Urey (1964), but normalized to the abundance determinations in C1 meteorites.

There are enormous variations in the abundance of mercury as determined in different C1 meteorite samples, but all of the abundances determined are much higher than any possible value which would be consistent with our understanding of the s- and r-processes of nucleosynthesis. It is evident that mercury is the only element which can definitely said to be enriched in C1 meteorites, and this constitutes a long-standing puzzle. The abundance of mercury given by Cameron (1968) was the highest possible value that could be reconciled with production by the s- and r-processes. At that time the writer would have preferred to adopt a value lower by a factor 2. It so happens that such a lower value is consistent with the mercury abundance in enstatites, which often have surprisingly reliable abundances of many of the elements.

There is a high degree of chemical similarity between the elements zirconium and hafnium, and the ratio of abundances of these elements is quite constant in different classes of meteorites. The major exception to this appears to be in C1 meteorites, where zirconium has a reasonable abundance, but where the hafnium-to-zirconium ratio, as determined by Ehmann and Rebagay (1970), is surprisingly anomalous. Under these circumstances the zirconium abundance in C1 meteorites has been multiplied by an average chondritic hafnium-to-zirionium ratio to obtain the hafnium abundance given in Table I.

The resulting distribution of atomic abundances is plotted as a function of atomic number in Figure 2.

The elemental abundances of Table I have been broken down into nuclide abundances in Table II. This table also contains an assignment of particular nuclides to a process of nucleosynthesis which may have been primarily responsible for production of each nuclide. These processes are described in more detail in a later section.

In general, the numbers in Table II have been generated by simply multiplying the elemental abundance in Table I by the fractional isotopic abundance of the nuclide. In some cases modifications have been needed to this procedure, and for these cases the percent abundance in Table II is either missing or is enclosed in parentheses. In some cases the modification simply consist of allowing for the decay of a nuclide since the formation of the solar system; these cases are noted in footnotes to Table I. A discussion of the remaining cases follows.

In recent years there has been a considerable discussion of the abundance of deuterium relative to hydrogen in the primitive solar nebula. It appears that the deuterium-to-hydrogen ratio in terrestrial sea water is considerably higher than that in the primitive solar nebula, as judged by $^3He/^4He$ measurements in the solar wind and in lunar fines (Geiss and Reeves, 1972), and in the CH_3D/CH_4 ratio measured in Jupiter (Beer and Taylor, 1973). However, the most reliable determination of the deuterium-to-hydrogen ratio is that just reported by Trauger *et al.* (1973). Their ratio is 1/61000, and this value has been adopted for Table II. It was received too late to be incorporated in the figure prepared from Table II (Figure 3).

TABLE II

Abundances of nuclides

Element	*A*	% Abundance	Process	Abundance
1 H	1	~ 100		3.18×10^{10}
	2		P	5.2×10^{5}
2 He	3		H, P	$\sim 3.7 \times 10^{5}$
	4	~ 100	U, H	2.21×10^{9}
3 Li	6	7.42	X	3.67
	7	92.58	P	45.8
4 Be	9	100	X	0.81
5 B	10	19.64	P	68.7
	11	80.36	P	281.3
6 C	12	98.89	He	1.17×10^{7}
	13	1.11	N	1.31×10^{5}
7 N	14	99.634	H	3.63×10^{6}
	15	0.366	N	1.33×10^{4}
8 O	16	99.759	He	2.14×10^{7}
	17	0.0374	N	8040
	18	0.2039	N, He	4.38×10^{4}
9 F	19	100	P	2450
10 Ne	20	(88.89)	C	3.06×10^{6}
	21	(0.27)	He, N	9290
	22	(10.84)	He, N	3.73×10^{5}
11 Na	23	100	C	6.0×10^{4}
12 Mg	24	78.70	C	8.35×10^{5}
	25	10.13	C	1.07×10^{5}
	26	11.17	C	1.19×10^{5}
13 Al	27	100	C	8.5×10^{5}
14 Si	28	92.21	O, Si	9.22×10^{5}
	29	4.70	O	4.70×10^{4}
	30	3.09	O	3.09×10^{4}
15 P	31	100	O	9600
16 S	32	95.0	O, Si	4.75×10^{5}
	33	0.760	O, Si	3800
	34	4.22	O, Si	2.11×10^{4}
	36	0.0136	C, R	68
17 Cl	35	75.529	O, Si	4310
	37	24.471	O, Si	1390

Table II (Continued)

Element	*A*	% Abundance	Process	Abundance
18 Ar	36	84.2	O, Si	9.87×10^4
	38	15.8	O, Si	1.85×10^4
	40		C, R	$\sim 20?$
19 K	39	93.10	O, Si	3910
	40		O, R	5.76
	41	6.88	O, Si	289
20 Ca	40	96.97	O, Si	6.99×10^4
	42	0.64	O, Si	461
	43	0.145	C	105
	44	2.06	O, Si	1490
	46	0.0033	C, R	2.38
	48	0.185	C, R	133
21 Sc	45	100	C	35
22 Ti	46	7.93	Si, E	220
	47	7.28	C	202
	48	73.94	Si, E	2050
	49	5.51	C	153
	50	5.34	C, E	148
23 V	50	0.24	C	0.63
	51	99.76	E	261
24 Cr	50	4.31	Si, E	547
	52	83.7	Si, E	1.06×10^4
	53	9.55	Si, E	1210
	54	2.38	E	302
25 Mn	55	100	Si, E	9300
26 Fe	54	5.82	Si, E	4.83×10^4
	56	91.66	Si, E	7.61×10^5
	57	2.19	E	1.82×10^4
	58	0.33	E	2740
27 Co	59	100	E	2210
28 Ni	58	67.88	E	3.26×10^4
	60	26.23	E	1.26×10^4
	61	1.19	E	571
	62	3.66	C	1760
	64	1.08	C	518
29 Cu	63	69.09	E	373
	65	30.91	C	167
30 Zn	64	48.89	E	608
	66	27.81	E	346
	67	4.11	C	51.1
	68	18.57	C	231

Table II (Continued)

Element	*A*	% Abundance	Process	Abundance
	70	0.62	C	7.71
31 Ga	69	60.4	E	29.0
	71	39.6	C	19.0
32 Ge	70	20.52	E	23.6
	72	27.43	E	31.5
	73	7.76	C	8.92
	74	36.54	E	42.0
	76	7.76	C	8.92
33 As	75	100	S, R	6.6
34 Se	74	0.87	P	0.58
	76	9.02	S	6.06
	77	7.58	S, R	5.09
	78	23.52	S, R	15.8
	80	49.82	S, R	33.5
	82	9.19	R	6.18
35 Br	79	50.537	S, R	6.82
	81	49.463	S, R	6.68
36 Kr	78	0.354	P	0.166
	80	2.27	S, P	1.06
	82	11.56	S	5.41
	83	11.55	S, R	5.41
	84	56.90	S, R	26.6
	86	17.37	R	8.13
37 Rb	85	72.15	S, R	4.16
	87		R	1.72
38 Sr	84	0.56	P	0.151
	86	9.86	S	2.65
	87		S	1.77
	88	82.56	S, R	22.2
39 Y	89	100	S, R	4.8
40 Zr	90	51.46	S, R	14.4
	91	11.23	S, R	3.14
	92	17.11	S, R	4.79
	94	17.40	S, R	4.87
	96	2.80	R	0.784
41 Nb	93	100	S, R	1.4
42 Mo	92	15.84	P	0.634
	94	9.04	P	0.362
	95	15.72	S, R	0.629
	96	16.53	S	0.661
	97	9.46	S, R	0.378

Table II (Continued)

Element	*A*	% Abundance	Process	Abundance
	98	23.78	S, R	0.951
	100	9.63	R	0.385
44 Ru	96	5.51	P	0.105
	98	1.87	P	0.0355
	99	12.72	S, R	0.242
	100	12.62	S	0.240
	101	17.07	S, R	0.324
	102	31.61	S, R	0.601
	104	18.58	R	0.353
45 Rh	103	100	S, R	0.4
46 Pd	102	0.96	P	0.0125
	104	10.97	S	0.143
	105	22.23	S, R	0.289
	106	27.33	S, R	0.355
	108	26.71	S, R	0.347
	110	11.81	R	0.154
47 Ag	107	51.35	S, R	0.231
	109	48.65	S, R	0.219
48 Cd	106	1.215	P	0.0180
	108	0.875	P	0.0130
	110	12.39	S	0.124
	111	12.75	S, R	0.189
	112	24.07	S, R	0.356
	113	12.26	S, R	0.181
	114	28.86	S, R	0.427
	116	7.58	R	0.112
49 In	113	4.28	P, S	0.008
	115	95.72	S, R	0.181
50 Sn	112	0.96	P	0.0346
	114	0.66	P	0.0238
	115	0.35	P, S	0.0126
	116	14.30	S	0.515
	117	7.61	S, R	0.274
	118	24.03	S, R	0.865
	119	8.58	S, R	0.309
	120	32.85	S, R	1.18
	122	4.72	R	0.170
	124	5.94	R	0.214
51 Sb	121	57.25	S, R	0.181
	123	42.75	S, R	0.135
52 Te	120	0.089	P	0.0057
	122	2.46	S	0.158
	123	0.87	S	0.056
	124	4.61	S	0.296

Table II (Continued)

Element	*A*	% Abundance	Process	Abundance
	125	6.99	S, R	0.449
	126	18.71	S, R	1.20
	128	31.79	R	2.04
	130	34.48	R	2.21
51 I	127	100	S, R	1.09
54 Xe	124	(0.126)	P	0.00678
	126	(0.115)	P	0.00619
	128	(2.17)	S	0.117
	129	(27.5)	S, R	1.48
	130	(4.26)	S	0.229
	131	(21.4)	S, R	1.15
	132	(26.0)	S, R	1.40
	134	(10.17)	R	0.547
	136	(8.39)	R	0.451
55 Cs	133	100	S, R	0.387
56 Ba	130	0.101	P	0.00485
	132	0.097	P	0.00466
	134	2.42	S	0.116
	135	6.59	S, R	0.316
	136	7.81	S	0.375
	137	11.32	S, R	0.543
	138	71.66	S, R	3.44
57 La	138		P	0.00041
	139	99.911	S, R	0.445
58 Ce	136	0·193	P	0.00228
	138	0·250	P	0.00295
	140	88·48	S, R	1.04
	142	11·07	R	0.131
59 Pr	141	100	S, R	0.149
60 Nd	142	27.11	S	0.211
	143	12.17	S, R	0.0949
	144	23.85	S, R	0.186
	145	8.30	S, R	0.0647
	146	17.22	S, R	0.134
	148	5.73	R	0.0447
	150	5.62	R	0.0438
62 Sm	144	3.09	P	0.00698
	147		S, R	0.0349
	148	11.24	S	0.0254
	149	13.83	S, R	0.0313
	150	7.44	S	0.0168
	152	26.72	R	0.0604
	154	22.71	R	0.0513

Table II (Continued)

Element	*A*	% Abundance	Process	Abundance
63 Eu	151	47.82	S, R	0.0406
	153	52.18	S, R	0.0444
64 Gd	152	0.200	P	0.000594
	154	2.15	S	0.00639
	155	14.73	S, R	0.0437
	156	20.47	S, R	0.0608
	157	15.68	S, R	0.0466
	158	24.87	S, R	0.0739
	160	21.90	R	0.0650
65 Tb	159	100	S, R	0.055
66 Dy	156	0.0524	P	0.000189
	158	0.0902	P	0.000325
	160	2.294	S	0.00826
	161	18.88	S, R	0.0680
	162	25.53	S, R	0.0919
	163	24.97	S, R	0.0899
	164	28.18	S, R	0.101
67 Ho	165	100	S, R	0.079
68 Er	162	0.136	P	0.000306
	164	1.56	P, S	0.00351
	166	33.41	S, R	0.0752
	167	22.94	S, R	0.0516
	168	27.07	S, R	0.0609
	170	14.88	R	0.0335
69 Tm	169	100	S, R	0.034
70 Yb	168	0.135	P	0.000292
	170	3.03	S	0.00654
	171	14.31	S, R	0.0309
	172	21.82	S, R	0.0471
	173	16.13	S, R	0.0348
	174	31.84	S, R	0.0688
	176	12.73	R	0.0275
71 Lu	175	97.41	S, R	0.0351
	176		S	0.00108
72 Hf	174	0.18	P	0.00038
	176	5.20	S	0.0109
	177	18.50	S, R	0.0389
	178	27.14	S, R	0.0570
	179	13.75	S, R	0.0289
	180	35.24	S, R	0.0740
73 Ta	180	0.0123	P	0.00000258
	181	99.9877	S, R	0.0210

Table II (*Continued*)

Element	*A*	% Abundance	Process	Abundance
74 W	180	0.135	P	0.000216
	182	26.41	S, R	0.0422
	183	14.40	S, R	0.0230
	184	30.64	S, R	0.0490
	186	28.41	R	0.0454
75 Re	185	37.07	S, R	0.0185
	187		S, R	0.0341
76 Os	184	0.018	P	0.000135
	186	1.29	S	0.00968
	187		S	0.0088
	188	13.3	S, R	0.0998
	189	16.1	S, R	0.121
	190	26.4	S, R	0.198
	192	41.0	R	0.308
77 Ir	191	37.3	S, R	0.267
	193	62.7	S, R	0.450
78 Pt	190	0.0127	P	0.000178
	192	0.78	S	0.0109
	194	32.9	S, R	0.461
	195	33.8	S, R	0.473
	196	25.3	S, R	0.354
	198	7.21	R	0.101
79 Au	197	100	S, R	0.202
80 Hg	196	0.146	P	0.000584
	198	10.2	S	0.0408
	199	16.84	S, R	0.0674
	200	23.13	S, R	0.0925
	201	13.22	S, R	0.0529
	202	29.80	S, R	0.119
	204	6.85	R	0.0274
81 Tl	203	29.50	S, R	0.0567
	205	70.50	S, R	0.135
82 Pb	204	1.97	S	0.0788
	206	18.83	S, R	0.753
	207	20.60	S, R	0.824
	208	58.55	S, R	2.34
83 Bi	209	100	S, R	0.143
90 Th	232	100	R	0.058
92 U	235		R	0.0063
	238		R	0.0199

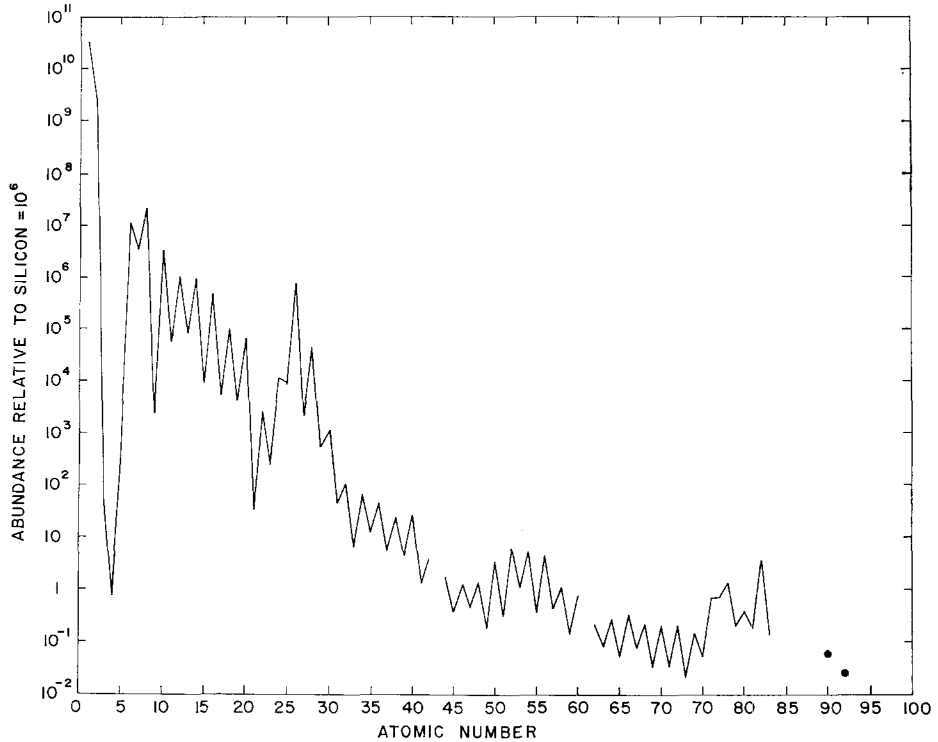

Fig. 2. Abundances of the elements in the primitive solar nebula according to the revised table in this article. Uranium and thorium are plotted as dots as of 4.6×10^9 yr ago.

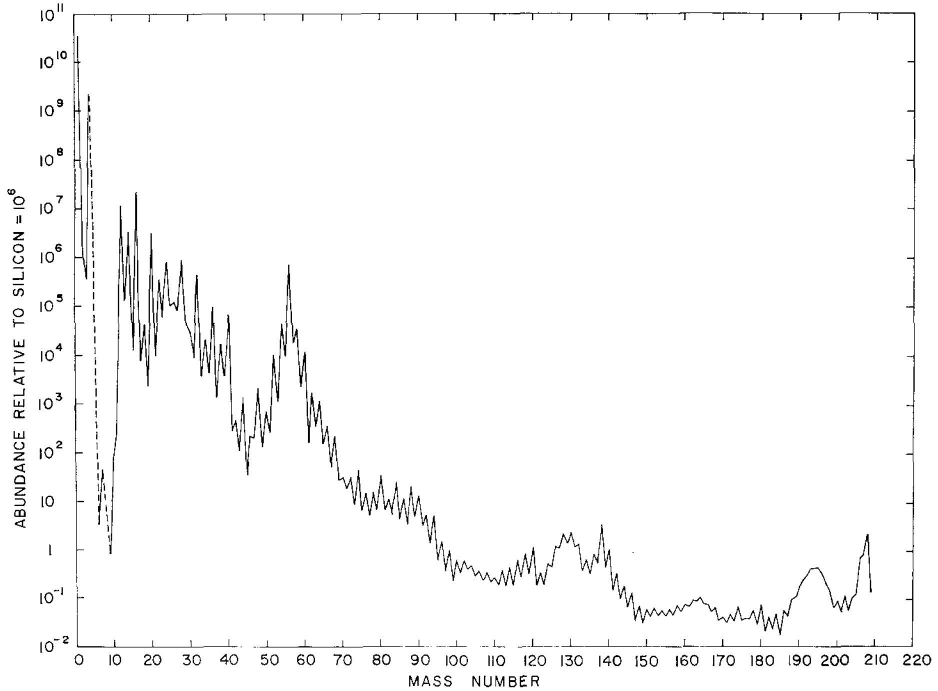

Fig. 3. Abundances of the nuclides in the primitive solar nebula corresponding to the values of Table II (except for deuterium for which an older higher estimate is plotted). Regions with a reduced odd-even abundance fluctuation represent the dominance of the r-process

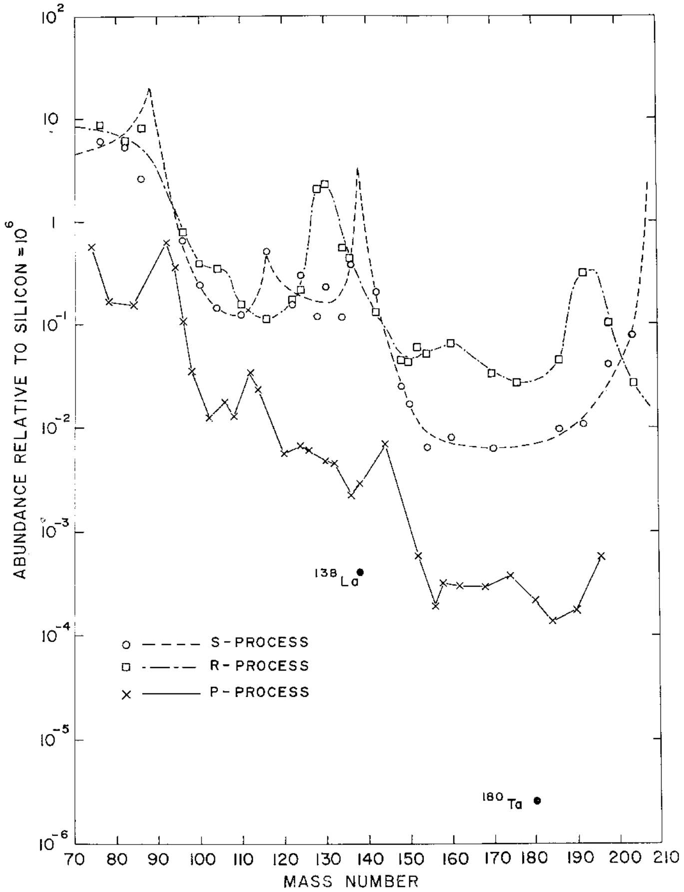

Fig. 4. Abundances of the heavy nuclides produced by the s-, r-, and p-processes. Symbols represent stable isobars predominantly produced by only one of these processes.

The abundance of ^{3}He was determined relative to helium in the sun by utilizing the helium isotope ratio characteristic of 'planetary' gases in meteorites (Mason, 1971). The difference between the ^{3}He content of the planetary and solar gas components of carbonaceous chondritic meteorites is consistent with the value of the deuterium abundance adopted in Table II (Black, 1972), indicating that the solar component of the gases represents a composition of the Sun after thermonuclear deuterium burning, but uncontaminated by the additional ^{3}He produced in the Sun since the mixing event deduced by Cameron *et al.* (1973) to have resulted in a depletion of lithium, beryllium and boron in the Sun.

The isotopic abundances of neon and xenon are not those characteristic of the terrestrial atmosphere, but rather of planetary gases extracted from meteorites (Mason, 1971). These are the values that seem to be characteristic of the primitive solar nebula.

The abundance of ^{40}Ar is a pure guess; this isotope appears to be made by a rapid neutron capture process comparable to that which produced the isotopes ^{36}S, ^{46}Ca, and ^{48}Ca. The assigned abundance is intermediate between those of the first two nuclides mentioned.

The abundance distribution of the nuclides is plotted as a function of mass number in Figure 3. Many features characteristic of the processes of nucleosynthesis can be seen in this figure, particularly the sharp s-process abundance peaks and the decrease in the odd-even abundance fluctuations where the r-process dominates.

3. The Silicon-Calcium Region

The region of elements lying between silicon and calcium is unusually interesting, because nucleosynthesis theory can make unusually quantitative predictions concerning abundances in this region, and the experimental data of many of these elements in C1 meteorites is fairly poor.

For matter which is in complete nuclear statistical equilibrium the number densities of nuclei of mass number A and charge Z are given by:

$$n(A, Z) = \omega(A, Z) \left(\frac{AMkT}{2\pi\hbar^2}\right)^{3/2} \left(\frac{2\pi\hbar^2}{MkT}\right)^{3A/2} \frac{n_\mathrm{n}^{A-Z} n_\mathrm{p}^{Z}}{2^{A}} \exp\left[Q(A, Z)/kT\right], \quad (1)$$

where $\omega(A, Z)$ is the nuclear partition function of the nucleus, M is the mass of an atomic mass unit, k is Boltzmann's constant, $\hbar$ is Planck's constant divided by 2π, T is the temperature, $Q(A, Z)$ is the total binding energy of the nucleus of mass number A and charge Z in the same units as kT, n_n is the number density of neutrons, and n_p is the number density of protons.

Under conditions of nuclear statistical equilibrium under reasonable conditions that might apply to a stellar interior, the silicon-to-calcium region would have a very small abundance compared to the iron region. However, during the course of explosive silicon burning or explosive oxygen burning, the composition of matter starts with nuclei which are very far from nuclear statistical equilibrium, and some incomplete approach to nuclear statistical equilibrium may take place. In this incomplete approach, nuclei may come into equilibrium with their immediate neighbors corresponding to approximately equal flows over forward and backward nuclear reaction links between these neighbors, for the given values of the free neutron and proton number densities. Under these conditions the number density $n(A, Z)$ of a nucleus will not be given correctly by Equation (1) relative to n_n or n_p, but the relative abundances of several such nuclei adjacent to one another in the nuclide chart will be given approximately for specified values of n_n and n_p. Thus, if matter consisting of pure ^{28}Si were heated to very high temperatures, of the order of 4×10^9 K, free neutrons and protons would be created by photodisintegration reactions, and the capture of such neutrons and protons would gradually build up the abundances of higher nuclei. Thus the abundance of calcium would steadily rise relative to that of silicon, but the abundance of the iron nuclei would rise even faster. The abundances in the silicon-calcium region thus should be approximated by these semi-equilibrium calculations if one chooses conditions in which the calcium-to-silicon ratio is properly preserved.

These conditions of frozen-out partial equilibrium were originally studied by Truran *et al.* (1966), they were very extensively examined by Bodansky *et al.* (1969), and more recently an exhaustive treatment of the subject has been given by Woosley *et al.* (1963).

Let us make a semi-equilibrium fit in the silicon-calcium region, and then utilize this to make predictions of the intervening elements. We start by noting that both silicon and calcium are very nonvolatile elements, and hence these elements have abundances which are well determined in C1 meteorites. From the ratio of ^{28}Si to ^{40}Ca we obtain from Equation (1) a relation between n_n, n_p, and T.

Sulfur is an element of intermediate volatility, and hence one should not, at this stage, rely on its abundance with any certainty. However, the relative abundances of the isotopes of sulfur are well determined, and hence from the relative abundances of ^{32}S, ^{33}S, and ^{34}S we obtain two relations between n_n and T.

From this approach one readily finds that the silicon-calcium region is characterized by a temperature $T = 3.45 \times 10^9$ K, and free particle densities $n_n = 3.5 \times \times 10^{19}$ cm^{-3} and $n_p = 2.1 \times 10^{24}$ cm^{-3}. Utilizing these numbers, the remaining nuclide abundances in the silicon-calcium region can be computed, and from these the expected elemental abundances relative to ^{28}Si.

The predicted abundances of ^{29}Si, ^{30}Si, and ^{31}P are much less than observed in C1 meteorites. However, it is known that explosive carbon burning forms larger amounts of these three nuclides in agreement with the relative abundances (Arnett, 1969; Truran and Arnett, 1970). Apart from ^{28}Si, we are therefore interested only in the region from ^{32}S to ^{40}Ca.

The abundance of ^{36}Ar given in the Tables I and II is just that interpolated in this manner between ^{28}Si and ^{40}Ca. As has already been mentioned, this abundance is in fairly good agreement with the rather scattered ratios of argon relative to neon measured in meteorites and lunar fines. The ^{36}Ar/^{38}Ar ratio predicted by the semi-equilibrium calculation is 3.36, which may be compared to an observed ratio of 5.33.

The predicted sulfur abundance is 5.38×10^5. This value may be compared with the sulfur value observed in C1 meteorites, which is 5.0×10^5 (Mason, 1971). In contrast, the observed abundances of sulfur in C2 and C3 meteorites are 2.3×10^5 and 1.2×10^5. The agreement with prediction for the abundance of this element of intermediate volatility with that in C1 meteorites, and the disagreement for C2 meteorites, can be taken as a strong additional indication that C1 meteorites should be chosen as the proper sample of nonvolatile elements in the primitive solar nebula.

For chlorine the predicted elemental abundance is 6530. There is a considerable disagreement among the measured abundances in C1 meteorites. In three determinations, Reed and Allen (1966) find an average value of 1750, and in one determination Greenland and Lovering (1965) find 1550. In contrast, Goles *et al.* (1967) find in four determinations an abundance of 5700. With this large disagreement in abundance observations, it appears more reasonable to select a part of the data rather than to average all of it, and on the basis of the semi-equilibrium prediction, the value of Goles *et al.* has been used in Table I. However, it is interesting that Woosley *et al.* (1973) find that in explosive oxygen burning, the abundances of such odd mass number nuclei as constitute the element chlorine, which have slight neutron excesses, tend to decrease significantly below the semi-equilibrium values determined in a manner similar to the present one. Therefore it is not clear that the present nucleosynthesis approach to this problem is truly definitive, and additional measurements of chlorine in C1 meteorites are clearly needed. The ratio of $^{35}Cl/^{37}Cl$ predicted by the semi-equilibrium relation is 4.10 which may be compared with the observed ratio of 3.09.

In the case of potassium, the abundance predicted from the semi-equilibrium formula is 7365. This would correspond to about 1000 ppm in C1 meteorites. There have been twenty determinations of potassium in C1 meteorites (Mason, 1971), of which none are quite as high as the predicted value, half are greater than 500 ppm, and half are less than this value but greater than 300 ppm. On the basis of the prediction, the ten higher measurements were selected from all of those given, and averaged to produce an abundance of 4200 which appears in Table I. It may be noted that this average is significantly lower than the predicted value. However, since potassium is one of the elements expected by Woosley, Arnett, and Clayton to be depleted relative to silicon and calcium in the freeze-out of the explosive oxygen-burning process, it is not clear that a straight average should not have been taken of all twenty of the measurements of potassium in C1 meteorites. The predicted ratio $^{39}K/^{41}K$ is 15.7, which may be compared with the observed ratio of 15.5. It is clear that additional attention is needed also to the potassium abundances in C1 meteorites.

Thus analysis of the silicon-calcium region has been instructive in indicating that C1 meteorites are those which should be chosen for abundance standards of non-volatile elements, but it is also clear from the relatively poor quality of the measurements in C1 meteorites of chlorine and potassium that no real choice can be given between the relative importance of explosive oxygen burning and explosive silicon burning in establishing the abundances of the elements in this range.

4. Mechanisms of Nucleosynthesis

The groundwork for the development of theories of nucleosynthesis of the elements in stars began with the publication of the Suess-Urey table of elemental abundances in 1956. The consideration that the abundances of the nuclides of odd mass number should for the most part vary smoothly played a major role in the construction of that table. This allowed some of the major nuclear processes which were responsible for the production of the elements to be identified, particularly the *s*-, *r*-, and p-processes responsible for the production of heavy elements. The nuclear physics aspects of these mechanisms could be studied essentially in isolation from detailed knowledge of stellar evolution, and rapid progress was then made in that direction. In subsequent years there has been a gradual development of the quantitative theory of stellar evolution and of supernova hydrodynamics, and many of the processes of nucleosynthesis have been fitted into astrophysical contexts via these theoretical developments. The reader may be referred to an article by Truran (1973) for a recent discussion of the mechanisms of nucleosynthesis.

In Table II an attempt has been made to assign all stable nuclides heavier than the proton to a mechanism of production. Twelve mechanisms are suggested in this connection, two of them not involving nucleosynthesis in stars. No attempt has heen made to list all of the mechanisms that may have played some role in the production of each nuclide; the attemps has been made simply to identify that process that may have produced a majority of the abundance of a nuclide, and where more than one process is listed, it is an indication that the matter is not clear. It must be emphasized that these assignments represent merely the present judgements of the writer of this article, and some of them are likely to prove to be in error. Indeed, some of these assignments were changed during the preparation of this article owing to recent developments in the theory of nucleosynthesis.

In what follows the symbols used to denote the various mechanisms of nucleosynthesis are defined. Brief descriptions are given of these processes, but no detailed references to work in these areas are given unless there have been developments subsequent to the compilation of Truran (1973).

4.1. U: COSMOLOGICAL NUCLEOSYNTHESIS

During the expansion of the universe from a hot dense state, some of the light elements may have been synthesized. The principal one of these is ^{4}He, but with a special selection of parameters, the nuclides ^{2}H, ^{3}He, and ^{7}Li might have been produced as well. It now appears more likely that the latter three nuclides were formed in supernova explosions, and there may have been mechanisms which produced the ^{4}He in a pregalactic stage of evolution of the universe involving rather massive stars.

4.2. H: HYDROGEN BURNING

The principal energy producing mechanism in stars, both on the main sequence and in the red giant branch, is hydrogen burning, involving either proton-proton chains or the CNO bi-cyle.

4.3. N: NOVA EXPLOSIONS

During nova explosions light nuclei may be exposed to high temperatures of the order of 10^8 K or more while they are surrounded by a bath of protons. Since the process takes only a short time, proton-rich lighter nuclei can be formed which can later decay to form some of the rarer nuclei not formed by ordinary hydrogen burning. This can perhaps be referred to as the hot CNO-Ne cycle.

4.4. HE: HELIUM BURNING

Following hydrogen exhaustion in a star, helium burning can take place in various thermonuclear reactions when the temperature is raised, and this may yield a variety of products. Among these products are neutrons which may be responsible for the s-process, but the only products listed with this symbol are those produced by the interaction of light nuclei with alpha particles.

4.5. C: EXPLOSIVE CARBON BURNING

Large amounts of carbon can exist in the envelopes of massive stars in advanced stages of evolution, and this carbon appears likely to undergo explosive thermonuclear ignition. The density is low enough so that the carbon is incompletely burned, but incomplete explosive carbon burning leads to a characteristic yield of nuclei in the vicinity of ^{24}Mg, and the neutron production occurring during explosive carbon burning may produce interesting yields of nuclei in the vicinity of and beyond the iron peak through capture on the more abundant of the nuclei with which the star would initially start.

4.6. O: EXPLOSIVE OXYGEN BURNING

A similar explosive ignition may occur, in massive giant stars in an advanced stage of evolution, of the oxygen in higher temperature regions where the carbon has been exhausted by previous thermonuclear burning. As pointed out by Woosley *et al.* (1973), explosive oxygen burning may be largely responsible for the production of nuclides between the vicinity of ^{28}Si and the iron peak region. Again, this occurs in regions where the density is sufficiently low so that the explosive oxygen burning does not go to completion.

4.7. Si: EXPLOSIVE SILICON BURNING

A similar explosive event which may take place on material which had received previous thermonuclear processing through carbon and oxygen burning, to leave ^{28}Si as the principal nuclear fuel. Woosley *et al.* (1973) find that it is very difficult to distinguish between the net final effects of explosive oxygen burning and explosive silicon burning. As discussed earlier in this paper, the abundance of the element chlorine may provide valuable clues to distinguish between these processes.

4.8. E: NUCLEAR STATISTICAL EQUILIBRIUM

When a nuclear detonation takes place at higher densities, it is possible that the nuclei will achieve nuclear statistical equilibrium, forming products in the vicinity of the iron equilibrium peak. The character of the nuclear freezing when the region of nuclear statistical equilibrium expands will vary depending upon the initial temperature, and the neutron-proton ratio, and this can provide a variety of abundance patterns in the vicinity of the iron equilibrium peak. The upper limit to the mass numbers of the nuclides formed under equilibrium freeze-out conditions in proton-rich environments is not yet known; it may not extend quite as far as mass 74 as is assigned in Table II.

4.9. S: THE S-PROCESS

During helium burning some neutrons can be produced using as target nuclei some neutron-rich nuclei of relatively low abundance. Various schemes have been proposed for cycling material between hydrogen-burning and helium-burning regions in order to produce more of these target nuclei, particularly ^{13}C. Attention is drawn in particular to the paper by Scalo and Ulrich (1973). The neutrons which are produced are captured by heavy seed nuclei that are present, and with a large and continuing flux of neutrons, the capture chain may result in the addition of more than 100 neutrons to a typical nucleus. The most important of the seed nuclei are those in the iron peak, and this slow neutron buildup can extend as far as the lead and bismuth nuclei.

4.10. P AND R: THE p- AND r-PROCESSES

Two other processes have been known for many years which produce heavy nuclei other than those which can be produced by the s-process. Some of these heavy nuclei are more neutron deficient than s-process products, while others are more neutron rich than s-process products, and these two classes of nuclei are those defined to be made by the p- and r-processes. The processes are not yet properly understood in terms of an astrophysical context, and possibly not even in terms of the basic nuclear reactions that ensue. The p-process has been thought to involve some combination of proton addition to heavy nuclei exposed to high temperatures in a hydrogen-rich environment, and photodisintegration of heavy nuclei exposed to high temperatures. There are some quantitative difficulties with these processes. The r-process has been thought to involve the exposure of seed nuclei to a highly neutron-rich environment, so that neutron addition causes the nuclei to follow a neutron capture and beta decay path which lies close to the neutron drip line (the line on a nuclide chart where the neutron binding energy drops to zero). However, as a result of recent work by Hoyle and Fowler (1973), Colgate (1973a, b), and Cameron *et al.* (1973), it appears that non-equilibrium nuclear reactions operating in association with supernova shock waves may provide the mechanism for the p- and r-processes. The supernova shock wave can produce for a brief interval ion temperatures of several MeV; under these circumstances energetic proton reactions such as (p, n) can produce nuclides on the proton-rich side of the valley of beta stability, and many of these may constitute the p-process nuclei. On light nuclei (p, α) reactions may become important, and in particular may produce ^{7}Li, ^{10}B, and ^{11}B. As the supernova shock wave proceeds through the supernova envelope, the ion temperature produced can steadily increase, and when this ion temperature exceeds 10 MeV, spallation of helium can take place. Under conditions where the majority of the helium is destroyed by these spallation reactions, 0.1 to 0.2 neutrons per hydrogen atom may be produced. The majority of these neutrons will ultimately be captured by the hydrogen, yielding deuterium. Some ^{3}He may also be formed at this time, but heavy nuclei may have capture cross-sections for these neutrons 3 orders of magnitude greater than those of the hydrogen atom. Hence such heavy nuclei could in principle capture of the order of 100 neutrons, particularly under conditions where the density is low enough so that the neutron capture path does not approach too close to the neutron drip line, so that neutron capture cross-sections are not too grossly reduced. Quantitative results are not yet available to test these ideas, but they appear very promising and are currently under investigation by J. W. Truran.

4.11. X: COSMIC RAY SPALLATION

It was not clear to Burbidge, Burbidge, Fowler, and Hoyle how the nuclei of low abundance lighter than ^{12}C were produced, so they termed the production of these nuclei the x-process. It has subsequently become clear that bombardment of C, N, and O nuclei in the interstellar medium by cosmic rays can produce many of these lighter nuclei (Reeves *et al.*, 1973). However, at the present time only the nuclides ^{6}Li and ^{9}Be seem to be predominantly produced by cosmic ray spallation of interstellar nuclei.

From this survey, both of the abundance situation and of the mechanisms of nucleosynthesis, it will be clear that there remain some important questions to be cleared up in both fields, and that a great deal of critical work remains to be done. Questions of the abundances of the elements form a part of the field of cosmochemistry which is a common meeting ground for the interaction of geochemists, astrophysicists, and physicists, and a better knowledge of the problems in each of these fields can influence research activities in the other fields. It is hoped that the revised tables of abundances presented in this paper will prove useful for investigations in a variety of fields.

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