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THE PERIODIC SYSTEM AND THE PROPERTIES OF THE ELEMENTS.

(FIFTH PAPER ON ATOMIC STRUCTURE.)

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The periodic system is the most important generalization of the facts embodied in the science of chemistry, and one of the most glaring errors in chemical pedagogy during the past fifteen years has been the neglect of this system, both in the so-called modern text-books and in the courses of instruction given in some of our universities. This has probably been due, in a large measure, to the unfortunate attempt which has been made by certain chemists to present chemistry without the use of the atomic theory. Recent remarkable discoveries made by physicists have, however, made it evident that the atomic theory and the periodic system are of supreme importance in both chemistry and physics.

The total number of elements in our present ordinary system from helium to uranium, inclusive, is 91, and with hydrogen this makes 92 elements in all. The system from helium to uranium seems to be completely known, though not all of the elements have been discovered, but nothing is known as to whether there are any elements which belong to the ordinary system and fall between hydrogen and helium in atomic weight (possibly with atomic weights 2 and 3). Of the 92 elements, 87 have already been discovered and 5 are still unknown. Of these 5, three belong to the seventh group, two being in group VIIB, and these may be given the provisional names eka-manganese I (atomic weight about 99), and eka-manganese II (divi-manganese) (atomic weight about 188). These elements, particularly the second, should have extremely high melting points. In group VIIA eka-iodine should have an atomic weight near 219, and in group IA eka-caesium, for which Baxter made a search, but without success, should have an atomic weight of about 225. An unknown element of the rare earth group may be called eka-neodymium (atomic weight about 146).

In addition to these 92 elements of the ordinary system, Nicholson assumes that there is another system of simpler elements such as protohydrogen, nebulium, protofluorine (coronium), arconium, and other elements, of atomic weights 0.082, 1.31, 2.1, and 2.9. Of these elements the spectra attributed to nebulium and arconium are found in the nebula and that of the hypothetical protofluorine is found in the corona of the sun. The evidence in favor of this simpler system is not very conclusive, but the existence of these spectra makes it evident either that some otherwise unknown elements exist in the nebulae and the corona of the sun or that the spectra are due to enhanced lines from some of the ordinary elements.[1] If such elements actually exist, they may belong to the ordinary system, or they may belong to another system, possibly with a simpler structure as Nicholson assumes. Nicholson's atomic weights were obtained from the width of the spectral lines, and also from the differences between the calculated and the observed values of the wave lengths. Both of these methods are very uncertain under the conditions of observation, so there is no conclusive evidence for the particular atomic weights which Nicholson gives.[2]

It has been found that the number of the element in the periodic table, beginning with hydrogen as 1, helium as 2, lithium as 3, etc.; or what is called the ATOMIC NUMBER is more characteristic of an element than its atomic weight. For example lead, with an atomic number of 82, consists of

	Atomic weight.
1. Lead from radium	206.1
2. Ordinary lead	207.20
3. Lead from thorium	208.1

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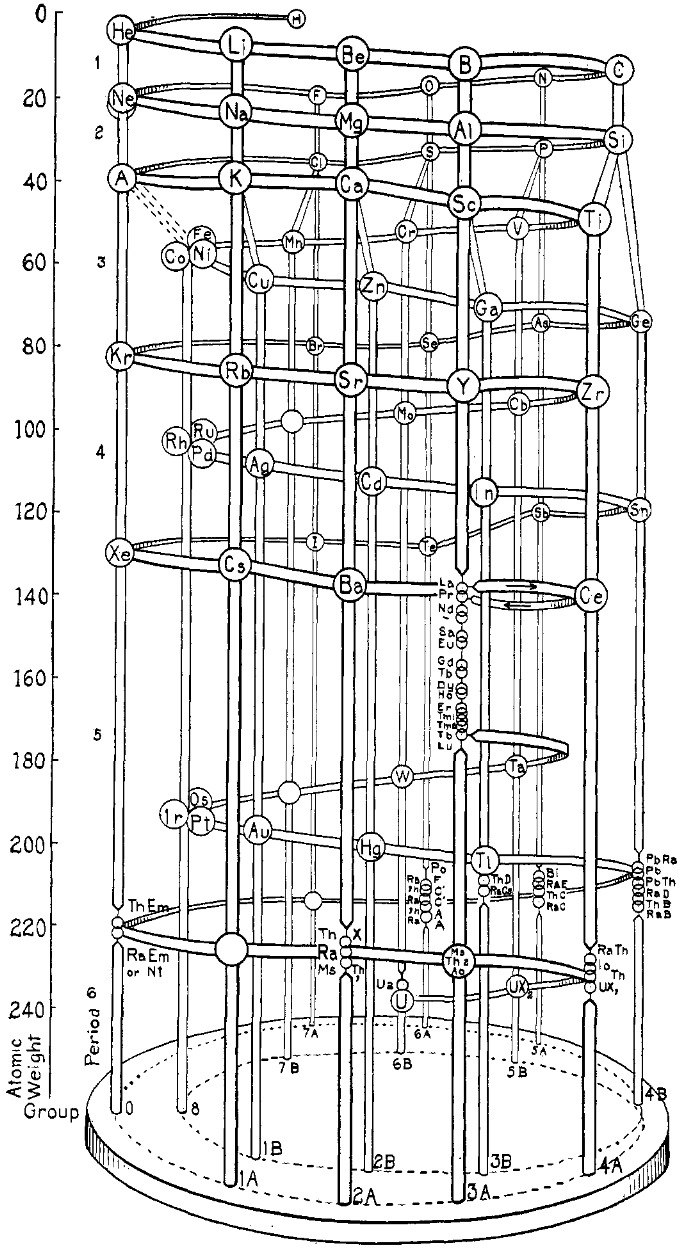
[1] Merton, *Proc. Roy. Soc.*, (*A*) 91, 498 (1915), has obtained enhanced lines by a discharge between carbon poles in a vacuum tube, previously filled with hydrogen, which have practically the same wave length, and the same nebulous character as eight of the lines obtained in the spectrum of the Wolf-Rayet stars.

[2] For a more complete description and discussion of Nicholson's work see a paper on "Recent Work on the Structure of the Atom," Harkins and Wilson, THIS JOURNAL, 37, 1396–1421 (1915).



Periodic Table by W.D. Harkins

Note, Fig. 1.—The connections between the main and the subgroups are shown better in Fig. 2 than in Fig. 1, since in Fig. 1 the connections were modified slightly by the artist to bring out the perspective.

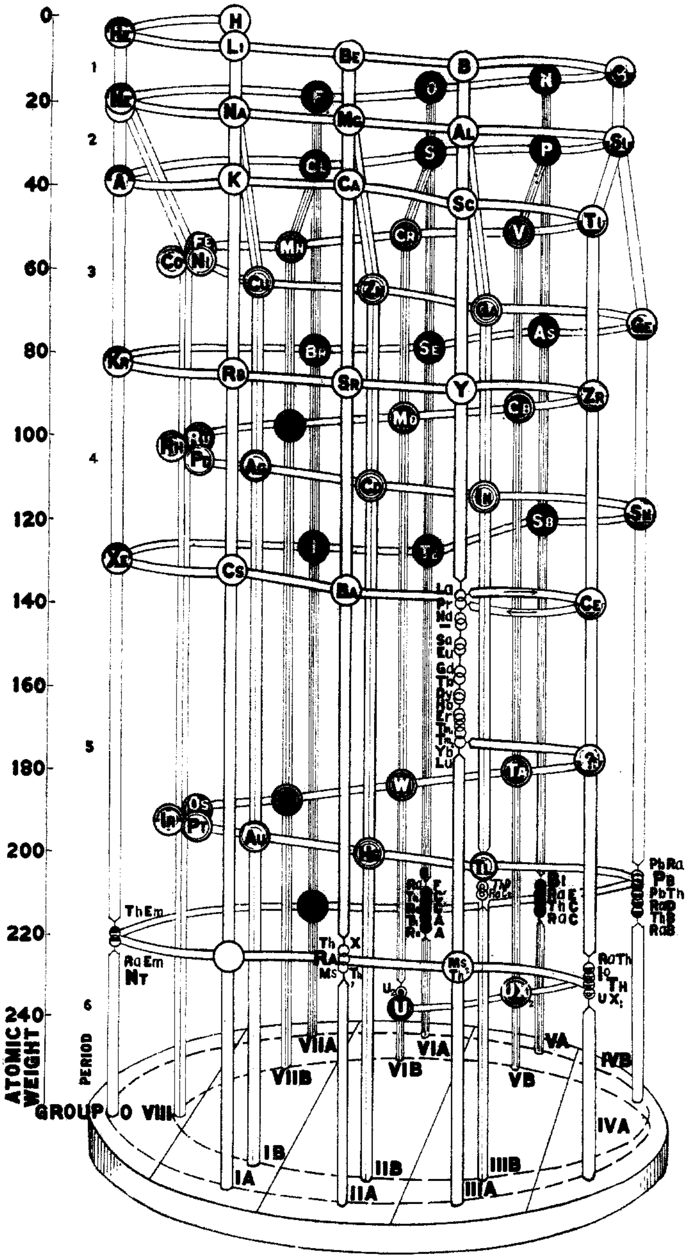

0
20
40
60
80
100
120
140
160
180
200
220
240
ATOMIC WEIGHT
PERIOD
1
2
3
4
5
6
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
A
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Cb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Pr
Nd
Sa
Eu
Gd
Tb
Dy
Ho
Er
Yb
Lu
Ce
Ta
W
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
ThEm
RaEm
Nt
Th X
Ra
Ms Th1
Ms2 Th
U2
U
UX2
RaTh
Io
Th
UX1
ThD
RaE
ThC
RaC
PbRa
PbTh
RaD
ThB
RaB
Ra A
Th A
GROUP 0
VIII
IA
IB
IIA
IIB
IIIA
IIIB
IVA
IVB
VA
VB
VIA
VIB
VIIA
VIIB

Fig. 2.

		Atomic weight.
4.	Radium D	210.1
5.	Thorium B	214.1
6.	Radium B	212.1
7.	Lead from actinium	Unknown
8.	Lead from actinium B	Unknown
9.	Product of branch chain, radium series	210.1
10.	Product of branch chain, actinium series	Unknown

Thus the same element may have very widely different atomic weights, but the atomic number, which presumably gives the number of positive charges on the nucleus of the atom, remains constant, and in the case of lead is 82.

A Periodic Table which Gives all of the Elements Plotted According to Their Atomic Weights, and Shows the Correct Relations from the Chemical Standpoint.

The periodic system of Mendeléeff classified the elements as well as was possible at the time when it was devised, and practically none of the more recent tables have made any improvement upon the original form, but the discoveries of the last few years make it possible to design a table which expresses the relations existing between the elements much more perfectly.

A modern table should meet the following requirements:

(1) It should plot the atomic weights so that the isotopes of such an element as lead may be included in it, their atomic weights shown, and so that the alpha and beta decompositions of the radioactive elements may be clearly depicted.

(2) It should give no blanks except those corresponding to atomic numbers of elements which remain to be discovered. The Mendeléeff table contains many blanks which can never be filled.

(3) It should in a natural way relate the main group elements to the elements in the corresponding sub-group. The principal defect of many of the periodic tables is that they have been constructed without any consideration of this important condition. A table which shows no relations between such a main group as the Be, Mg, Ca, Sr, Ba and Ra main group, and the corresponding sub-group, Zn, Cd, Hg, is not at all correct from the chemical standpoint. On the other hand, the form of the table itself should distinguish between the main and the sub-group elements. One of the disadvantages of the Mendeléeff table is that the table by its form makes no such distinction, since it throws the main and sub-groups together. However, the Mendeléeff form is much to be preferred to those given by Staigmüller, Werner and others, in which these chemical relations are not shown at all.

(4) Both the zero and the eighth groups should fit naturally into the system.

(5) All of the above relations should be shown by a continuous curve which should connect the elements in the order of their *atomic numbers.* In the ordinary form of table there is nothing to indicate the relation of one series to the next.

(6) As has been shown by Harkins and Wilson, the atomic weights are a linear function of the atomic numbers, and can be represented by the equation

$$W = 2(n + n') + 1/2 + 1/2(-1)^{n-1},$$

where n is the atomic number and n' is ZERO for the LIGHTER ELEMENTS. It is therefore better to plot the atomic weights themselves than to plot the logarithms as has been done.[1]

A modern table which meets these requirements and also shows other relationships not expressed by the ordinary form of table, may be constructed as a helix in space, or as a spiral on a plane. The space form is more nearly like the ordinary table, and is therefore to be preferred. A model of this space form, a photograph of which is shown in Fig. 3, has been constructed, and is in use in the work in inorganic chemistry in the University of Chicago. The atomic weights are plotted from the top down, one unit of atomic weight being represented by one centimeter, so the model is about two and one-half meters high.

Although the model gives the relations with extreme clearness, it is difficult to photograph it so that all of the details are visible. However, this is remedied in Fig. 1, which gives a drawing of the system. In order that the atomic weights may be plotted directly, the drawing has been made as a *vertical projection* of the model, but drawn with line perspective, and the base is given in perspective so that the table may be easily visualized in space.

The balls representing the elements are supposed to be strung on vertical rods. All of the elements on one vertical rod belong to one group,[2] have on the whole the same maximum valence, and are represented by the same *color.* The group numbers are given at the bottom of the rods. On the outer cylinder in Fig. 2, the electro-negative elements are represented by black circles at the back of the cylinder, and electro-positive elements by white circles on the front of the cylinder. The transition elements

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[1] Stoney, *Chem. News,* **57**, 163 (1888); and *Proc. Roy. Soc.,* **46**, 115 (1888).

[2] In Figs. 1 and 2 some of the elements are represented by small, and others by larger circles. The small circles are not meant to show any difference in the elements which they represent, but are used whenever there is not room on the diagram for the larger circles. At the bottom of the table many isotopes are represented, and each intersection of the helix with a vertical group rod represents only one element, even where there are six circles as there are for the isotopes of lead. While the six circles for lead represent only one atomic number, each of the small circles on the rare earth loop represents an atomic number of its own. The three-eighth group triads, and the rare earth group resemble each other in that in these four cases the atomic number increases while the group number remains constant.

of the zero and fourth groups are represented by circles which are half black and half white. The inner loop elements are intermediate in their properties. Elements on the back of the inner loop are shown as heavily shaded circles, while those on the front are shaded only slightly.

In order to understand the table it may be well to take an imaginary journey down the helix in Fig. 2, beginning at the top. Hydrogen (atomic number and atomic weight = 1) stands by itself, and is followed by the first inert, zero group, and zero valent element helium. Here there comes the extremely sharp break in chemical properties with the change to the strongly positive, univalent element lithium, followed by the somewhat less positive bivalent element, beryllium, and the third group element boron, with a positive valence of three, and a weaker negative valence. At the extreme right of the outer cylinder is carbon, the fourth group transition element, with a positive valence of four, and an equal negative valence, both of approximately equal strength. The first element on the back of the cylinder is more negative than positive, and has a positive valence of five, and a negative valence of three. The negative properties increase until fluorine is reached and then there is a sharp break of properties, with the change from the strongly negative, univalent element fluorine, through the zero valent transition element neon, to the strongly positive sodium. Thus in order around the outer loop the second series elements are as follows:

Group number	0	1	2	3	4	5	6	7
Maximum valence	0	1	2	3	4	5	6	7
Element	He	Li	Be	B	C	N	O	F
Atomic number	2	3	4	5	6	7	8	9

After these comes neon, which is like helium, sodium which is like lithium, etc., to chlorine, the eighth element of the second period. For the third period the journey is continued, still on the outer loop, with argon, potassium, calcium, scandium, and then begins, with titanium, to turn for the first time into the inner loop. Vanadium, chromium, and manganese, which come next, are on the inner loop, and thus belong, not to main but to sub-groups. *This is the first appearance in the system of sub-group elements.* Just beyond manganese a catastrophe of some sort seems to take place, for here three elements of one kind, and therefore belonging to one group, are deposited. The eighth group in this table takes the place on the inner loop which the rare gases of the atmosphere fill on the outer loop. The eighth group is thus a sub-group of the zero group.

After the eighth group elements, which have here appeared for the first time, come copper, zinc, and gallium; and with germanium, a fourth group element, the helix returns to the outer loop. It then passes through arsenic, selenium, and bromine, thus completing the first long period of

18 elements. Following this there comes a second long period, exactly similar, and also containing 18 elements.

The relations which exist may be shown by the following natural classification of the elements. They may be divided into cycles and periods as follows:

TABLE I.

	Cycle 1 = 4^2 elements.	
1st short period.......	He — F	= 8 = 2 × 2^2 elements.
2nd short period......	Ne — Cl	= 8 = 2 × 2^2 elements.
	Cycle 2 = 6^2 elements.	
1st long period........	A — Br	= 18 = 2 × 3^2 elements.
2nd long period.......	Kr — I	= 18 = 2 × 3^2 elements.
	Cycle 3 = 8^2 elements.	
1st very long period...	Xe — Eka - I	= 32 = 2 × 4^2 elements.
2nd very long period...	Nt — U	

The last very long period, and therefore the last cycle, is incomplete. It will be seen, however, that these remarkable relations are perfect in their regularity. These are the relations, too, which exist in the completed system,[1] and are not like many false numerical systems which have been proposed in the past where the supposed relations were due to the counting of blanks which do not correspond to atomic numbers. This peculiar relationship is undoubtedly connected with the variations in structure of these complex elements, but their meaning will not be apparent until we know more in regard to atomic structure.

The first cycle of two short periods is made up wholly of outer loop or main group elements. Each of the long periods of the second cycle is made up of main and of sub-group elements, and each period contains one-eighth group. The only complete very long period is made up of main and of sub-group elements, contains one-eighth group, and would be of the same length (18 elements) as the long periods if it were not lengthened to 32 elements by the inclusion of the rare earths.

The first long period is introduced into the system by the insertion of iron, cobalt, and nickel, in its center, and these are three elements whose atomic numbers increase by steps of one while their valence remains constant. The first very long period is formed in a similar way by the insertion of the rare earths, another set of elements whose atomic numbers increase by one while the valence remains constant.

In this periodic table the MAXIMUM valence for a group of elements may be found by beginning with ZERO for the zero group and counting

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[1] If elements of atomic weights two and three are ever discovered then the zero cycle would contain 2^2 elements, and period number one should then be said to begin with lithium. Such extrapolation, however, is an uncertain basis for the prediction of such elements.

toward the front for POSITIVE valence, and toward the back for NEGATIVE valence.

The negative valence runs along the spirals toward the back as follows:

0	—1	—2	—3	—4
Ne	F	O	N	C
A	Cl	S	P	Si

Beginning with helium the relations of the maximum theoretical valences run as follows:

Case 1. He — F..... 0, 1, 2, 3, 4, 5, 6, 7, but does not rise to 8. Drops by 7 to 0.
Ne — Cl.... 0, 1, 2, 3, 4, 5, 6, 7, but does not rise to 8. Drops by 7 to 0.
Case 2. A — Mn.... 0, 1, 2, 3, 4, 5, 6, 7, 8, 8, 8. Drops by 7 to 1.
Fe, Co, Ni.
Case 1. Cu — Br
Case 2. Kr — Ru, Rh, Pd.

In the third increase, the group number and maximum valence of the group rise to 8, three elements are formed, and the drop is again by 7 to 1.

Thus in every case when the valence drops back the drop in maximum group valence is 7, either from 7 to 0, or from 8 to 1.[1] This is another illustration of the fact that the eighth group is a sub-group of the zero group. The valence of the zero group is zero. According to Abegg the contra-valence, seemingly not active in this case, is eight.

In Fig. 2 the table is divided into FIVE DIVISIONS by four straight lines across the base. These divisions contain the following groups:

Division	0	1	2	3	4
Groups	0,8	1,7	2,6	3,5	4,4

The two groups of any division are said to be complementary. It will be seen that the sum of the group numbers in any division is equal to 8, as is also the sum of the maximum valences. The algebraic sum of the characteristic valences of two complementary groups is always zero. *In any division in which the group numbers are very different, the chemical properties of the elements of the complementary main groups are very different, but when the group numbers become the same, the chemical properties become very much alike.* Thus the greatest difference in group numbers occurs in division 8, where the difference is 8, and in the two groups there is an extreme difference in chemical properties, as there is also in division 1 between Groups 1 and 7. *Whenever the two main groups of a division are very different in properties, each of the sub-groups is quite different from*

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[1] It should be noted that while in the change from the seventh to the zero group the valence always drops to zero, in the change from the eighth to the IB group, there is a tendency to drop only part way, that is to a valence of 3 for gold (or silver), or to 2 for copper, though these elements also show the valence of one normal for the group, but by the time Group IIB is reached in zinc, cadmium, and mercury, the valence comes to the normal value. which is 2 for this group.

its related main group. Thus copper in Group IB is not very closely related to potassium group IA in its properties, and manganese is not very similar to chlorine, but *as the group numbers approach each other the main and sub-groups become much alike.* Thus scandium is quite similar to gallium in its properties, and titanium and germanium are very closely allied to silicon.

One important relation is that *on the outer cylinder the main groups IA, IIA, IIIA, become less positive as the group number increases, while on the inner loop the positive character increases from Group IB to IIB,* and at the bottom of the table the increase from IIB to IIIB is considerable. Thus thallium is much more positive than mercury. It has already been noted that in the case of the rare earths also the usual rule is inverted, that is the basic properties decrease as the atomic weight increases.

Another important relation between the members of the main and the sub-groups is that when the atomic volume of the elements in the main group is large, the atomic volume of the elements in the corresponding sub-groups is small, and as the atomic volume for the main group decreases, that for the sub-group increases. Thus, the zero group elements have very high atomic volumes, while those for the corresponding sub-groups (Group VIII) are very low. The same is true of the potassium group (high atomic volume) and the copper group (low atomic volume). On the other hand, the members of Groups IVA and IVB do not differ materially in regard to this property. The difference in chemical properties between main and sub-groups is just that which should result from their differences in atomic volume. From this standpoint it may be considered that the difference in chemical properties between the main and the sub-group elements is the result of the fact that the long periods for the cohesional properties (atomic volume, etc.) are twice the length of the series which condition the valence. In cycle 1 (short periods 1 and 2), the valence and the cohesional properties have periods of exactly the same length, so both of the periods represent main groups or outer cylinder elements, but in cycle 2 the valence passes through two periods while the cohesion (Fig. 12) is passing through one, so here sub-group elements appear for the first time. While the cohesion does not fix the valence, it does affect the chemical affinity. The increase in the basic properties of the sub-group elements as the group number increases from IB to IIIB, seems to be related to the occurrence of the secondary minimum in cohesion (and melting points) which comes in group IIIB. (See Fig. 8.)

On the first inner loop the positive character of the metal, as measured by the potential between the ions of the elements in unimolar solutions and the metal itself, decreases from manganese to copper, and then increases very rapidly in the one step to zinc, as is shown below in Table IA.

TABLE 1A.—POSITIVE CHARACTER OF THE METALS IN SOLUTIONS WITH THEIR BIVALENT IONS.

Mn = +0.798 volt
Fe = +0.122 volt
Co = —0.0138 volt
Ni = —0.108 volt
Cu = —0.606 volt
Zn = +0.493 volt

The Rare Earths.

There are some questions concerning the placing of the rare earth elements which are of minor importance, and may be settled by each user of such a table to suit his own convenience. Thus cerium, following the usual custom, has been put in the fourth group. This makes an extra small loop in the table which could be avoided by placing cerium in the third group with the other rare earths. That after passing lanthanum there is a tendency to swing into the fourth group with cerium, and then with praseodymium and neodymium to swing back into the third group, is indicated by the fact that cerium forms an extremely stable dioxide (CeO_2); praseodymium forms a dioxide less stable than manganese dioxide, which is itself not extremely stable; while neodymium is said to form a higher oxide only when mixed with cerium and praseodymium, or perhaps not at all; and samarium forms no higher oxide.

On the other hand, the position of the rare earths as a whole is very important. Their valence, the difficulty with which they are separated from yttrium, and their chemical reactions clearly indicate that they should be related to the third group, but put on a loop of their own. In many periodic tables, for example, even in the otherwise very good table given by Rydberg,[1] thulium is put in the chlorine family, samarium in the eighth group, europium in the silver group, etc. The system presented here shows that such a procedure is altogether unjustified, for there are not enough rare earths to go around the table, since there are *four less than the required number*, even when the one unknown rare earth is counted. That the number of elements in this, the fifth period, is taken correctly as 32 can be seen from the work of Moseley upon the X-ray spectra of the elements, and is indicated also by the regularity in the numerical relations between the number of elements in the different periods as already pointed out by Table I. If the rare earths are to be distributed around the table, then there should be a considerable variation in their atomic volumes. Although the atomic volumes of very few of the rare earths have been determined, the data are available for the calculation of the molecular volumes of a number of the chlorides and oxides. Thus the molecular volumes of the chlorides are as follows:

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[1] Hicks, *Phil. Mag.*, [6] **28**, 139 (1914).

$LaCl_3$	63.8
$CeCl_3$	62.9
$PrCl_3$	60.8
$NdCl_3$	60.6
$SmCl_3$	57.5
$GdCl_3$	58.3
$TbCl_3$	61.1
$DyCl_3$	73.3

In order to understand the interpretation of these molecular volumes in terms of the atomic volumes of the rare earths, their basic properties must be taken into account. The order of the rare earths in terms of their basic properties is as follows, where the most basic element is given first: Lanthanum, praseodymium, neodymium, cerium^{III}, (yttrium), samarium, gadolinium, terbium, holmium, erbium, thulium, and ytterbium. Thus, exactly the opposite of the usual rule holds, for in this rare earth group the basic properties decrease just in the order in which the atomic weights increase. Cerium is the only element which falls out of the regular order, and it is the element which in the table (Fig. 2) is classified differently from the others. If the rare earth elements were to be distributed around the table, then samarium, europium, and gadolinium would fall in the eighth group, and therefore should have minimum atomic volumes. That these are the elements of the rare earths which *do have minimum atomic volumes* is indicated by the molecular volumes of the chlorides. The increase in the molecular volume of the chlorides in the case of dysprosium chloride seems to indicate that there is a *minor peak* in the atomic volumes beyond this point. It would be interesting in this connection to know the molecular volumes of ytterbium and lutecium trichlorides, or much better of course, the atomic volumes of ytterbium and lutecium. These facts may be taken to indicate that when in the formation of the elements the 57th element, lanthanum, belonging to the third group, is passed, there is a tendency for the elements to form according to the usual rule, that is, that the valence shall increase by steps of one and the atomic volume shall vary as usual. From this point on, the tendency for the atomic volumes to hold to the regular system of variation is quite likely partly effective. On the other hand, the valence succeeds only in rising by one to four in the case of cerium, the 58th element, and then only for a few of its compounds. With praseodymium and neodymium the valence returns toward three, and for samarium and the remainder of the group the highest valence seems to be constant at three. Such relationships as these need not seem peculiar, since the valence is usually supposed to be due to only a few of the electrons in the atom, in this case to three electrons, while the atomic volumes are undoubtedly conditioned by the other electrons in the atom, external to the nucleus, as well. That the atomic volumes do not wholly follow the ordinary rule is shown by the fact that the atomic volumes of samarium, europium, and gadolinium do not fall nearly so low as the ordinary eighth group elements.

The exceptional behavior of the rare earths in regard to their basic properties may be explained in somewhat the same way as the probable atomic volume relations. Just before coming to the rare earths the basic properties decrease rapidly from caesium, to barium, and to lanthanum. This decrease persists through the rare earth loop, which may be called a tertiary loop, but probably the opposing tendency, that is for the elements of any one main group to increase in basic properties, also has an effect, for the rare earths do not decrease in basic properties with anything like the rapidity which would be apparent if they were distributed around the table in the order of the other elements.[1] If they were thus distributed, either ytterbium or lutecium should be chemically similar to iodine, and that is not the case. The elements on the outer cylinder in Table I may be said to be on primary loops, the inner loops may be designated as secondary, and the rare earths as a tertiary loop. This tertiary loop connects lanthanum and cerium to tantalum, and could be drawn inside the outer cylinder, but since the valence of the rare earths is three, it has been thought best to show them on the vertical rod which represents this valence, in order to make the figure as simple as possible. Thus, the rare earths belong in a sense to the third group, but bear a somewhat peculiar relationship to the other elements of the group.

Supposed Imperfections of the Periodic System.

A great deal of attention has been given in papers in journals, and in books, to what have been called the imperfections in the periodic system. Among the most emphasized of these has been the fact that when arranged in a periodic table in the order of their properties, a few elements, argon, cobalt, and tellurium, are not in the strict order of their atomic weights. It has now been shown by Moseley that the elements in the periodic system are not plotted according to the *order of their atomic weights, but according to the order of their X-ray spectra, or what is called the atomic number*. According to a theory developed by Rutherford, the atomic number represents the number of positive charges on the nucleus of the atom. If this is true THE PERIODIC SYSTEM SHOWS THE RELATION BETWEEN THE PROPERTIES OF THE ELEMENTS AND THE NUCLEAR CHARGE OF THE ATOMS, AND THIS IS PRESUMABLY EQUAL TO THE NUMBER OF NEGATIVE ELECTRONS EXTERNAL TO THE NUCLEUS. *It is probably the spacing and arrangement of these external electrons which determines the chemical properties*

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[1] In this decrease of basic properties with increase in atomic weight inside one group the rare earths act in the same way as the elements on the front of the inner loop, and it is quite possible that it is better to state the fact thus than to give the somewhat involved explanation expressed above.

and those physical properties of the elements which are not functions of the nuclear mass. When considered in this way it is apparent that there remain no imperfections in the system to be explained, for it is not necessary that the mass of the atom shall vary just as the nuclear charge. Neither is it to be supposed that all of the properties of the atoms should vary according to the same function of this charge.

Explanation of Regularities and Irregularities in the Atomic Weight Relations.

In a recent series of papers[1] Harkins and Wilson have presented a theory in regard to the formation of complex from simple atoms, which may be used to explain some of the remarkable relations in the atomic weights, such as exist in one of the triads of Dobereiner.

	At. wt.	Difference.
Lithium	6.94	
		16.06
Sodium	23.00	
		16.10
Potassium	39.10	

In addition to the occurrence of the difference 16 in this triad it is found that the atomic weights of six of the eight elements of the third series may be found by adding 16 to the atomic weights of the elements just above them. Between Series 3 and 4, two of the differences are again 16, and five amount to 20. The greatest common divisor of these numbers is 4, and this is assumed to mean that in general the differences in mass between the atoms of any one group in the periodic table are due to differences in the number of helium atoms, of mass 4, which have been used up in their formation. The proof of this system can not be given here, but can be found in the papers to which reference has been made.

The explanation of these regularities is made more apparent by Table II.

The explanation for the *irregularities* in the atomic weights may be illustrated by citing the case of argon, which has an atomic weight greater than potassium, which comes just after it. This irregularity is due to the tendency for the atoms as they grow larger to take on helium units more rapidly. If argon followed the rule of aggregation as followed in Series 2, its mass would be 36, but the tendency to take on helium atoms more rapidly characterizes Series 4. The elements of the third series are formed from those of the second by the addition of four helium units, but this difference grows to five helium units between Series 3 and 4. Thus from neon to argon is 5 helium units or 20, and 20 + 20 gives 40, the atomic weight of argon. Only in the cases of potassium and calcium does the increment between the series fall back to that between the sec-

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[1] THIS JOURNAL, 37, 1367–96 (1915); *Phil. Mag.*, 30, 723–34 (1915).

TABLE II.—A PERIODIC SYSTEM REPRESENTING IN GENERAL THE SYSTEM ACCORDING TO WHICH THE ELEMEMTS HAVE BEEN BUILT UP FROM HYDROGEN AND HELIUM.

H detd. = 1.0078.

Group.	0.	1.	2.	3.	4.	5.	6.	7.	8.	
Series 2.	He He	Li He+H_3.	Be 2He+H.	B 2He+H_3.	C 3He.	N 3He+2H.	O 4He.	F 4He+H_3.		
Calc.....	=H_4	7	9	11	12	14	16	19		
Detd....	4	6.94	9.1	11	12	14.01	16	19		
Series 3.	Ne 5He.	Na 5He+H_3.	Mg 6He.	Al 6He+H_3.	Si 7He.	P 7He+H_3.	S 8He.	Cl 8He+H_3.		
Calc.....	20	23	24	27	28	31	32	35		
Detd....	20	23	24.3	27.1	28.3	31.02	32.07	35.46		
Series 4.	A 10He.	K 9He+H_3.	Ca 10He.	Sc 11He.	Ti 12He.	V 12He+H_3.	Cr 13He.	Mn 13He+H_3.	Fe 13He.	Co 14He+H_3.
Calc.....	40	39	40	44	48	51	52	55	56	59
Detd....	39.88	39.1	40.07	44.1	48.1	51	52	54.93	55.84	58.97

Increment from Series 2 to Series 3 = 4 He.
Increment from Series 3 to Series 4 = 5 He. (For K and Ca = 4 He.)
Increment from Series 4 to Series 5 = 6 He.

ond and third series, that is to 4 times 4 or 16. In other words, potassium has the atomic weight which it should have according to the rule that the atomic weight increases four units for each increase of two in the atomic number. Argon has a weight four more than this, due to the taking on of one too many helium units, which, however, is what all of the fourth series elements do except potassium and calcium.

The Radioactive Elements.

The periodic table presented in this paper is admirably adapted to show the relations existing between the radioactive elements as expressed by the rule of Soddy and Fajans. These relations are expressed on the space model (Fig. 3), and better still, on a space model on which the vertical scale is made much greater, for example, four centimeters to one unit of atomic weight. Fig. 4 gives an enlarged view of the bottom part of the table shown in Fig. 3, and shows the elements from tantalum to uranium. In this figure the elements derived from thorium by disintegration are designated by rectangles, and the members of the radium series, by sections or circles. The actinium series has not been included, since the atomic weights are not known, but they can easily be added as soon as the atomic weight of actinium is determined. This series has been included in Fig. 5 but the scheme is doubtful so far as the actinium series is concerned.

Uranium (atomic weight 238.2), the parent of the members of the radium series, belongs to Group VIB on the back of the inner loop. It shoots off an alpha particle (the doubly positively charged nucleus of a helium atom) and changes into uranium X_1 (at. wt. 234.2), which belongs to Group IVA. This gives off a beta particle and changes into uranium

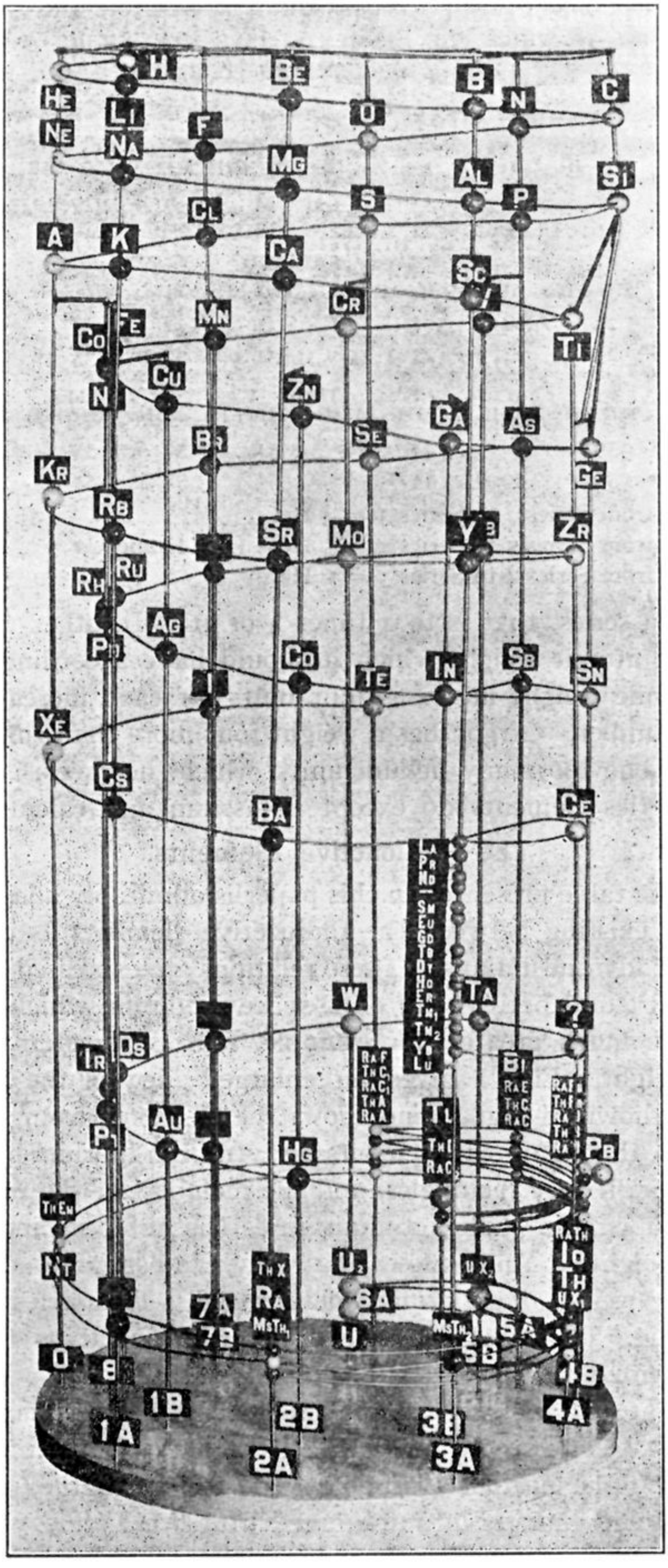
H
Be
B
He
Li
N
C
Ne
Na
F
O
Mg
Al
Si
S
P
Cl
A
K
Ca
Sc
Cr
Mn
Co
Fe
Ti
Cu
Zn
Ni
Ga
As
Se
Br
Kr
Ge
Rb
Sr
Mo
Y
Zr
Ru
Rh
Ag
Pd
Cd
In
Sb
Sn
Te
I
Xe
Cs
Ce
Ba
La Pr Nd — Sm Eu Gd Tb Dy Ho Er Tm1 Tm2 Yb Lu
W
Ta
?
Ir
Os
Bi
RaE ThC RaC
RaF ThC1 RaC1 ThA RaA
Tl ThD RaC2
Au
Pt
Hg
Pb
ThEm
Nt
RaTh Io Th UX1
ThX Ra MsTh1
U2
UX2
6A
7A
7B
U
MsTh2
5A
5B
0
8
1B
4B
1A
2B
3B
4A
2A
3A

Fig. 3.

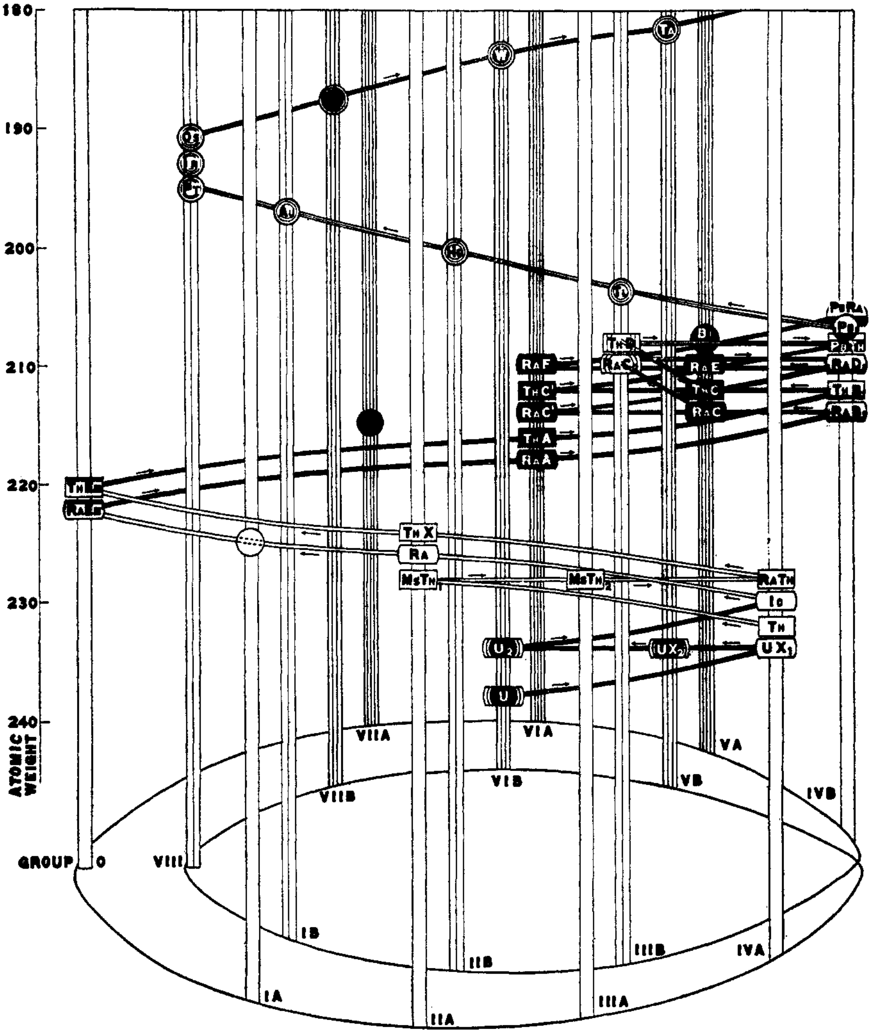

Fig. 4.—Periodic system showing the radioactive elements of the thorium and radium series.

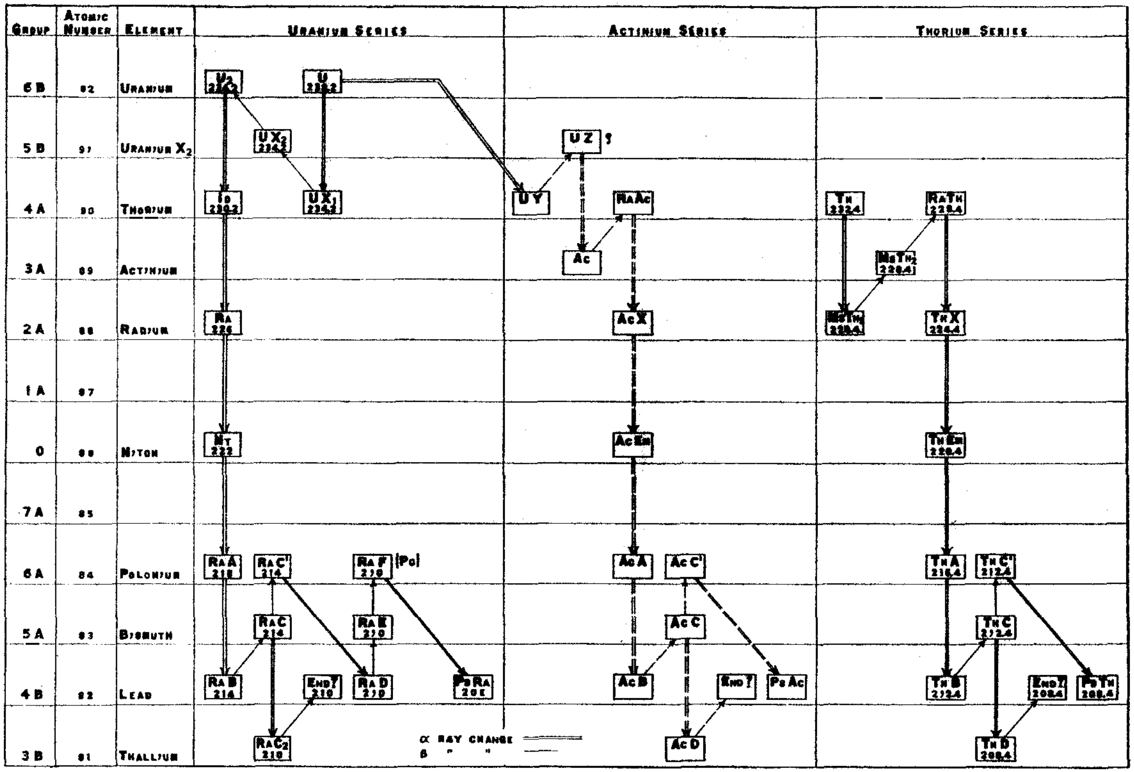

Fig. 5.—Table of the radioactive elements. Note: A new determination of the atomic weight of thorium gives 232.2, so the decimal in the thorium series should be 0.2. The actinium series is not yet fixed with any certainty.

X_2 (Group VB) without a change of atomic weight. A second beta change converts uranium X_2 into uraniums, isotopic with uranium and with an atomic weight four less. This is converted into ionium by an alpha

TABLE III.—PERIODS OF THE RADIOACTIVE ELEMENTS, WITH ISOTOPES CLASSED TOGETHER.

At. No.	Isotopes of	Name of isotope.	Atomic weight.	Ray.	Period.	
92	Uranium	Uranium$_2$	234.2	α	2 million years	1
		Uranium	238.2	α	5 billion years	
91	Uranium X_2	Uranium X_2	234.2	β	1.15 minutes	2
90	Thorium	Radiothorium	228.2	α	2.02 years	3
		Ionium	230.2	α	200,000 years	
		Thorium	232.2	α	18 billion years	
		Uranium X_1	234.2	α	24.6 days	
		Radioactinium	...	α,β	19.5 days	
		Uranium Y	...	...	1.5 days	
89	Actinium	Meso-thorium 2	228.2	β	6.2 hours	4
		Actinium	...	...	......	
88	Radium	Thorium X	224.2	α	3.64 days	5
		Radium	226.2	α	1730 years	
		Meso-thorium 1	228.2	α	5.5 years	
		Actinium X	...	...	11.4 days	
87	(Unknown)					
86	Niton	Thorium emanation	220	α	54 seconds	6
		Radium emanation	222	α	3.85 days	
		Actinium emanation	...	α	3.9 seconds	
85	Unknown					
84	Polonium	Radium F	210	α	136 days	7
		Thorium C′	212	α	10^{-11} seconds	
		Radium C′	214	α	10^{-6} seconds	
		Thorium A	216	α	0.14 second	
		Radium A	218	α	3 minutes	
		Actinium A	...	α	0.002 second	
81	Thallium	Thorium D	208	β	3.1 minutes	8
		Radium C_2	210	β	1.4 minutes	
		Actinium D	...	β	4.71 minutes	
		Bismuth	208	...	Extremely long	
83	Bismuth	Radium E	210	β	5 days	9
		Thorium C	212	α,β	60 minutes	
		Radium C	214	α,β	19.5 minutes	
		Actinium C	...	α	2.15 minutes	
82	Lead	Lead from Ra	206	...	Extremely long	10
		Lead from Th	208	...	Extremely long	
		Radium D	210	β	16.5 years	
		Thorium B	212	β	10.6 hours	
		Radium B	214	β	26.7 minutes	
		Actinium B	...	β	36.1 minutes	
		Lead from secondary branch of radium series				
		Lead from secondary branch of actinium series				

change, and this in turn changes into radium by another alpha transformation. These changes, and the others until the disintegration ends with lead from radium (Pb Ra), can be easily traced by following the lines in the table. In each loss of an alpha particle the atomic weight decreases by approximately four, and the valence and group number both decrease by two. Each loss of a beta particle increases the valence and group number by one, but causes no change of atomic weight.

The half-period of a radioactive element is the time in which one-half of the element would disintegrate. The half-periods of each set of isotopes are given in Table III.

The table giving the periods of the radioactive elements shows that the period for any one isotope varies with the atomic weight in some regular way. It is difficult to make any comparison in this sense which includes the members of the actinium series, since their atomic weights are unknown. In the case of the isotopes of thorium, thorium itself has the longest period, and thus decreases in each direction as the atomic weight decreases or increases. The periods of the isotopes of lead decrease as the atomic weight increases, and the same is true of the periods of bismuth and its isotopes. However, in the case of the isotopes of polonium (Radium F), Thorium C′ has the minimum period, and the period increases on each side as the atomic weight either increases or decreases.

The Nature of Isotopes.

It is now known,[1] as has already been pointed out, that a single element, with a single atomic number, may consist of several different kinds of atoms, which are alike in that they seem to have the same nuclear charge, and therefore presumably, the same number of external negative electrons. Isotopes seem to be identical chemically, and so far as is known they give identically the same spectrum, but they may or may not differ in certain physical properties, such as the melting points. Thus neon and meta-neon, which differ in atomic weight by two, were separated by diffusion. On the other hand, Soddy finds that lead from thorium and ordinary lead have the same atomic volume, that is, the lead obtained from thorium minerals is denser than ordinary lead in the ratio of the atomic weights. Richards[2] has found that the lead from radium is also different in density from ordinary lead. Such isotopes as these differ in those properties which are functions of the mass of the particle, and they may be called isotopes of the first class. A second kind of isotopism is that in which there is no difference in mass except that due to a difference in the packing effect. Thus Radium D and the end number of the secondary radium disintegration series, which is as yet unnamed, have the same atomic weight except for the very slight difference

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[1] *Le Radium*, 10, 171.

[2] THIS JOURNAL, 38, 221 (1916).

in mass due to a difference in the internal energy of the atoms, and this difference is so slight as to be experimentally undetectable, so these may be called isotopes of equal mass. Also, though the atomic weight of actinium has not been determined as yet, enough is known of its disintegration series so that it is practically certain that a number of actinium derivatives show this form of isotopism with members of the radium series. Thus if we assume that the atomic weight of actinium is 230, then radio-actinium and ionium which are isotopic must both have atomic weights of 230, but the latter has a half-period of 200,000 years, and the former of only 19.5 days, so there is a very great difference in stability. Even if the atomic weight of actinium is different, it will be seen from Fig. 5 that some of the other members of the two series must show this form of isotopism.

Isotopes of approximately equal atomic mass are derived from the same ancestral atom, that is from either uranium or thorium, for no thorium disintegration product is known which has the same mass as a uranium disintegration product. In the formation of isotopes of this class, different amounts of energy seem to be given out, so they must differ in internal energy, and to a greater or lesser extent in stability. It does not seem improbable that this difference may be due to the expulsion in the different cases of alpha and beta particles which lie in structurally different positions in the nucleus.

The Nuclei of Complex Atoms.

According to the above views, and those advanced by Harkins and Wilson in the first four papers of this series, which advanced the theory that the nuclei of complex atoms are built up from hydrogen and helium nuclei according to the system presented in Table II, it may be assumed that the chemical nature of the atom is independent of the number of particles present in the nucleus of the atom, and therefore of the mass of the atom, and is also independent of the structure of the nucleus, so long as the structure does not affect the nuclear charge. The chemical properties of the atom are, according to this view, dependent wholly upon the nuclear charge. When the complex nucleus is built up from only a few hydrogen and helium nuclei, there are not many stable arrangements which give a single nuclear charge, but when the nuclei are very complex, the possible number of more or less stable structures should be considerably increased. Therefore it is to be expected, as was found by Harkins and Wilson, that the atomic weights of the lighter elements should follow some regular system with only small deviations, but that these deviations should become much more considerable in the case of the more complex heavier elements. In other words, isotopes should be found much more abundantly among the heavy than among the light elements. The fact that the isotopes of any two different series differ in atomic weight by about two units, suggests that the difference is caused by the presence of two hydrogen atoms in one set of atoms, and their absence from the other. As examples it may be remembered that neon and meta-neon are supposed to differ in atomic weight by two units, and within the accuracy to which the atomic weight of thorium has been determined, there is the same difference between two adjacent isotopes of the thorium and the uranium series.

A Plane or Spiral Form of the Periodic Table.

The periodic table presented in this paper is a space form, though it is easily represented on a plane as in Fig. 2. The space form may, however, be easily converted into a plane diagram by plotting the atomic weights radially from a point in a plane. This gives the table represented in Fig. 6. While this spiral form of table does not seem to the writers to be so well adapted to general use as the space form, it does show exactly the same relations between all of the chemical and physical properties of the elements.[1] This table is different, too, from other spiral tables, for none of the earlier tables have been so constructed as to classify the elements correctly. Thus, for example, the spiral table given in Erdmann's chemistry classifies Ne, Ni, Rh, and Ir, in one group, Na, Cu, Ag, Gd, and Au in another, and Li, K, Rb, Cs, leaving out Na, in a third. These are obviously improper classifications. The error in all previous spiral tables has been due to a failure in plotting to distinguish between the long and the short periods. In Fig. 7 the short-period elements occur only above the median line, while the long periods make a continuous line both above and below.

It is interesting to note that around the long periods the group numbers run 0, 1A, 2A, 3A, 4A, 5B, 6B, 7B, 8, 1B, 2B, 3B, 4B, 5A, 6A, 7A, 0, which is exactly the order in the tables presented in Figs. 2 and 4. Table 7 is the first spiral table to give the chemical relations correctly.

The Relation between the New Form of the Periodic Table and the other Modifications.

In his book entitled "New Ideas on Inorganic Chemistry," Werner,[2] in discussing the periodic system, says:

> ". . . . up to the present the satisfactory grouping of the iron group and the rare earths appears to be almost impossible. Most of these difficulties are not difficulties of principle, *i. e.*, they are not to be referred to the nature of the metal in question, but rather to the particular arrangement adopted to illustrate the periodic occurrence of chemically allied elements.
>
> "The principle chosen by Mendeléeff, of bringing analogous elements as near as possible together in order to bring out the less evident similarities which exist between such elements, has been followed by his successors. This process has led to a crowding

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[1] Except that it does not show so well the relations between what have been called complementary groups.

[2] English edition, Longmans, 1911, p. 4.

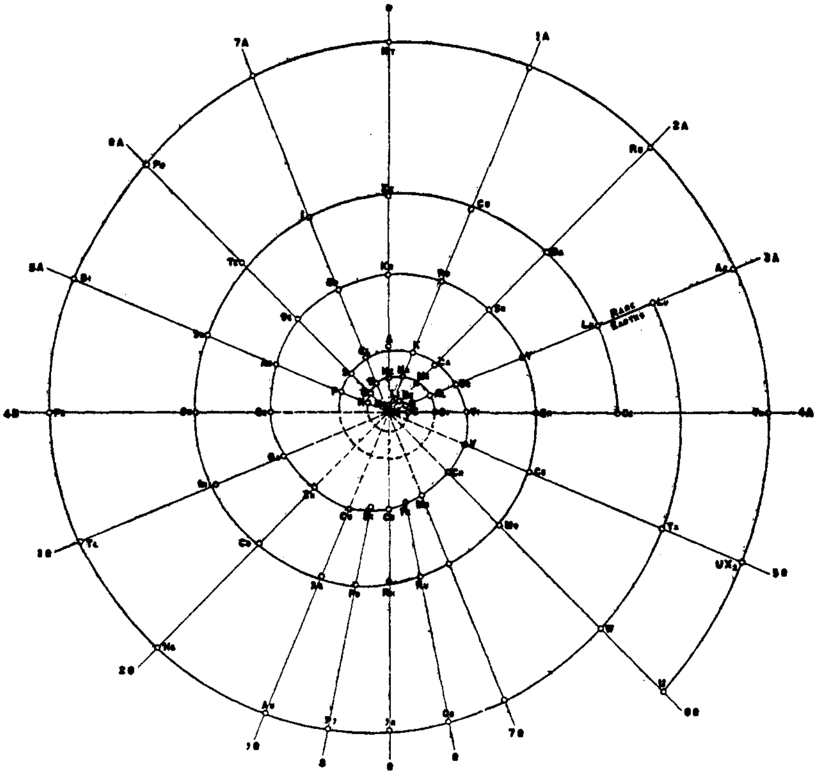

Fig. 6.—A spiral form of the periodic table.

together (Ineinanderschachtelung) of the elements which is harmful to the synoptical character of the periodic system, and this is especially true when we consider only the less important analogies: the result of equal valencies. This compression of the elements into the least possible space is the chief cause of many elements not finding a suitable position in Mendeléeff's scheme. This remark is particularly applicable to the eighth group, and to the metals of the rare earths."

However, in finding a remedy for the defects which he discusses, Werner goes to the opposite extreme, and places the elements in such a way that many important analogies become obscured. By placing the elements farther apart on the helix, but close together in space, the new table is able to combine all of the advantages, and to eliminate the disadvantages of such widely different forms. The relation between these different tables is discussed below.

If, in Figs. 1, 2, or 3, the lines of the helix are cut between the seventh and the zero groups, and between the eighth and the 1B groups, the table when spread out on a plane becomes much like that of Mendeléeff, except that there are no blanks except those which correspond to atomic numbers, that the rare earths are arranged differently, and that the drawing would still show the distinction between the main and the sub-groups. However, if all of the connecting lines are taken out, the table becomes essentially that of Mendeléeff. If the helix is cut only between the seventh and the zero groups, unrolled, and laid on a plane, it takes on the general form of the Carnelley-Richards table,[1] which is probably the best of all of the plane tables except that of Mendeléeff. If the helix is cut between carbon and nitrogen, between silicon and phosphorus, and between the seventh and the zero groups, and again spread on a plane, it gives the form attributed to Meyer, to Palmer, and to Staigmüller.[2] The essential advantage claimed by Staigmüller is that in his table a line separating the non-metals and the metals may be easily drawn, and that the non-metals fall into one group in the table. The elements which he classifies as non-metals are B, C and Si, N, P (and partially As); O, S, Se (and partly Te); F, Cl, Br, and I; and also He, Ne, A, Kr, and Xe. If this is an advantage of the Staigmüller table, it is much more an advantage of the new space form here presented, as in our table the non-metals are much more closely grouped, as they lie entirely in one group on the outer cylinder, and all except B, C and Si, lie at the back.

Werner's table,[3] except for the arrangement of the rare earths, may be obtained by cutting the helix so that the elements in each of the following pairs of elements become separated: Li and Be, Na and Mg, Ca and Sc, Sr and Y. It should also be cut between the 0 and 1A groups, and then spread out on a plane. The transformation into the form devised by

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[1] *Chem. News*, 78, 193–5 (1898).

[2] Nernst's "Theoretische Chemie," *Siebente Auflage*, p. 184.

[3] *Ibid.*, p. 185.

Walker[1] is also a simple one, since the spiral needs only to be cut between the seventh and zero groups, and the vertical rods severed between K and Rb, between Ca and Sr, Sc and Y, Si and Ti, P and V, S and Cr, and between Cl and Mn.

As has already been seen, the new table may be represented on a plane as a spiral, or in space as a figure 8. The use of a figure 8 space form of table was first suggested by Crookes,[2] but the arrangement of the elements in his table was very different. The use of a figure 8 diagram has been advocated by Soddy,[3] who gives the best table previously devised but such a representation obscures both what have been called the complementary relations and the relations between the main and the sub-groups.

While in the development of the periodic table in space as presented in this paper, no use was made of any previously devised system except that of Mendeléeff, it will be seen that it is a generalized form, of which the Mendeléeff, Carnelley-Richards, Werner, Staigmüller, and other modifications, are special cases, each of which expresses certain relations well, but others poorly or not at all. The space form eliminates the disadvantages of the different plane tables, and at the same time combines their advantages. That at first sight it seems more complex than the Mendeléeff table is due to the fact that it classifies all of the elements, but it is actually more simple, since it contains no blanks except the five which correspond to atomic numbers. Experience has shown that students who have no previous knowledge of the Mendeléeff table find the space form the more simple, at least when they have the model to use in their study.

COHESIONAL PROPERTIES.

Atomic Volumes, Melting Points, and Related Properties.

In Fig. 1 the elements of highest atomic volume lie at the left of the outer loop, while the elements of lowest atomic volume lie at its right (carbon, silicon and aluminium) as long as the outer loop persists at the extreme right, and when the outer loop disappears at this extremity, the line of lowest atomic volume jumps over to the left end of the inner loop. To show these atomic volume relations somewhat more simply the table has been drawn in the form given in Fig. 7. From the standpoint of the chemical relations this latter table is much less perfect than the former, but it has the one advantage that the elements of high atomic volume are at the left of the table, and those of low atomic volume are at the right, so if this table is hung with its left side as the top, *the loops take the general form of*

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[1] *Chem. News*, 63, 251–3 (1891).

[2] *Ibid.*, 78, 25 (1898); *Proc. Roy. Soc.*, 63, 408–11 (1898); and *Z. anorg. Chem.*, 18, 72–6 (1898).

[3] Chemistry of the Radioactive Elements," Part II, p. 11.

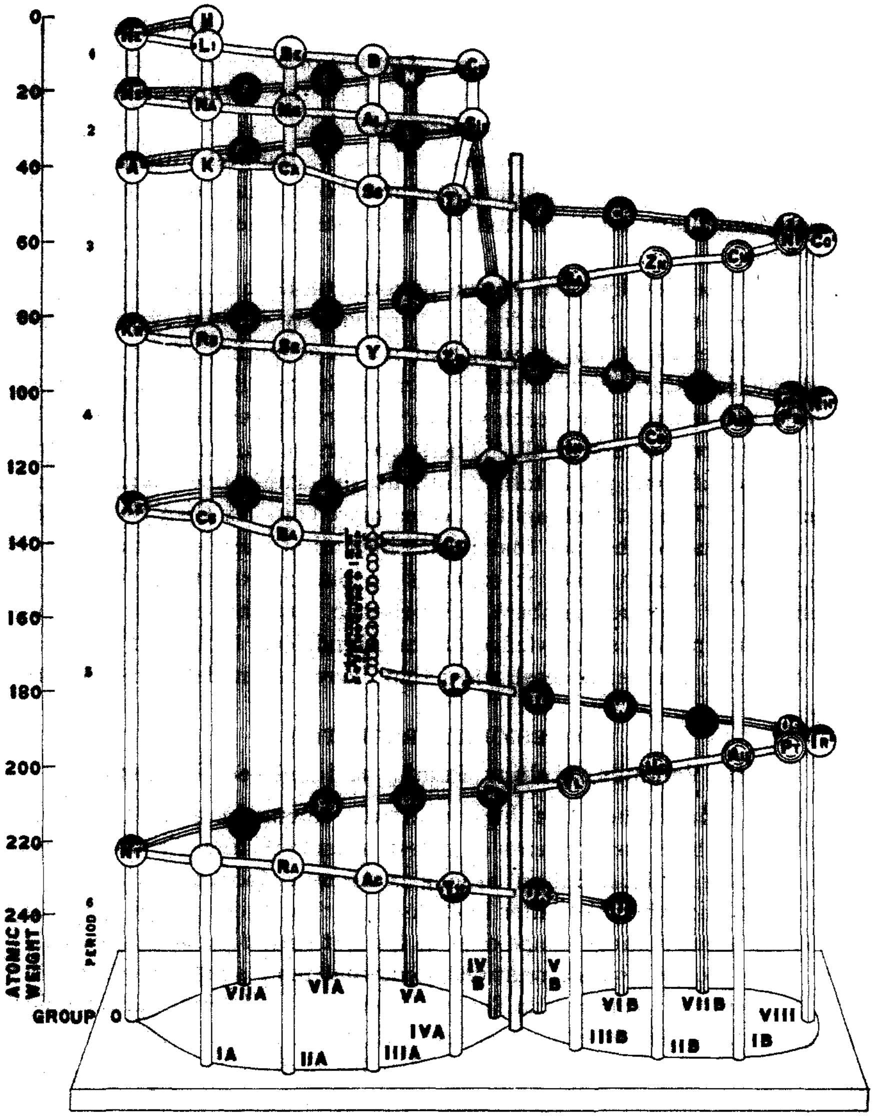


Fig. 7.—Periodic table modified so as to show the atomic volume relations in a simple way.

the atomic volume curve.[1] Fig 7 has the great disadvantage that it does not show the relations which exist between the main and the sub-groups. It is formed from the table in Fig. 2 by turning each inner loop on a horizontal axis from front to back at its right ends until it falls outside to the right. The atomic volumes of the elements have been plotted against their atomic numbers in Fig. 8. A comparison of Figs. 1, 2, 7 and 8 will show how simply the present form of table expresses the atomic volume relations.

The elements of lowest melting point lie at the left of the table (Figs. 1, 2, and 7). The absolute melting points for these elements are:

Hydrogen	14°
Helium	2°
Neon	20°
Argon	85°
Krypton	104°
Xenon	133°
Niton	202°

The line[2] of highest melting points begins exactly opposite at the right of the outer loop with carbon, melting point about 3900° absolute, and silicon, 1693°. These are the elements of lowest atomic volume except for the fact that the atomic volume of aluminium is slightly less than that of silicon. It might seem that the line of maximum melting point would here jump at once to the elements of lowest atomic volume in the next series, that is, to the iron group. Instead of doing this, however, it passes to titanium (m. p. 2060° Abs.), and then still further toward the eighth group, but reaches only to Group VIB, and passes straight down through molybdenum (2800°), tungsten (3300°), and uranium. The tendency toward the shift of the maximum melting point from the fourth group to Group VIB is already seen in the elements titanium and vanadium. Thus the difference between the melting points of carbon (4th group) and the adjacent element in the fifth group, nitrogen, is 3800°. Between silicon and phosphorus the corresponding drop is 1400°. Just below this the drop from titanium (4th group) to vanadium (Group VB) is only 70°. This enormous decrease in the fall between the fourth and fifth groups, clearly predicts a reversal in the next series, where zirconium (4th group) has a melting point of about 2000° absolute. Columbium (niobium, 5th group) melts at 2500°, and molybdenum (Group VIB) melts at about 2800°.

[1] If the loops at right, representing the sub-groups, are untwisted, this table takes on the form advocated by Emerson in his "Helix Chemica," *Am. Chem. J.*, **45**, 160–210 (1911), except that the new table classifies the rare earths in a different way. While this is also a useful form of the table, it has not been thought necessary to include a figure showing it, since it is easy to see how Emerson's table can be modified so as to classify the rare earths correctly.

[2] For the lines of maximum melting points, and the lines of primary and secondary minima, see Fig. 9.

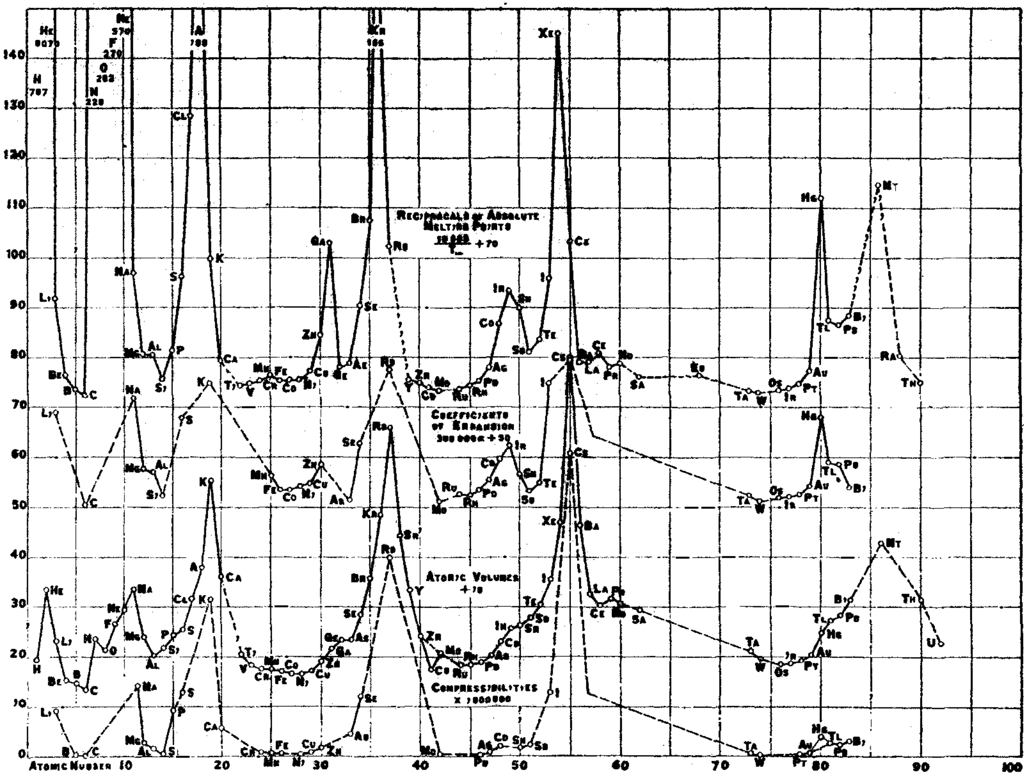
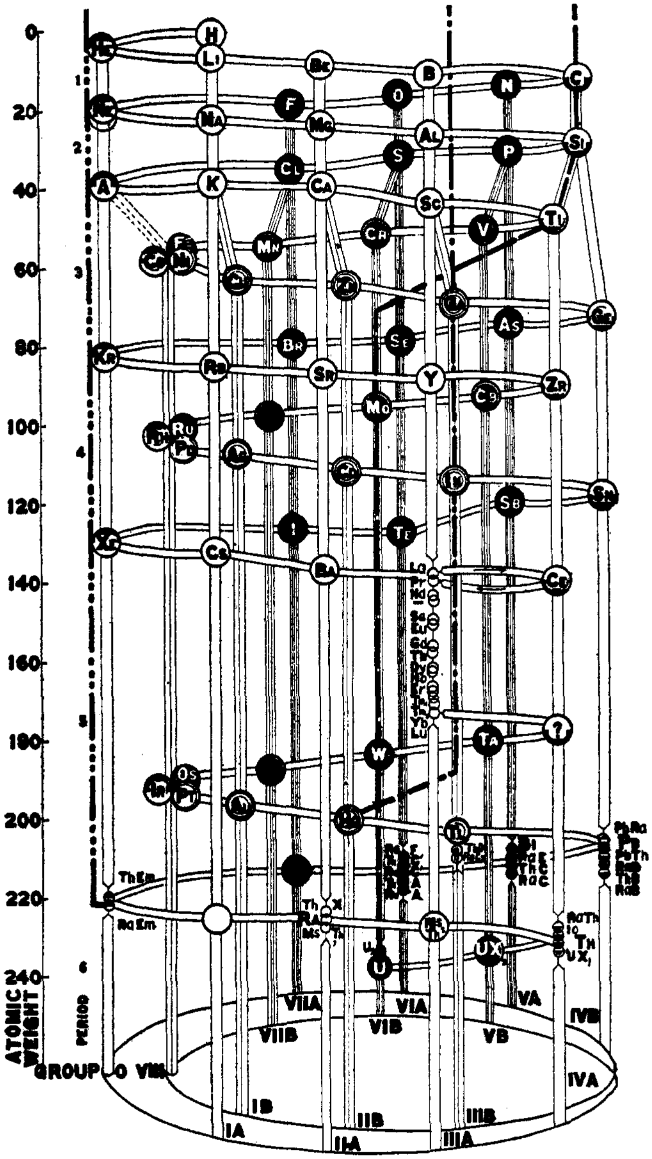


Fig. 8.—Cohesional properties of the elements. (The atomic volume of Cb is probably not correct.)



MELTING POINTS
Line of Maxima ▬ ▬ ▬ ▬ ▬
Line of Primary Minima ▬ . . . ▬
Line of Secondary Minima ▬ . ▬

Fig. 9.

TABLE IV.—THE ELEMENTS ARRANGED ACCORDING TO ATOMIC NUMBERS, WITH THE ATOMIC WEIGHTS, ATOMIC VOLUMES, MELTING POINTS, COMPRESSIBILITIES, CUBIC COEFFICIENTS OF EXPANSION, MAGNETIC SUSCEPTIBILITIES, ATOMIC FREQUENCIES, AND VALUES OF T_m/V REPRESENTING COHESION.

At. No.	Element	At. wt.	At. vol.	Density.	Cubic coeffs. of expansion $3\alpha \times 10^5$.	M. p. absolute.	Compressibility at 20° $\times 10^6$. (Richards.)	Susceptibility $\times 10^7$.	Atomic frequency $\times 10^{12}$.	T_m/V.
1	Hydrogen	1.008	9.2	0.11[1] (—252)	...	14	...	...	5.5	1.52
				0.0763 (—259.9)						
2	Helium	4.00	23.5	0.17 (—258)	...	2	...	...	0.8	0.085
				0.146 (—271.5)						
3	Lithium	6.94	13.1	0.534 (20)	19.0	459	9.0	5.0	10.7	35.0
4	Beryllium	9.1	5.3	1.73 (15)	...	1573	...	—10.0	23.4	296.4
5	Boron	11.0	4.7	2.34	...	2800	0.3	—7.0	29.5	596.0
6	Carbon	12.005	3.4	3.51 (Diamond)	0.3	> 3873	Very small	—4.9	37.0	1139.0
			5.3	2.26 (Graphite)	7.2	...	3.0	—5.21	..	....
7	Nitrogen	14.01	13.7	1.0265 (—252.5)	...	63	...	...	2.8	4.6
8	Oxygen	16.00	11.2	1.4256 (—252.5)	...	55	...	1160	2.6	4.9
9	Fluorine	19.00	16.7	1.14 (Liq.) (—200)	...	50	...	...	2.0	3.0
10	Neon	20.00	19.2	1.04[2] (Calc.)	...	20(?)	...	...	1.2	1.04
		22.00								
11	Sodium	23.00	23.7	0.9725 (0)	21.6	371	15.6	5.1	4.4	15.7
12	Magnesium	24.32	14.0	1.74	7.83	924	2.9	2.6(?)	7.9	66.0
13	Aluminium	27.1	10.4	2.60	7.2	932	1.47	6.0	8.3	89.5
14	Silicon	28.3	11.7	2.42	2.3	1693	0.32	—1.3	10.6	145.0
15	Phosphorus	31.04	14.4	2.15 (Red)	...	863	9.2	—9.0	6.7	60.0
			17.0	1.82 (White)	...	317	20.5	...	..	....
16	Sulfur	32.06	15.5	2.07 (Rhombic)	18.0	386	12.9	—4.9	4.4	24.9
17	Chlorine	35.46	21.4	1.7106 (—93.7)	...	171.5	(95) (?)	—5.90	2.5	8.0
18	Argon	39.88	28.0	1.423 (Liq.) (—189)	...	85	...	—500 (?)	1.5	3.0
19	Potassium	39.10	45.5	0.859 (0)	25.0	335	31.7	0.58	2.6	7.3
20	Calcium	40.07	26.2	1.53	...	1083	5.7	11.0	5.4	41.5
21	Scandium	44.1	..	..	...	...	...	...	..	....

22	Titanium	48.1	10.7	4.50[3] 3.988[4]	...	2063	...	12.4	9.2	193.0
23	Vanadium	51.0	8.5	5.987[5]	...	1993	...	15.0	9.5	234.0
24	Chromium	52.0	7.4	7.06	...	1793	0.9	29.0	9.5	242.0
25	Manganese	54.93	7.5	7.37	6.2	1533	0.84	89.3	8.4	204.0
26	Iron	55.84	7.1	7.85	3.6	1803	0.60	...	9.2	254.0
27	Cobalt	58.97	6.7	8.8	3.8	1751	...	...	9.0	262.0
28	Nickel	58.68	6.7	8.7	4.2	1725	0.43	...	8.9	258.0
29	Copper	63.57	7.1	8.92	5.0	1356	0.75	—0.85	7.5	191.3
30	Zinc	65.37	9.2	7.13	8.7	692	1.7	—1.55	4.8	75.4
31	Gallium	69.9	11.8	5.92	...	303	...	—2.4	2.8	25.7
32	Germanium	72.5	13.3	5.459	...	1231	...	—1.2	5.4	92.6
33	Arsenic	74.96	13.1	5.72 (Metal)	1.6	1123	4.5	—0.1	5.1	85.8
			16.1	4.64 (Gray)[6]	...	...	...	...	..	....
34	Selenium	79.2	16.5	4.8 (Gray)	11.4	490–3	12.00	—3.2	3.0	29.7
35	Bromine	79.92	25.6	3.12 (Liq.) (20)	...	266	52	—3.99	1.9	10.4
36	Krypton	82.92	38.5	2.155 (Liq.) (—146)	...	104	...	...	1.0	2.8
37	Rubidium	85.45	56.0	1.5248 (0)	27.0	311	40	0.7	1.6	5.6
38	Strontium	87.63	34.4	2.55	...	>Ca<Ba?	...	—2.0	3.4	....
39	Yttrium	88.7	23.3	3.80	...	1773(?)	...	...	4.3	76.2
40	Zirconium	90.6	14.2	6.40	...	1973	...	—4.5	6.0	138.8
41	Columbium	93.5	7.4	12.7[7] 8.40	...	2473(?)	...	...	8.2	334.0

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[1] Occluded in wood charcoal. *Tables Annuelles*, 1913.

[2] *Z. physik. Chem.*, 76, 570 (1911).

[3] Crystalline. THIS JOURNAL, 32, 336 (1910).

[4] Amorphous. *Tables Annuelles*, 1912.

[5] *Tables Annuelles*, 1914; *Z. anorg. Chem.*, 79, 221.

[6] Liebig's *Ann.*, 361, 1 (1908).

[7] *Landolt-Börnstein-Meyerhoffer Tabellen.* The values for columbium vary greatly, and there is a need for a new determination of the density of the pure substance.

TABLE IV (*continued*).

At. No.	Element.	At. wt.	At. vol.	Density.	Cubic coeffs. of expansion $3\alpha \times 10^5$.	M. p. absolute.	Compressibility at 20° $\times 10^6$. (Richards.)	Susceptibility $\times 10^7$.	Atomic frequency $\times 10^{12}$.	T_m/V.
				7.37						
				7.05						
42	Molybdenum	96.0	10.7	9.0	1.1	2773	0.46	0.39	7.6	259.6
43	Eka-manganese I		...	..	...	..	...	...	..	....
44	Ruthenium	101.7	8.4	12.063	2.88	2573	...	4.3	7.7	306.4
45	Rhodium	102.9	8.5	12.1	2.55	2213	...	11.0	7.0	260.6
46	Palladium	106.7	8.8	12.13	3.8	1822	0.54	52.0	6.2	207.0
47	Silver	107.88	10.3	10.5	5.7	1234	1.01	—2.0	4.8	120.0
48	Cadmium	112.40	13.1	8.6	9.3	594	2.1	—1.8	3.2	45.3
49	Indium	114.8	15.8	7.277	12.5	428	...	—1.1	2.3	27.1
50	Tin	118.7	16.3	7.29	6.7	505	1.9	—0.2	2.5	31.0
51	Antimony	120.2	17.9	6.71	3.3	903	2.4	—8.2	3.2	50.4
52	Tellurium	127.5	20.5	6.218	5.0	725	...	—3.2	2.7	35.4
53	Iodine	126.92	25.7	4.94	25.0	386	13.0	—3.6	1.8	15.0
54	Xenon	130.2	37.0	3.52 (Liq.) (—102)	...	133	...	...	0.9	3.6
55	Caesium	132.81	69.8	1.9029 (0)	29	299	61.0	—1.0	1.1	4.3
56	Barium	137.37	36.3	3.78	...	1123	...	—9.0	2.6	30.8
57	Lanthanum	139.0	22.6	6.15	...	1083(?)	...	...	3.1	48.0
58	Cerium	140.25	20.3	6.92	...	913	...	150	2.9	44.9
59	Praseodymium	140.9	21.8	6.47	...	1213(?)	...	250	3.2	55.7
60	Neodymium	144.3	20.7	6.96	...	1113(?)	...	360	3.1	53.8
61	Eka-neodymium	...	...	..	...	...	...	...	..	....
62	Samarium	150.4	19.5	7.7	...	1573–1673	...	...	3.8	82.0
63	Europium	152.0	...	..	...	...	...	...	..	....
64	Gadolinium	157.3	...	..	...	...	...	...	..	....
65	Terbium	159.2	...	..	...	...	...	...	..	....
66	Dysprosium	162.5	...	..	...	...	...	...	..	....
67	Holmium	163.5	...	..	...	...	...	...	..	....

68	Erbium	167.7	35.3(?)	4.77(?)	...	1523(?)	...	323.0	..	....
69	Thulium I	168.5	...	..	...	...	...	...	..	....
70	Thulium II	...	...	..	...	...	...	...	..	....
71	Ytterbium	173.5	...	..	...	...	...	...	..	....
72	Lutecium	175.0	...	..	...	...	...	Very high	..	....
73	Tantalum	111.5	10.9	16.67	2.3	3123	0.53	8.0	7.4	286
74	Tungsten	184.0	9.7	19.23	1.1	3300	0.27	2.2	6.2	340
75	Eka-manganese	...	...	..	...	...	...	...	..	....
76	Osmium	190.9	8.5	22.48	2.0	2973(?)	...	0.4	6.0	350
77	Iridium	193.1	8.6	22.4	1.97	2573(?)	...	1.3	5.5	300
78	Platinum	195.2	9.1	21.31	2.7	2028	0.38	8.0	4.8	223
79	Gold	197.2	10.3	19.24	4.29	1336	0.64	—1.5	3.7	129.4
80	Mercury	200.6	14.8	13.55 (20)	18.2 (Liq.)	234	3.95	—1.9	1.4	15.8
81	Thallium	204.0	17.2	11.83	9.0	575	2.3	—2.4	2.0	33.4
82	Lead	207.20	18.2	11.37	8.79	600	2.33	—1.2	2.0	33.0
83	Bismuth	208.0	21.2	9.80	4.03	544	3.0	—14.0	1.8	25.7
84	Polonium	210.0	...	..	...	...	...	...	..	....
85	Eka-iodine	...	...	..	...	...	...	...	..	....
86	Niton	222.4	39.0	5.7 (Liq.) (—71)	...	202	...	...	0.9	5.2
87	Eka-caesium	...	...	..	...	...	...	...	..	....
88	Radium	226.0	...	..	...	973	...	...	..	....
89	Actinium	...	...	..	...	...	...	...	..	....
90	Thorium	232.4	21.2	11.00	...	> 1973(?) <Pt	...	0.8	3.3	....
91	Uranium X_2	234.2	...	..	...	...	...	...	..	....
92	Uranium	238.2	12.7	18.7	...	(?)	...	26.0	..	....

The unknown element eka-manganese 2 may prove to have a higher melting point than tungsten. The drop in melting point between carbon, atomic number 6, and nitrogen, atomic number 7, is the most remarkable sharp change in the whole system, amounting as it does to more than 3800°. It will be shown later that the relations of the physical properties of carbon to those of the other elements, are remarkable in many other respects.

In addition to the line of minimum melting points, which lies in the zero group, there is a line of secondary minima, possibly beginning with aluminium, with a very slight minimum. The next element in the third group below this is scandium, and unfortunately its melting point is not known. Below this in Group IIIA there is a very considerable minimum beginning with gallium (at. no. 31) of absolute melting point 303°, while just before it zinc (at. no. 30) has a melting point of 692°, and just after it comes germanium (at. no. 32) with a melting point of 1231°. Below gallium the minimum continues in the same group, IIIB, with indium (m. p. 480°), and then shifts to the left (Fig. 9) toward the iron group, so that the next minimum comes in Group IIB with mercury. Here it is remarkable that the secondary minimum where mercury melts at 234° absolute, is almost as low as the corresponding primary minimum at niton, which melts at 202°, or only 32° lower. It will be seen that the line of maximum melting points at the back of the inner loop, and the line of secondary minima at the front of the inner loop, both move to the left toward the iron group as they move down the table. In Fig. 8 the melting points have been plotted as reciprocals, and these secondary minima may be seen as secondary maxima on the curve.

Fig. 8 is similar to a figure given by Richards,[1] but differs in the fact that it is plotted to atomic numbers instead of atomic weights, and also gives data for some of the properties of as many as 72 elements, while Richards' figure shows only 38. The increase in the number of data changes not only the form of individual curves, but it also changes their relationship to each other. When so many data are plotted, there is a considerable advantage in plotting to atomic numbers instead of atomic weights, since when the atomic weights are plotted, each curve is apt to cross itself whenever the atomic weights are not in the order of the atomic numbers, as is the case with argon. Another point in favor of plotting these physical properties according to the atomic numbers instead of atomic weights, is, as will be shown later, that it is the number of external electrons in the atom, and the number of these runs in the same order as the atomic numbers, which, in all probability, determines the cohesional properties of the elements. Moseley's work seems to indicate that the atomic number and the nuclear charge, pre-

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[1] This Journal, 37, 1649 (1915).

sumably equal to the number of external electrons, are expressed by the same number.

The data on compressibility given in Table IV, and plotted in Fig. 8, have been taken from Richards' work, and the other data were obtained from what seemed to be the most reliable sources, though in many cases there is considerable doubt as to which work is the most trustworthy. A few of the data plotted have been taken from work on liquids, but wherever this is done the fact is specified in Table IV. A dotted line in the figure indicates that data are not available for the elements along the line, while an unbroken line shows that no data have been omitted.

The four curves representing the reciprocals of absolute melting points, coefficients of expansion, atomic volumes, and compressibilities, have all the same form, though they are not so closely similar as those plotted by Richards. The deviations have been introduced by the addition of more data. The two curves at the top, giving the reciprocals of the melting points and coefficients of expansion,[1] are almost exactly similar where the data are complete. Thus the secondary minima in the melting points have corresponding maxima in the coefficients of expansion for indium and mercury, and a maximum may be predicted for gallium, though no determination has been made for this metal. The atomic volume curve does not show any corresponding maxima, and they seem also to be absent from the compressibility curve, though not all of them are known in the latter case.

The only minimum melting point which exactly corresponds to a maximum atomic volume, is that for helium. Below this in the table (Figs. 1 and 8), the maximum atomic volume shifts one group to the alkalies, while the minimum melting point continues to remain in the zero group. In a very similar way carbon is the only element of minimum atomic volume which has the maximum melting point. In the next series the maximum melting point again comes in the fourth group with silicon, but the minimum atomic volume has shifted one group to aluminium in Group III. In the next period molybdenum has the highest melting point, but the element of lowest atomic volume is either ruthenium or columbium, the latter if the density used is correct, but as to this there seems to be considerable doubt, so the minimum is probably at ruthenium. In the next period osmium has the lowest atomic volume, while tungsten with an atomic number two less, has the highest melting point.

To a considerable extent,[2] the rule holds that elements of low characteristic valence have low melting points, high atomic volumes, high co-

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[1] In the figure this curve seems to have much flatter maxima than the one above it, but this is mostly due to the fact that the maxima, which lie in the helium group, are omitted from this curve on account of the absence of data.

[2] This is not a true, but only an apparent relation, as is shown later.

efficients of expansion, and high compressibility. On the other hand, to the same extent, elements of high maximum characteristic valence have low atomic volumes, small coefficients of expansion, small compressibilities, and high melting points. Blom[1] has calculated a quantity, W, which he finds to have the dimensions of a cohesion. His equation for W is

$$W = \text{constant}\ \frac{\nu^2.A}{V^{1/3}}$$

where ν is the frequency calculated from the specific heats, A is the atomic weight, and V is the atomic volume. The curve for log W has the general form of the melting point curve, and the reciprocal of this curve would therefore have the general form of those plotted in Fig. 6. In other words, the four properties plotted in Fig. 6 are closely related to the cohesion, or it may be considered that the cohesion, or the attraction between the particles, conditions all of the other four properties. The point at which the parallelism between *valence* and *cohesion* meets its worst failure is in the case of the sub-group elements such as copper and zinc, which fall just beyond the eighth group, since the valence of these elements is low and their cohesion high. Therefore a better rule than the above is that in Fig. 2 the elements at the ends of the PERIODS He, Ne, A, Kr, Xe, Nt, are elements of high atomic volume, high coefficients of expansion, high compressibilities, low cohesion, and low melting points, while the elements at the middle of the short and long periods, and around the eighth group near the middle of the very long period, are in general the elements of high cohesion and melting points, and low atomic volumes, compressibilities, and coefficients of expansion.

There is also, as might be expected, a general relation between the hardness of an element and the properties under discussion. Thus, the very hard elements lie near the middle of the PERIODS while the softest elements lie near the ends of the periods.

From the above considerations it seems likely that the apparent connection between maximum characteristic valence and cohesion, which however fails so badly in the case of elements of low valence on the inner loop, is not real, but that the *cohesion* is conditioned by the spacing of *all* the electrons of the atom external to the nucleus, and that this spacing is a periodic function varying in the *periods* corresponding to those given in Fig. 2. On the other hand, the *valence* varies in SERIES, and only partly according to the periods. Thus the valences 1, 2, 3, 4, 5, 6, 7 depend only on the position in the series; and only the occurrence of the two valences 0 and 8 depends upon the position in the periods.

It seems probable that the atom is a system consisting of a positive nucleus, surrounded by one or more negative electrons which are describing

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[1] *Ann. Physik*, [4] **42**, 1397–1416 (1913).

orbits at a high speed. It is not improbable that the force which keeps two atoms apart is due to the repulsion of the negative electrons of one atom for those of the other. The compression of a solid would bring these atoms closer together and the closer approach of the external electrons would rapidly increase the repulsion. The principal decrease in volume, is, in all probability, most largely due to the decrease in distance between the atoms. When such large pressures as those used by Bridgeman are used, it would seem likely that there may be a considerable decrease in the size of the atoms themselves. That the atoms are compressible would seem almost certain, but the possibility exists that the atoms may be very much less compressible than the spaces around them.

The Dimensions of Atoms.

It is of interest in this connection to compare what are often called atomic diameters, but which are more properly considered as the distances between the centers of two atoms in a gas during a collision, as determined from the kinetic theory, and the distances between the centers of the same atoms in their positions of equilibrium in the solid or liquid state. Such a comparison is given in Table V.

TABLE V.—ATOMIC DIAMETERS OF MONATOMIC GASES (DISTANCE BETWEEN ATOMIC CENTERS DURING COLLISION) AS DETERMINED FROM THE KINETIC THEORY, AND THE DISTANCES BETWEEN THE CENTERS OF THE ATOMS IN LIQUIDS OR SOLIDS.

Substance.	Number of external electrons.	Atomic diameter × 10^8 cm. in gases at 0° C. = D.	Distance × 10^8 cm. between centers of atoms in solids or liquids.	T_m/V.
			3.38 (—258° adsorbed in charcoal)	
He	2	1.7	3.94 (—271.5°)	0.085
Ne	10	2.1	3.17 (calc.)	1.04
A	18	2.5	3.56 (Liq., —189°)	3.0
Xe	54	3.2	3.94 (Liq., —102°)	3.6
Molecular Diameters of Diatomic Gases.				
H_2		2.1	3.12 (—252°)	
N_2		2.8	3.56 (—252.5°, solid)	
O_2		2.6	3.33 (—252.5°, solid)	

At first sight it might seem that the data on the distance between the centers of the atoms in gases during collisions could be explained on the basis that the lighter atoms approach each other more closely because they have the greater velocities, but that this is not true can be seen when it is remembered that the heavier atoms have the greater momentum, so the closer approach of the lighter atoms of the helium group is due to the fact that either (1) the atoms are smaller, or (2) that the fields of force around them are less intense on account of the fact that they have a smaller number of electrons external to the nucleus (as well as a higher nuclear charge). Probably each of these factors plays a part. Thus if the number of external electrons is equal to the nuclear charge, and we use the hypothesis that the nuclear charge is equal to the atomic number, then it might reasonably be expected that the 54 external electrons of xenon would both occupy more space, and create a more intense field of force than the 2 external electrons of helium. If the number of external electrons is indicated by N, then $\frac{N_{Xe}^{1/3}}{N_{He}^{1/3}} = 3$, so that if the distances between the centers of like atoms during collision were proportional to the cube root of the number of external electrons, then since this distance D is 1.7 for helium it would be 5.1 for xenon, while the calculated value is less than this, or 3.2. However, the momentum of the xenon atom is 5.7 that of the helium atom, so that the higher momentum would cause the atoms to approach closer than a distance of 5.1, but it is doubtful if even a momentum 5.7 times as great would be able to reduce D to 3.2. In Table V*A*, values are given for different roots of N, the momentum, and the calculated values of D from Table V.

TABLE V*A*.

Atom.	Relative momentum.	$D \times 10^8$ cm.[1]	$k_1N^{1/5}$.	$k_2N^{1/4}$.	$k_3N^{1/3}$.	N.
He............	1.0	1.7	1.7	1.7	1.7	2
Ne............	2.2	2.1	2.3	2.5	2.9	10
A.............	3.15	2.5	2.6	2.9	3.5	18
Xe............	5.7	3.2	3.3	3.9	5.1	54

The table shows that the distance of approach D varies quite closely as the fifth root of the number of external electrons N. If all of the atoms at 0° had the same momentum this might be thought to be the law which conditions their approach, but since the momentum increases rapidly with the mass of the atom, it is probable that D would vary more nearly as the fourth or third root if the momenta were the same. That D is found to vary as the fifth root of N, when the momentum is involved in addition to the number of external electrons N, is probably due to the fact that the momentum is a function of the atomic weight, which is a function of the atomic number, or N, in this case the number of charges

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[1] The values of D are taken from Landolt-Börnstein-Meyerhoffer *Tabellen* and are calculated from the equation $D = \sqrt{\frac{350\ \rho\bar{c}}{\sqrt{2}\ \pi n \mu}}$, where n is the number of molecules per cc. at 0° and 760 mm. Hg = 2.705×10^{19} cm.$^{-3}$, and μ is the viscosity of the gas, with the application of Sutherland's correction for cohesional force (*Phil. Mag.*, **17**, 320 (1904)), and Jean's correction for the persistence of velocities. The constants involved in this calculation are not very well known, and may vary for different kinds of atoms, but are probably the same for atoms of the same kind, such as those of the helium group. In a table prepared by the General Electric Company the values of D are given as follows: He = 1.905, A = 2.876, and these numbers are in the same ratio as those given by Landolt-Börnstein. On account of the uncertainty in the constants, it has not been thought worth while to recalculate the numbers, since the relative values would not be affected.

on the nucleus. In other words the various factors involved are functions of the same variable.

If the heavier helium group atoms are larger it may seem surprising that in the liquid state the distance between the atomic centers is practically the same, but this is due to the fact, as is shown by the last column in Table V, that the cohesion increases very rapidly with the atomic number. At present little is known as to the actual dimensions of atoms, and it seems probable that their dimensions are smaller, rather than larger than those usually cited. It is somewhat difficult to know what is meant by the atomic diameter, since in a simple atom, such as hydrogen, it might be expected that the diameters would be very different in the different directions.

In the calculation the number of gram molecules per gram molecular weight was taken as 6.062×10^{23}. According to the table the centers of the atoms in liquids or solids are much farther apart than the distance between the centers in gases at the time of their closest approach during collision. Even in their collisions it is improbable that the exterior electrons come very closely in contact in comparison with their dimensions. The data in Table V are in accord with the usual assumption that a large part of the space in liquids and solids is outside the boundaries of the atoms, though the interatomic spaces are certainly regions in which the electro-static and electro-magnetic forces are intense.

Atomic Frequencies.

The properties of the elements which have been considered thus far are properties of the atoms in bulk, undoubtedly conditioned however, by the structure of the single atoms. An endeavor has been made to find some property which is more characteristic of the atoms themselves. This attempt has met with success in the discovery that the atoms of solid substances have characteristic atomic frequencies. While in the simple theory the atomic frequency may be considered as independent of the nature of the substance, this is not altogether true, since, for example, there is found to be a difference in the values obtained for diamond and graphite. On the other hand, it is remarkable, as has been pointed out by Nernst, that the frequencies of sodium atoms in metallic sodium and in sodium chloride, though not exactly, are approximately the same, so as a first approximation the atomic frequencies may be considered as a property of the atom.

The characteristic equation for the frequency is the formula for the simple pendulum

$$\nu = \frac{1}{2\pi}\sqrt{\frac{D}{A}}$$

where A is the atomic weight, and D is the directional force. The frequencies for the different atoms are given in Table II, and in Fig. 10.

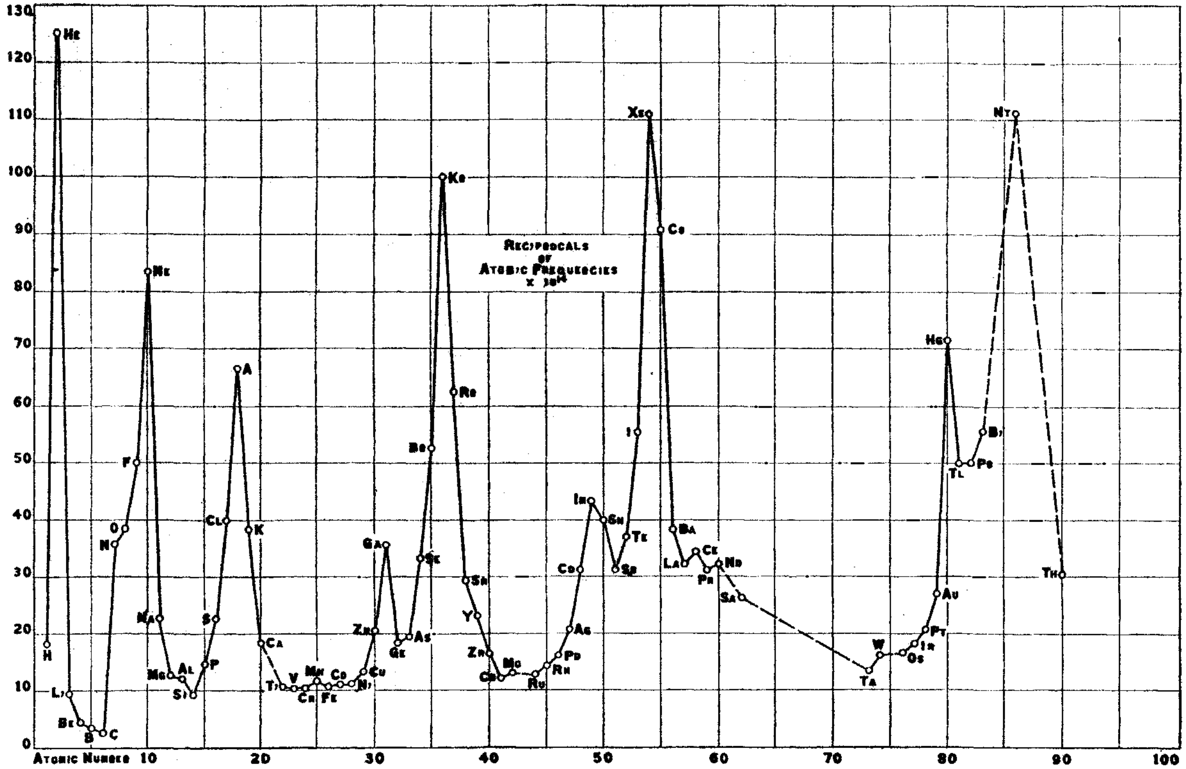
Reciprocals of Atomic Frequencies x 10^14
Atomic Number
0
10
20
30
40
50
60
70
80
90
100
110
120
130
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
A
K
Ca
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Cb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sa
Ta
W
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Nt
Th

Fig. 10.

However, in the figure the reciprocals of the frequencies have been plotted instead of the values themselves, since the change makes the curve comparable with those representing the atomic volumes, compressibilities, coefficients of expansion, and reciprocals of the melting points, as plotted in Fig. 8.

The different equations which may be used for the calculation of ν have been discussed by Blom,[1] who has compared them and finds that no one is exclusively better than the others. The equations are given below, where the symbols have the following meanings:

T_m = absolute melting point.
d = density.
V = atomic weight.
K = compressibility.
α = linear coefficient of expansion.
C_p and C_v = atomic heats.

1. Einstein's equation.[2]

$$D = \text{const.}\ \frac{V^{1/3}}{K}.$$

$$\nu = 3.3 \times 10^7 . A^{-1/3} . d^{-1/6} . K^{-1/2}.$$

2. Lindemann's equation,[3] derived from the hypothesis that at the melting point the orbits of the atoms become just large enough so that the atoms come into direct contact, and that on account of the consequent energy exchange between the atoms, they are no longer able to hold to their positions relative to the space lattice, but begin to slide past each other.

$$D = \text{const.}\ \frac{T_s}{V^{2/3}}.$$

$$\nu = 3.1 \times 10^{12} . \sqrt{\frac{T_m}{A . V^{2/3}}}.$$

3. Alterthum,[4] from dimensional considerations, found the following:

$$D = \text{const.}\ \frac{1}{\alpha V^{2/3}}$$

$$\nu = 4.2 \times 10^{11} \sqrt{\frac{1}{A \alpha V^{2/3}}}$$

4. Benedicks[5] considered D as proportional to the internal pressure of the solid as determined by van der Waal's equation.

$$D = \text{const.}\ \frac{R}{3 \alpha V}.$$

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[1] *Ann. Physik*, **42**, 1397–1416.

[2] *Ibid.*, **34**, 170 (1911); **35**, 679 (1911).

[3] *Inaug. diss., Berlin*, 1911; *Physik. Z.*, 11, 609–12 (1910).

[4] *Verh. deutsch. physik. Ges.*, **15**, 68 (1913).

[5] Benedicks, *Ann. Physik*, **42**, 154 (1913).

$$\nu = 6.3 \times 10^{11} \sqrt{\frac{d}{\alpha}}.$$

5. Grüneisen's[1] equation:

$$D = \text{const.}\ \frac{C_v}{3\alpha V^{2/3}}$$

$$\nu = 2.9 \times 10^{11} \sqrt{\frac{C_v}{3\alpha V^{2/3}}}\ (\text{gr. cal.}).$$

6. Debye's well known equation is

$$\nu = 7.4 \times 10^7.A^{-1/3}.d^{-1/6}.K^{-1/2}.f(o)^{-1/2},$$

where $f(o)$ is a function of Poisson's constant. Debye considers ν to have a maximum value, which is the one given by the equation. The other authorities cited consider ν to have only one value under definite conditions. Blom finds, however, that the more exact equation of Debye does not give better values, since the data involved are not so good as those required by some of the other equations.

Of all the equations given, only that of Lindemann can be used if a comparison including nearly all of the elements is desired, so this method of calculation has been chosen for the data plotted in Fig. 8. About half of the values have been calculated from those given by Biltz,[2] who used a different constant, and the rest have been calculated from the other data given in Table II.

The figure shows that the curve has a considerable resemblance to that giving the reciprocals of the melting points (Fig. 6). The greatest minimum in atomic frequencies (maximum on the curve) comes at helium, lesser minima at neon and argon, and then greater minima at krypton, xenon and niton. The secondary minima come at gallium, indium, mercury, just as in the melting point curve. The maxima occur at carbon, silicon, titanium to nickel, columbium to ruthenium, tantalum, and thorium (U), with minor maxima at germanium, antimony, and thallium to lead.

As has been pointed out by Biltz, carbon, which forms the greatest number of compounds of any of the elements, many of them very complex, has by far the highest atomic frequency (37.0), and silicon, which does the same to a lesser degree, is also at a peak in the frequency curve, but with a value only about one-third of that of carbon. The elements which form a large number of complex ammonia compounds, occur at maxima in the frequency curve (minima in the reciprocal curve). Such elements are chromium, cobalt, platinum, etc. Further, elements just to the right of these maxima, on descending branches of the frequency curve, also form these complexes. Beryllium, which forms very stable

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[1] Grüneisen, *Ann. Physik*, 39, 293 (1912).

[2] *Z. Elektrochem.*, 17, 170–4 (1911).

hexammines, has a very high frequency, equal to 23.4. The fact that on the curve hydrogen has the same relative position as the halogens, is taken by Biltz[1] to indicate that it belongs to the halogen group, but this does not prove the point, since in chemical behavior hydrogen is not like the halogens. A study of the frequency curve will reveal many other relations which cannot be discussed here.

According to Equations 1, 2, 3 and 5, the following quantities must be proportional to each other:

$$\frac{1}{K},\ \frac{T_m}{V},\ \frac{R}{3\alpha V},\ \text{and}\ \frac{C_v}{3\alpha V}$$

Blom[1] considers that these represent the *cohesion pressure.* He plots the logarithm of this cohesion pressure for each of these functions, and all of the curves have exactly the general form which the curve of the reciprocals of the atomic frequencies would have (Fig. 8) if it were inverted. A comparison of the above functions shows the relationships which exist. Thus from (2) and (3) $T_m = \text{const.}\ \alpha$ and from (2) and (5) $T_s \backsim C_v/\alpha$. A number of these relations have been studied by Grüneisen.[2] From (1) and (2) it may be found that $K = \text{const.}\ V/T_m$. Richards finds empirically that this relation does not contain the density to a high enough power, and that the expression $K = \text{const.}\ \dfrac{A}{D^{1.25}(T_m - 50)}$ is much more exact. In order to correspond more closely to the above expressions Richards' equation should be put in the form $K = \text{const.}\ \dfrac{V}{(T_m - 50)\ D^{0.25}}$.

This equation may be interpreted to mean that the compressibility varies not only as the atomic volume, and as the reciprocal of the melting point, but also as the reciprocal of some function of a quantity which varies very nearly as the density. It is possible that this quantity is the number of external negative electrons in the gram atom divided by the atomic weight, or the number of external negative electrons per unit volume. This may be called the electronic density (d_ϵ). Reasoning from the standpoint of modern theories of atomic structure, there would seem to be no reason why the density of the material itself should enter into the theoretical equation as a modifying factor in addition to its occurrence in the atomic volume, but it is easily apparent that the electronic density might be a factor.

An empirical equation which holds as well as that given by Richards, for the sixteen cases for which he calculates the values,[3] and which is simpler, is

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[1] *Loc. cit.*

[2] *Ann. Physik,* **33,** 33, 65 (1910); **39,** 300 (1912).

[3] THIS JOURNAL, **37,** 1652 (1915).

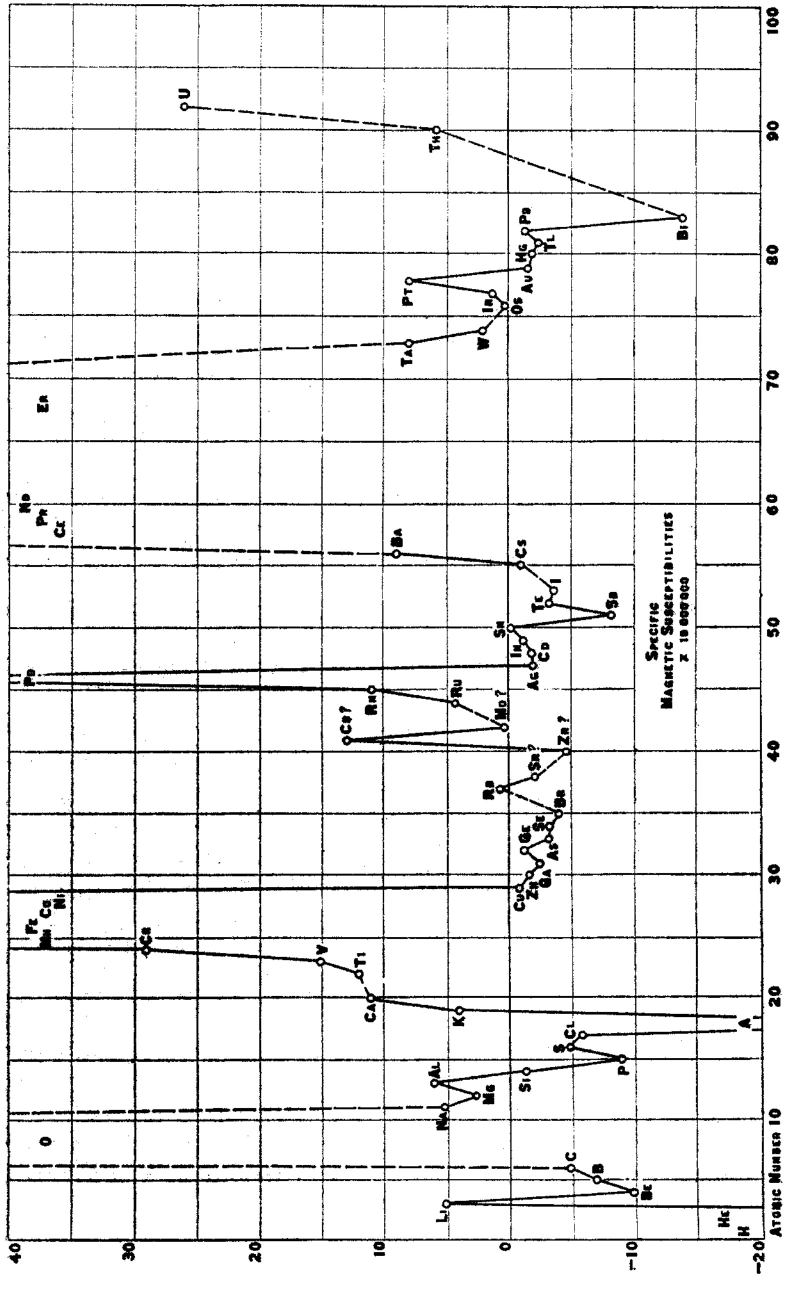
Specific
Magnetic Susceptibilities
× 10 000 000
Atomic Number
10
20
30
40
50
60
70
80
90
100
40
30
20
10
0
−10
−20
H
He
Li
Be
B
C
O
Na
Mg
Al
Si
P
S
Cl
A
K
Ca
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Rb
Sr?
Zr?
Cb?
Mo?
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Cs
Ba
Ce
Pr
Nd
Er
Ta
W
Ir
Os
Pt
Au
Hg
Tl
Pb
Bi
Th
U

Fig. 11.

$$K = \text{const.}\ \frac{N}{T_m D^{1.25}}.$$

Which equation gives better results in general has not been tested.

Hardness.

The hardness of the elements[1] has been studied by Rydberg, who finds that the curve for hardness has the general form of the melting point curve, or of the curve which represents cohesion (Fig. 12). The minor differences in the two sets of curves are as follows: In the melting point or cohesion curves the line of minor minima runs gallium, indium, mercury, while in Rydberg's curve of hardness it runs gallium, indium, thallium, but this difference between mercury and thallium is probably due to the temperature at which the hardness of the mercury was determined as compared with that at which the thallium was measured. Another point of difference is that chromium stands very much higher in the curve of hardness than in either of the other curves. The data for hardness are very inaccurate, but the conclusion is inevitable that the hardness is proportional to some function of the cohesion. Traube[2] finds that the hardness and modulus of elasticity also run parallel. Blom[3] gives curves for a number of oxides of the type RO, and shows that when the mean atomic heat, the square root of the atomic volume, and the softness (reciprocal of the hardness on Moh's scale) are plotted, as functions of the atomic weights, the three curves have the same form. The same relation is found to hold for oxides of the form R_2O_3.

The Elastic Properties of the Elements.

Johnston[4] gives tables which show that for the twelve metals which he considers, the hardness, modulus of elasticity (Young's), rigidity, and tenacity, all increase in the same order, and in the order in which the compressibility decreases. A study of the elements as a whole, shows that somewhat the same general relations hold to some extent for elements which are not metals, but the exceptions to the rule are numerous, and the magnitude of the exception is often considerable. The regularity of the behavior of the metals with respect to these properties is remarkable.

Cohesion.

A very simple experiment upon isotopes would give much light as to which part of the atom by its variation in structure or mass, conditions the changes in cohesion. Fig. 12 shows the variation in the values of T_m/V, where T_m is the absolute melting point and V the atomic volume. Blom[3] claims that the values of this function represent the cohesion. In the curve the logarithm of the function is plotted, since other-

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[1] *Z. physik. Chem.*, **33**, 359 (1900).

[2] *Z. anorg. Chem.*, **34**, 420–4 (1903).

[3] *Loc. cit.*

[4] *Z. anorg. Chem.*, **76**, 365 and 367 (1912).

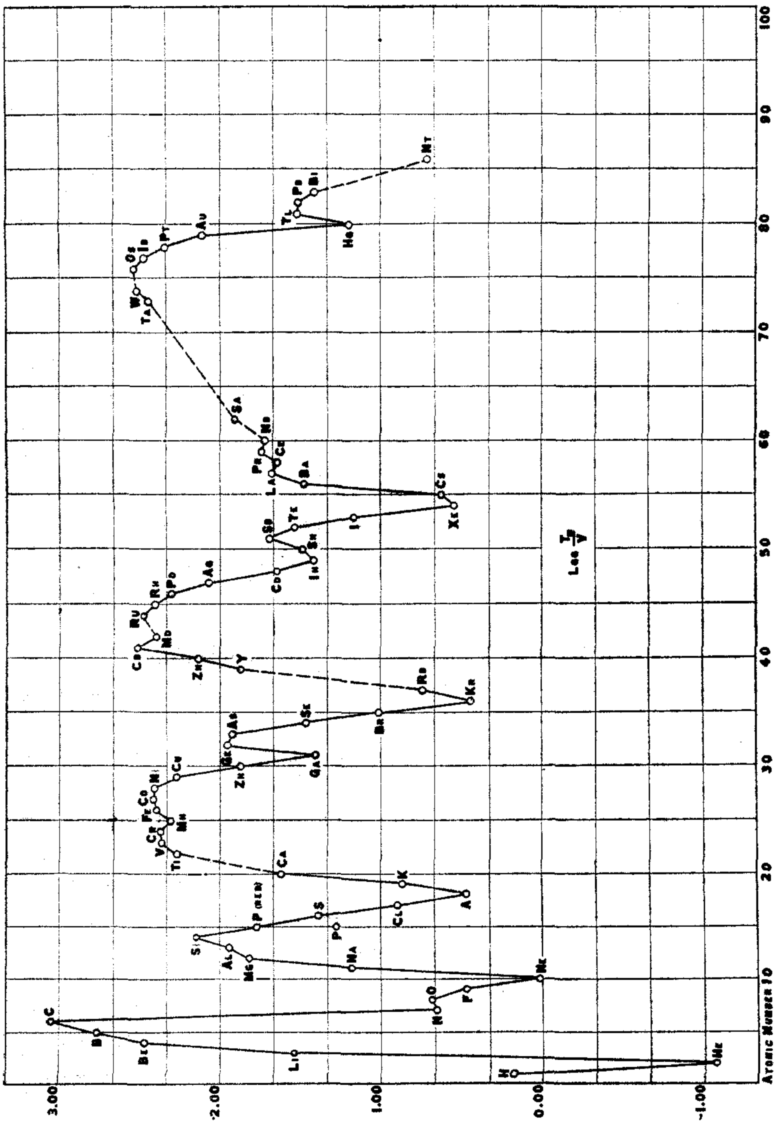
Log $\frac{T_B}{V}$
Atomic Number 10
20
30
40
50
60
70
80
90
100
3.00
2.00
1.00
0.00
-1.00
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P (red)
P
S
Cl
A
K
Ca
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Y
Zr
Cb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sa
Ta
W
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Nt

Fig. 12.

wise the curve for the function itself would be difficult to plot on one page. Lindemann[1] proves by thermodynamics, on the basis of certain assumptions, that the melting points of isotopes are proportional to their atomic weights. According to this conclusion lead from thorium should have a melting point about six degrees greater than that of lead from radium. Lindemann's result may be stated as follows in terms of recent atomic theories: Whenever the nuclear charge remains constant the melting point and the cohesion vary as the mass of the nucleus. He concludes, therefore, that "the forces of attraction and repulsion between atoms, the interaction of which results in the solid state, have their origin in the nucleus." Lindemann's calculation, however, involves several doubtful assumptions, so it is not certain that his conclusion is correct, and it may be well to consider the question from another point of view.

Following out his line of reasoning, it could be predicted that if an isotope of carbon, of atomic number six (and possibly of nuclear charge six also) could be obtained with a mass of 14, its melting point would be about 4400°. If this should then undergo a beta change, it would become nitrogen, with a melting point of 63°, or of about one-seventieth the melting point which it had before the loss of the one negative electron from the nucleus. Presumably when the nucleus loses a negative electron, the number of external electrons increases by one in the formation of the neutral atom. If this is true, a change of one electron from the nucleus into an external electron, without a change of mass, would cause this enormous change of melting point amounting to more than 4300°, or of six thousand per cent. when calculated on the basis of the melting point of nitrogen. If Lindemann's idea is on the other hand incorrect, and if isotopes have the same melting points, then it will be seen that the isotope of carbon of mass 14 would have a melting point of about 3800°, and the melting point would be changed about sixtyfold by the change of one electron from the nucleus to the external region. Changes similar to these actually occur among the radioactive elements, but the changes of melting point with these heavier atoms are not so striking. A single beta change (that is the loss of an electron by the nucleus, and the resultant increase of one in the nuclear charge, and probably in the number of external electrons) may decrease the melting point, for example, in the beta change from an isotope of lead to an isotope of bismuth the decrease is 56°, or in another case, such as the beta change of thorium, it may increase the melting point. Thus the great changes of cohesion which occur inside of one period in the periodic system, whether of electrostatic or of electro-magnetic origin, and more probably of both, must depend much more on the arrangement and frequencies of the particles, either in the nucleus, or in the external region of the atom, than they do

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[1] *Nature*, 95, 7 (1915).

upon the changes of mass. Thus, in the first period, as the cohesion curve shows, there occur both the lowest minimum and the highest maximum in cohesion in helium and carbon, respectively, elements which differ in atomic mass by only eight. It is evident that such extreme changes would result from differences in arrangement only when the number of electrons is small.

The question under consideration here is not the origin of cohesion, but of its variation with the atomic number. This variation may be caused either by a change in arrangement or frequency in the nucleus, or among the external electrons, but there are several arguments which seem to indicate that it is the external changes which are the important ones, and that it is the external electrons which determine the spacing of the atoms, and therefore the atomic volume. It is evident, of course, that it is the nuclear charge which determines the number of these electrons, and therefore their arrangement. There is a very close relation between the variations of valence in the periodic system, and the variations in cohesional properties. Since the valence is undoubtedly conditioned by electrons external to the nucleus, it is probable that the same is true of the related cohesional properties, but that it is the whole system of external electrons which is effective in the latter case. The nuclei of atoms fall into two series, which differ in stability according as the atomic number is odd or even. This subject will be more fully considered in a later paper, but as to the fact there is no doubt. Now neither the chemical nor the physical properties of the elements show this marked distinction between the odd and even numbered elements, which would seem to indicate that it is not the changes in the nucleus which are here effective. On the other hand, it must be realized that electromagnetic effects caused by the rotation of the nucleus, or of its parts, *may* have an effect upon the arrangement of these external electrons.

The cohesion is not a function of the properties of the atoms alone, but it is also conditioned by the form of the space-lattice in the solid, as is evident if graphite and the diamond are compared.

Magnetic Susceptibility.

In Fig. 11 the susceptibilities of the elements per unit mass times 10^7 have been plotted. Most, but not all, of the data were taken from a paper by M. Owen.[1] The maxima for the elements of positive susceptibility come with oxygen, and then an extremely high maximum in the first eighth group, Fe, Co, and Ni. The next maximum is not nearly so high, but comes in the eighth group again with Pd. After this there is a high maximum in the rare earths, a minor maximum in the eighth group with Pt, and a maximum of moderate height at uranium. It is interesting that the highest maximum is in the eighth group the FIRST time it ap-

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[1] *Ann. Physik*, [4] 37, 657–99 (1912).

pears in the system, and that the next highest maximum comes with the FIRST and only appearance of the rare earth group. Both of these groups are related to each other in that in them the valence remains constant as the atomic number increases. Neon, *not* determined by Owen, seems to be a minimum on the susceptibility curve. At least this is true if the experimental work is trustworthy. The minima found by Owen are Be, P, Zr, Sb, and Bi. A rough relationship between the atomic volume curve and the susceptibility curve may be seen by bringing the two together, but there are many points of deviation between the two. A plot showing the atomic magnetism would of course greatly exaggerate the deviations from the zero line for elements of high atomic weight.

Fig. 11 is interesting in that it proves conclusively that the old standard rule that elements of the even series are paramagnetic, and that elements of the odd series are diamagnetic, is not *entirely* correct, and that, for example, the susceptibility changes from positive to negative in a single series. The fifth series, however, seems to be entirely negative, as is also the seventh, and the ninth, as far as it is known.

Thus in the short periods there is a change from diamagnetic to paramagnetic in each *series*, but in the long periods beginning with argon, which is strongly diamagnetic, there is a first jump to a slightly paramagnetic substance in potassium. Then in these long periods *the elements on the front of the outer loop and the back of the inner loop are paramagnetic; those on the front of the inner loop and the back of the outer loop are diamagnetic.* Beginning with the long periods, *the iron group elements are the maxima of the paramagnetic elements* (with an additional maximum in the rare earths), and *the maxima of diamagnetism in all probability occur in the zero group elements.* Thus the zero and eighth groups form the two extremes in the curve representing magnetic properties, just as they do with respect to atomic volume, cohesion, and related properties. This suggests that cohesion is partly due to magnetic forces. That it is not the only factor involved is, however, shown by the many deviations between the course of the two sets of curves. Thus carbon, which forms a maximum in the cohesion curve, is very far from the maximum on the susceptibility curve.

The Number of Lines in the Spectrum of an Element.

On pages 36 and 37 of their book "Die Spektren der Elemente bei Normalem Druck," Volume 1, Exner and Haschek give curves showing the relationship between the atomic weight and the number of lines in the spectrum of an element. It is somewhat difficult to see just how they have decided upon the number of lines in each case, as they give only one line for the spark spectrum, and none for the are spectrum of hydrogen, and only one line for the arc spectrum of carbon. The values of such results depend upon their method of choosing the lines to be counted.

They find that the curve giving the number of lines in the spark spectrum has maxima at V, Mo, W, and U, and this falls very nearly along the line of maximum melting points. Secondary maxima occur at Fe, Nd, Er and Ir. Of all of the elements they find uranium with the heaviest atom and the greatest number of external electrons, to give the most lines.

Complex Compounds of the Periodic System.

It is a well-known fact that the *elements which form the greatest number of compounds*, such as carbon and silicon, *are elements of low atomic volume*. Thus they are elements of high cohesion, and they also have a high valence.

The stability of a particular type of complex compounds has been studied carefully by Ephraim, who measured the temperature at which the vapor pressure of ammonia from complex metal ammonia compounds of the type $MX_2.6NH_3$, becomes equal to 500 mm.

TABLE III.—TEMPERATURES AT WHICH THE VAPOR PRESSURES OF HEXAMMINE COMPOUND BECOMES EQUAL TO 500 mm.

Metal.	Atomic volume.	T_m/V.	Dissociation temperatures. Hexammines. Chlorides.	Sulfates.
Be	5.3	296.4	High temp.	...
Ni	6.7	258.0	165	398
Co	6.7	262.0	130	378.5
Fe	7.1	254.0	106.5	369
Cu	7.1	191.3	95	364.5
Mn	7.5	204.0	82	340
Zn	9.2	75.4	51	299
Cd	13.1	45.3	50.5	323.5
Mg	14.0	66	24.5	...
Hg, Sn, Pb	>14	<42	Do not give comparable compounds at room temperatures.	
Ca, Sr, Ba	..			

For any one series investigated, Ephraim[1] finds that the product of the cube root of the atomic volume ($V^{1/3}$) by the cube root of the temperature of decomposition ($T_D^{1/3}$) is practically a constant. In the case of the substituted ammonia compounds, the stability of the ammine seems to depend also upon the molecular volume of the organic base. The nature of the anion influences the stability.

The elements which form complex ammonia compounds belong, mostly, in the inner loop of the periodic table (Figs. 1 and 2) and are sub-group elements. On the whole, the elements at the left of the inner loop form the greatest number of these compounds. That the stability increases as the atomic volume of the metal decreases, is apparent from Table III, though there are some minor exceptions to the rule. Thus cadmium, with an atomic volume of 13.1, seems to form a more stable hexamminosulfate than zinc, with an atomic volume of 9.2. However, the ammino-

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[1] *Ber.*, 45, 1323 (1912); *Z. physik. Chem.*, 81, 513, 539 (1913); 83, 196 (1913).

chlorides of these elements follow the usual rule. The values of T_m/V for the elements which represent the cohesion, seem to be in as close a relation to the dissociation temperatures of the chlorides as the atomic volumes.

Valence and Electroaffinity.

The important subject of the relation between the periodic system and electroaffinity has been so thoroughly treated in the classic papers of Abegg and Bodlander,[1] and Abegg,[2] that it need not be considered here. It may be pointed out that while in general, in any one group, the positive character of the elements increases as they go down the rod on which they lie in the table, this rule is reversed for those elements which are at the left (iron group) and on the front of the inner loop and for the rare earths. Thus copper, silver and gold are progressively more negative, and the same is true of iron, ruthenium, and osmium, and also of zinc, cadmium, and mercury.

Other Properties of the Elements.

According to Cary Lea,[3] the maxima for color in the ions formed by the elements are in the three-eighth groups and in the rare earth group, with a final maximum at uranium. This is interesting in so far as it is true, in that this relationship is similar to that found for the maxima of susceptibility, for in both cases the maxima occur in the groups where the valence remains constant as the atomic number rises.

Other properties of the elements, beside those discussed in this paper, which vary in a more or less regular way with their position in the periodic system, are given in the following list, which, however, is not complete:

Electrical conductivity[4]
Conductivity for heat
Boiling points[5]
Heats of chemical combination[6,7]
Electrode potentials[7]
Changes of volume on fusion[8]
Solubility[9]
Latent heat of fusion[10]

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[1] L. Abegg, "Die Valenz und das periodische System Versuch einer Theorie der Molekularverbindungen," *Z. anorg. Chem.*, **39**, 330–80 (1904).

[2] Abegg and Bodlander, *Ibid.*, **20**, 453–99.

[3] *Chem. News*, **73**, 203, 260–2 (1896); *Z. anorg. Chem.*, **9**, 312–28 (1895); *Am. J. Sci.*, [3] **49**, 357 (1895).

[4] Sander, *Elektrochem. Z.*, **6**, 133.

[5] Carnelley, Numerous papers in *Trans. Chem. Soc.*, *Proc. Roy. Soc.* and *Phil. Mag.*, from 1876 on.

[6] Laurie, *Phil. Mag.*, [5] **15**, 42 (1883); Richards, *Trans. Chem. Soc.*, **99**, 1201 (1911); Carnelley, *Phil. Mag.*, [5] **18**, 1–22 (1884).

[7] Abegg, *Z. anorg. Chem.*, **39**, 330–80 (1904).

[8] Topler, *Wied. Ann.*, **53**, 343 (1894).

[9] Abegg and Bodlander, *Am. Chem. J.*, **28**, 220–8 (1902); Locke, *Am. Chem. J.*, **20**, 581–92 (1898); **26**, 166–85, 332–45 (1901); **27**, 455–81 (1902).

[10] Rudorf, "Das Periodische Gesetz," pp. 143–9.

Ionic mobilities[1]
Ultraviolet vibration frequencies[5]
Refractive indices[2]
Spectra[3]
Mechanical properties[4]

Summary.

1. In this paper a periodic table has been presented, which shows graphically the relations between the main and the sub-groups of elements. The main defect of the periodic tables which have been designed formerly, is that they do not show these relations correctly.

2. The table arranges the elements in the exact order of their atomic numbers, and gives no blanks for unknown elements which do not correspond to atomic numbers as determined by Moseley's work on the X-ray spectroscopy of the elements.

3. It also plots the elements according to their atomic weights, so the isotopic forms of an element may be shown graphically on the table, and the alpha and beta decompositions of the radioactive elements may also be plainly depicted.

4. Both the zero and the eighth groups fit naturally into the system.

5. The table may be best represented as a helix in space, but may be shown as a spiral in a plane. The space form is represented by its vertical projection on a plane, but drawn with line perspective so that it may easily be visualized.

6. Beginning at the zero group, the maximum positive valence of a group is found by counting toward the front and toward the right, Li = 1, Be = 2, etc., and negative valence by counting toward the back, Fe = —1, O = —2, N = —3, etc.

7. The elements in the table divide themselves into cycles,

Cycle 0
Cycle 1 = 4^2 elements
Cycle 2 = 6^2 elements
Cycle 3 = 8^2 elements

but the latter part of the third cycle is missing. The cycles are each divided into two periods. The periods are as follows:

Period O_1
Period O_2
Period 1 = 2×2^2
2 = 2×2^2
3 = 2×3^2
4 = 2×3^2
5 = 2×4^2
6 = 2×4^2

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[1] Bredig, *Z. physik. Chem.*, **13**, 289 (1894).

[2] *Ibid.*, 149–57; Bishop, *Am. Chem. J.*, **35**, 84 (1906).

[3] *Ibid.*, 157–171; Baly, "Spectroscopy."

[4] *Ibid.*, 187–96.

[5] Byk, *Ann. Physik*, [4] **42**, 1417–53 (1913).

These relations are undoubtedly a numerical expression of a function connected in some way with the system according to which the nuclei of the elements have been built up.

8. Whenever the valence drops, in passing along the continuous line connecting the elements in the order of their atomic numbers, it always drops by seven, either from seven to zero, or from eight to one. In the latter case there is evidenced a certain sluggishness in the drop, so that it is not entirely complete, so that copper, silver and gold, the members of which should have the maximum valence one, often exhibits a higher valency, such as two for copper and three for gold.

9. The table arranges the groups into 5 divisions, numbered 0, 1, 2, 3, 4. These divisions comprise the following groups:

Division..............................	0	1	2	3	4
Groups..............................	0.8	1.7	2.6	3.5	4.4

The two groups of one division are said to be complementary. The sum of the group numbers of two complementary groups is always 8, as is also the sum of the maximum valences. The algebraic sum of their *characteristic* valences is, on the other hand, always zero. Thus the characteristic valence for Group 1 is +1, and for Group 7 is —1. The characteristic valence of the eighth group needs to be defined in this sense, and must be taken as —0, which accords with Abegg's valence system.

10. Another very important relationship given graphically in this table, and not at all by any other which the writers have found, is that between the main and the sub-groups in any one division. Whenever the group numbers in any one division differ considerably, as is the case in divisions 0 and 1, then the elements in the sub-groups are quite different chemically from the members of the main group, although they are in general alike in valence. As the group numbers in the division approach each other in magnitude, the elements of the sub-group become chemically much like those of the main group. This is true of groups 4A and B, where the group numbers are the same, and the two groups are practically indistinguishable in their general chemical nature.

11. On the outer cylinder the main Groups 1, 2, 3 become LESS positive as the group number increases, while the corresponding sub-groups become MORE positive.

12. Whenever the atomic volume of a main-group element is large, that of the corresponding sub-group element is small, and as the atomic volume of the main group element decreases, that of the sub-group increases, until the values become about the same in Groups 4A and 4B.

13. The rare earths are put in the third group, since their valence is three, and since if they are distributed around the table there are not enough known and undiscovered elements together to go around. Cerium may be classified either with the third or the fourth group. A discussion

of this minor question is given. The elements of the rare earth group (not including yttrium or cerium) decrease in basic properties as the atomic weight increases, which is exactly the opposite of the general rule. As has been explained in the paper, in the rare earths the atomic number, and therefore the nuclear charge, keeps on increasing, while the valence remains constant. On the other hand, it seems probable that the atomic volume tends to keep on as it usually does, but this tendency is masked partly by another influence which tends to keep the atomic volume constant. The rare earths lie on the front of the table, where the elements in general become less basic as the atomic number increases, so they, in this case, as they probably do with atomic volumes, effect a compromise between this tendency and that which seeks to cause the elements in a single group to become more basic with increase in atomic weight. The resultant effect is that they become less basic as the atomic number increases, but not with anything like the rapidity which would be shown if they were to go around the table in the usual manner. In this sense the rare earth group forms a loop of its own, but a loop of practically constant valence.

14. The periodic table shows the relation between the properties of the elements and the nuclear charge, and this is presumably equal to the number of external electrons. It is probably the spacing and arrangement of these electrons which determines the chemical and most of the physical properties of the elements.

15. In Table II it may be seen that the spiral forms a series of lines which in any part of the table lie very nearly parallel. This is a graphical expression of the well-known fact that the atomic weights increase in a very regular way in any one group, and at about the same rate in all of the groups. This regularity may be explained on the basis of the theory of Harkins and Wilson, that the nuclei of the elements are built up from hydrogen and helium nuclei, according to a regular system, according to which the differences in mass in any one group are generally due wholly to differences in the number of helium nuclei present, at least in the case of the lighter elements.

16. In Fig. 4 and 5 the relations of the radioactive elements to the periodic table have been given. The nature of isotopes is discussed.

17. A number of figures and tables have been given to illustrate the relationship between the cohesional properties of the elements and the periodic system. The following properties have been plotted graphically: Melting points, with lines of maxima and primary and secondary minima, atomic volumes, density, cubic coefficients of expansion, compressibility, susceptibility, atomic frequency, elastic properties, cohesion and hardness. For the discussion of the relations between these properties the body of the paper should be consulted.

18. A theory as to the factors conditioning variations of cohesion is given.

19. The ordinary theory, that the atoms in solids do not occupy all of the space is supported.

Several problems related to the periodic system are now under investigation in this laboratory. One of these is the endeavor to prove whether or not the exceptional atomic weight of chlorine is due to its existence in two isotopic forms. This is a very important problem in its bearing on the theory of complex atoms, whatever may be the facts. Work is also being done upon the melting point of lead derived from radium. A third problem is the attempt to prove whether ordinary lead is or is not a mixture of isotopes.

The writers wish to thank Mr. W. A. Roberts for aid in the construction of the model of the periodic system.

The next paper in this series will be on "The Evolution of the Elements and the Stability of Complex Atoms."

[Contribution from the Wolcott Gibbs Memorial Laboratory of Harvard University.]

THE DENSITY OF LEAD FROM RADIOACTIVE MINERALS.

By Theodore W. Richards and Charles Wadsworth, 3rd.

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The startling differences observed by several investigators[1] in the atomic weight of lead from radioactive sources obviously suggest that other properties also may vary in different specimens; and the comparison of these may be of service in tracing the true causes of the differences in atomic weight. The phenomena are of interest whether or not one accepts the plausible hypothesis of Soddy and Fajans concerning the "isotopes." In a new field of this sort, of course, as great a variety of facts as possible is peculiarly important.

The present paper details one of a number of lines of research in this direction which are in progress in this laboratory, with the idea of finding out more about the substance admixed with ordinary lead in radioactive minerals—a substance so like ordinary lead that the usual modes of purification do not separate it, and that it produces no change in the ultraviolet spectrum.

The first among the properties to be studied was density.[2] The densi-

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[1] Richards and Lembert, This Journal, 36, 819 (1914); Honigschmid and St. Horovitz, *Compt. rend.*, 158, 1798 (1914); M. Curie, *Compt. rend.*, 158, 1676 (1914); Soddy and Hyman, *J. Chem. Soc.*, 105, 1402 (1914); also especially, Hönigschmid, *Sitzb. k. Akad. Wiss. Wien.*, 123, IIa (Dec. 1914).

[2] The density of lead from thorianite has already been studied by Soddy, and discussed by Lindemann, respectively, *Nature*, 94, 615 and 95, 7 (1915). Professor F. W. Clarke has kindly called our attention to the desirability of studying also several other properties.