THE NON-MOLECULAR STRUCTURE OF SOLIDS.*

BY

ARTHUR H. COMPTON,

Research Laboratory, Westinghouse Lamp Company.

ONE of the most striking things in the structure of crystals as worked out by Prof. W. H. and Mr. W. L. Bragg † is the orderly manner in which the atoms of the different crystals are

FIG. 1.

arranged. The evidence of X-ray analysis points definitely to a structure in the simple crystals which have been examined in which there is no evidence whatever of any grouping of the atoms into molecules. It seems rather that the position of an atom depends equally upon all the neighboring atoms, so that the whole

* Communicated by the Author.

Contribution from the Research Laboratory of the Westinghouse Lamp Company, East Pittsburgh, Pa., January 5, 1918.

This paper was sent to three members of the Physics faculty at Princeton University on July 25, 1914. It was read before the Physics Colloquium of Princeton University on October 8 1914. Though not originally prepared for publication, the subject has become one of such general interest that it has been thought worth while to publish the article at this time without alteration.—THE WRITER.

† Proc. Roy. Soc., 1913-1914.

mass is a homogeneous bundle of atoms which have no tendency to form into molecules.

If we take, for example, a crystal of rock-salt, we find the atoms of sodium and chlorine arranged alternately in a simple cubic pattern (Fig. 1). Any one sodium atom *a* is equally strongly bound to any one of six chlorine atoms, 1, 2, 3, 4, 5, 6, or *vice versa*. It is evident that it is easy for the atoms to pair off into molecules on passing into the liquid state. In doing so, however, there are equal probabilities for an atom to combine with any one of six others, so that we cannot expect the same pair of atoms to form a molecule after the substance melts as were together before they assumed the solid state. Thus no particular

FIG. 2.

pair of atoms in the crystal can be said to belong to the same molecule.

In order to make more evident the absence of true molecular structure, let us consider a salt crystal to be made up of two cubes (Fig. 2), each cube having an odd number of atoms on its edge. Then the whole crystal has an equal number of sodium and chlorine atoms, but if it be split in the middle, one half will contain an excess of chlorine and the other of sodium atoms. Thus by the simple operation of splitting the crystal along a cleavage plane we must have performed the exceedingly delicate operation of mechanically severing a molecule into two parts—a chemical process—if there is a true molecular structure in the crystal. Exactly similar arguments show the non-molecular structure of the other kinds of crystals which the Braggs have determined.¹

¹ So far as the writer is aware, the fact that the work of the Braggs thus indicates a non-molecular structure in the crystals which they examined was first pointed out by him in *The Scientific American Supplement*, July 4, 1914, page 5.

In these simple crystals, then, if the structure as determined by X-rays is correct, each atom is held in position equally by all the neighboring atoms. It is natural to suppose, therefore, that in substances which are chemically more complicated, as in these simple crystals, each atom is affected by forces equal, on the average on all sides, so that there will be no grouping into molecules. Thus by the definite indication by X-ray analysis of a non-molecular structure for certain simple crystals we are led to the idea that very possibly the structure of all compounds, however complicated, is non-molecular in the solid state.

We may therefore state the thesis that we hope to prove, thus: *Every atom in a solid has its position so determined by the other atoms that it cannot be said definitely to belong or not to belong to the same molecule as some other one atom.* That is, in the solid state the atoms of the substance are so intimately intermingled that particular molecules cannot be definitely defined. Since this proposition is apparently not in accord with the generally accepted molecular theory of solid matter, it is important to see how it is confirmed by a study of the general properties of matter as well as by the molecular theory itself. In this way we hope to form an argument which will show that *non-molecular structure is an essential attribute of all solid matter.*

ARGUMENT FROM THE PROPERTIES OF SOLID MATTER.

From an historical standpoint, the way in which the conception of molecules in the solid state was formed was by a deduction from the kinetic theory of gases. It was easy to explain the change from gas to liquid as due to a shrinking of molecular distances to something comparable with the diameter of the molecules, at which distance the molecules would be held together by intermolecular forces. Likewise the passage from the liquid to the solid state was explained as the settling of the molecules into positions of stable equilibrium. Since the molecules have a definite form in the gaseous state, it was natural to suppose that they would keep this form in the liquid and solid states. We have already seen, however, that there is no trouble with an explanation of the passage from the solid to the liquid state, even with a non-molecular structure in the solid. For example, NaCl, which is known to have a non-molecular structure, actually does melt, so that a molecular structure of the solid is not neces-

sary. The explanation of this we saw was simply that the atoms in the salt crystal paired off when assuming the liquid state. Since, therefore, a non-molecular structure accords as well with the general kinetic theory of gases and liquids as does a molecular solid, there is no *a priori* reason why solids should be molecular in structure.

It will be convenient, however, to speak of the atoms in the solid state as belonging to molecules, meaning either the molecules to which they belonged before assuming the solid state or those to which they will belong if they assume again the liquid or the gaseous state. We shall then employ a sort of *reductio ad absurdum* method, and try to show that these groups of atoms cannot exist in the solid as definitely defined molecules.

In order to prove the thesis as stated above, it will be necessary to show that at least some of the atoms of every molecule are bound as strongly to atoms of other molecules as they are to their own. It is evident that this means a non-molecular structure, since there can be no definable boundary to the molecules in such a case. We shall attempt to prove this point by steps, showing:

1. That each atom in a solid oscillates about a definite position of stable equilibrium.

2. That the forces holding the atoms in their positions of stable equilibrium are of the same nature and are comparable in magnitude with the forces binding together the atoms of the same "molecule"; and

3. That at each of the frequent collisions the forces between the atoms of different "molecules" become so great that an atom has even chances to be torn from the atoms of its own "molecule," so that, on the average, it is bound equally to all the neighboring atoms.

The evidence for the fact that each atom has a definite position in a solid is well known. In the first place it is a generally accepted part of the molecular theory that in the solid state the molecules are in positions of stable equilibrium from which they hardly move. The fact that a true solid will not change its shape under small forces even for great periods of time shows that the molecules are not free to move from place to place. Also, the existence of the latent heat of fusion and of sublimation shows that in the solid state the molecules are in positions of minimum potential energy and hence of stable equilibrium.

But we can show, also, that the molecules in a solid are arranged in definite directions as well as in definite positions, which means, of course, that the atoms are in definite positions. We shall point out below that the structure of all solids is crystalline, so anything which we prove for crystals will hold for all solid matter. Now it is evident that to form any regular crystal structure the molecules must be arranged in a regular order. But it is generally accepted that the crystal form is some function of the chemical constitution. Unless, however, the atoms in the molecule are arranged in a definite order, it is hard to see how the crystal form can be influenced by the chemical composition. As a matter of fact, a definite arrangement of the atoms in crystals is assumed in the explanation of many of the properties of matter. For example, Lord Kelvin, in explaining pyro- and piezo-electricity (Poynting and Thomson, "Electricity and Magnetism"), assumes that the molecules in the crystals which show this effect have their parts arranged in a certain definite manner, as described below (p. 27). Likewise Bridgman, in explaining the phenomenon of polymorphism under high pressures, says (*Phys. Rev.*, iii, p. 199): "It seems natural that the crystalline form assumed under the free action of the orienting forces is one in which the potential energy of the attractive forces is a minimum; that is, that the local centres of attraction within the molecule have approached as close as possible to each other. If the molecules are forced to assume a different arrangement, even one occupying less volume, these centres of attraction must be pulled apart, and work done against the attractive forces while decreasing the volume. That is, the internal energy of the form with the smaller volume will be the greater." Also, it may easily be shown that the explanation of the expansion of certain substances on solidification depends upon the existence of local centres of attraction within the molecules. It is possible to imagine systems in which the arrangement which would bring the local centers of attraction nearest together would not be the arrangement of minimum volume, so that when the molecules would be in stable equilibrium the volume might be a maximum. Indeed, it is difficult to see how there can be any other explanation. These local centres of attraction, however, can be nothing other than atoms or groups of atoms. We shall see below (p. 11) that if the orienting forces are the attractions between the atoms, such a position of

the molecules in the solid state is very easily accounted for. It seems evident, therefore, that in order to explain the crystal structure the molecules must be oriented in such a manner as to give to each atom a definite position.

Aside from this evidence that atoms in crystals have their positions defined, we have further evidence that the atoms in any solid oscillate about definite centres of stable equilibrium. According to the theory of the equipartition of energy, each degree of freedom of an atom in the solid state should possess the same average kinetic energy as a degree of freedom of an atom in the gaseous state at the same temperature. But if we give to each atom in the solid state three degrees of freedom, the specific heat of the atom calculated from the rate of increase of the kinetic energy is only half that which corresponds to Dulong and Petit's law for the atomic heat. Since an atom is supposed to have but three degrees of freedom, in order to account for this difference it is necessary to ascribe to each degree of freedom of the atom potential energy as well as kinetic energy, which increases as the temperature, to give the atom the proper amount of specific heat. But the existence of this potential energy means that the atom is vibrating about a position of stable equilibrium. As the kinetic energy of the atom accounted for half the specific heat, the potential energy must account for the other half, and must therefore be equal, on the average, to the kinetic energy. This indicates that the motion of an atom is, in general very nearly harmonic motion about a central position.

In the explanation of heat radiation, also, we have an indication that the atoms oscillate about centres of stable equilibrium. The explanation referred to is the common one that in solids heat waves and long light waves are produced chiefly by the oscillation of the atoms in harmonic motion about positions of stable equilibrium. Thus from two different lines of evidence we come to the conclusion that the atoms in any kind of a solid must oscillate about positions of stable equilibrium.

THE NATURE AND MAGNITUDE OF THE INTERMOLECULAR FORCES.

The next question is, What is the nature of the forces which hold the atoms in position? This will become evident as we discuss the phenomenon of the cohesion of solids. The accepted molecular theory explains cohesion as due to the settling of the

molecules into positions of stable equilibrium, where they are held by the intermolecular forces. It is evident, on the kinetic theory, that the collisions of each molecule with the neighboring molecules will be very frequent in the solid state. But we can show that when two molecules are in "contact" the attraction between atoms of the different molecules is of the same nature and of the same order of magnitude as the attraction between the atoms of the same molecule. This is evident from a consideration of the forces which occur in chemical action. For instance, the fact that some compounds are dissociated when they are dissolved in water implies that the atoms in the water molecules exert a greater force on the atoms of the compound than these do on each other. Similarly when two molecules interact directly, as in an organic reaction in which dissociation takes no part, the atoms of one molecule must exert a greater force on certain atoms in the second molecule than do the other atoms of the second molecule. In fact, the universality of reversible reactions shows that in every case there is a delicate balance between the forces binding an atom to its own molecule and the forces tending to make it join the molecule with which it is in contact. There can be little doubt, therefore, that at least while two molecules are in contact the forces between their atoms are not only of the same nature but also of the same order of magnitude as the forces binding together the atoms of a chemical molecule. (It might be thought at first that this theory of attraction between the atoms of different molecules is opposed to the theory of chemical valency which would seem not to allow an atom to attract more other atoms than it has chemical bonds. According to Stark's theory (Campbell, "Modern Electrical Theory," p. 341), which is possibly as good as any explanation yet offered of the mechanism of valency, a chemical combination between two atoms is not a direct attraction of one atom for another, but a simultaneous attraction of both atoms for the same electron, which thus forms a bond between them. This common electron is one which originally belonged to the electropositive atom, but which was more strongly attracted by the electronegative atom, and on being brought nearer to this atom has the effect of giving it a negative charge and of giving the electropositive atom a positive charge. This method of binding may be illustrated by Fig. 3.

(According to Stark, the band spectra of substances represent

the vibrations of the electrons concerned in chemical combination, which are, of course, these "valency" electrons. The fact that the spectrum bands widen as the pressure of the gas increases indicates that these electrons are influenced by neighboring atoms as well as by the atoms of their own molecule. This suggests that the valency electrons may not be fixed in position, but that their positions may be altered by the presence of other molecules.

FIG. 3.

So, if another molecule should come near the first, we might expect them to be held together in some such manner as shown in Fig. 4.

(Since the electronegative atom acts as though negatively charged, and the electropositive atom as though positively charged, on account of the position of the valence electron, it is easy to see how a whole system of atoms may be held together, due to

FIG. 4.

FIG. 5.

the electrostatic forces. For example, when two molecules composed of oppositely charged atoms come together, a position of stable equilibrium is as illustrated in Fig. 5. If two more come near, a position of stable equilibrium is as shown in Fig. 6, which is the elementary cube of an alkali halide. It seems probable that if the equivalent charge and the diameter of every atom were known it might be possible in this way to calculate the different crystalline forms of every compound.)

Since, therefore, we know that the forces between atoms of different molecules are of the same nature and of the same order of magnitude for at least a considerable portion of the time as those binding a molecule together it is natural to assume that these forces are always similar. Evidence that the forces between the atoms of different molecules are, in general, comparable with the forces between atoms of the same molecule results from a consideration of the atomic heat of substances in the solid state. We found above that in order to explain the specific heat of an atom in the solid state it was necessary to assign to it three degrees of freedom. This is true in whatever way the atom may be combined chemically, so long as the substance obeys Kopp's

FIG. 6.

extension of the Dulong-Petit law. According to the Staig-müller-Boltzmann theory, however, in the gaseous state an atom has no degrees of freedom along its chemical bonds. In order, therefore, that in the solid state it shall have three degrees of freedom, the attractions of the atoms of the neighboring molecules must loosen the chemical bonds enough to allow other degrees of freedom. But in order to do this these attractions must be at least of the same order of magnitude as the forces binding the atom to its own molecule.

If, as we have assumed above from a consideration of the Dulong-Petit law, an atom in the solid state has degrees of freedom along its chemical bonds, an atom on the surface of a solid ought, according to the law of velocity distribution, to break away occasionally from the solid as in sublimation. A single atom subliming in this manner should carry with it either a posi-

tive or a negative change,² so that we should expect the vapor from a subliming solid to be partially ionized. The proportion of the ionized atoms would, of course, be relatively small, since it would be much easier for a group of atoms forming a gaseous molecule to leave the solid than for a single atom, which would be held back by an opposite charge in the solid. Moreover, even though an atom in the *interior* of the solid may have three degrees of freedom, it is easily possible that at the *surface* of the solid, since all the attractions are from one side, the atom might be held firmly to the other atoms so as not to be free to escape. If this be true, it should be possible to show that in the form of very thin foil a substance has smaller specific heat than when in lumps. But even in this case it would seem that an atom on the surface of a solid should not be held as firmly along its chemical bond as it would be in the gaseous state. So we should expect a vapor to become ionized at a lower temperature when in contact with its solid than when not in contact. Is it possible that this is the explanation of the production of thermions from hot salts?

There is evidence, also, from an altogether different source that the forces which hold the molecules of a solid in positions of stable equilibrium are the attractions of the neighboring atoms, and are comparable in magnitude with the forces between the atoms of the same molecule. A measure of the forces holding the atoms together in a molecule is the total heat of combination. Also, since a substance melts when its molecules attain kinetic energy enough to tear them away from the neighboring molecules, the melting-point may be taken as a rough measure of the firmness with which the molecules are held together in the solid. We should expect, therefore, if the firmness with which the molecules are held together depends upon the same properties of the atom as the firmness with which the atoms are held together in the molecule, that the melting-point should vary roughly as the heat of combination.

In order to test this prediction fairly it must be remembered that the melting-point of a solid must depend to some extent upon

² This statement, of course, assumes that the substance is a polar compound, in which case the atoms carry electric charges. If the combination is non-polar, no such evaporation of ions could occur. This is possibly the reason why the emission of thermions of atomic size is confined to the strongly polar compounds, such as the alkali and alkaline earth halides.

the arrangement of the atoms in the molecule as well as upon the magnitude of the attractions between the different atoms. Also, it seems very probable that at the melting-point only a definite proportion of the molecules escape from positions of stable equilibrium, the rest remaining in small groups forming "liquid crystals." (This is the explanation that is given for the expansion of water below four degrees. The high specific heat of liquids in general may be explained as due to the latent heat of fusion of these "liquid crystals" as they melt with rising temperature.) It is probable that the relative number of molecules which have sufficient kinetic energy to escape from the positions of stable equilibrium is different for different substances at their melting-points, which would also indicate that the melting point is only a rough measure of the stability of a molecule in a solid. Moreover, the heat of combination is not an absolute measure of the stability of the molecule, for, in the first place, this varies with the stability of the different atoms in the elemental state; *e.g.*, CO_2 from amorphous carbon has a heat of formation of 97.3×103 , while from diamond it is only 94.3×103 . In the second place, the heats of formation of substances differ relatively at their melting-points and at room temperature. In view of these and other disturbing factors, we have no reason to expect more than a rough agreement between the atomic heats of formation and the melting-points of the different substances.

In testing this prediction I have grouped similar compounds together, since one would expect that the atomic arrangement of such compounds in the solid state would be similar (see Table I).

TABLE I.

Showing Relation Between the Melting-points (m.p.) and the Atomic Heats of Formation (A.H.F.) of Various Substances.

(A) ALKALI HALIDES, ETC.						
Substance	A.H.F.	m.p.	Substance	m.p.	Substance	m.p.
KCl	53 × 10 ³	770	KBr	750	KI	723
NaCl	49	801	NaBr	765	NaI	695
LiCl	47	600				
HgCl	15.5	500				
AgCl	14.5	460	AgBr	427	AgI	540
HCl	11	-111	HBr (4)	-86	HI (-3)	-51

(B) BICHLORIDES, BROMIDES AND IODIDES.

Substance	A.H.F.	m.p.	Substance	m.p.	Substance	m.p.
(BaCl ₂		960)	BaBr ₂	880	BaI ₂	740
SrCl ₂	62	825	SrBr ₂	630		
CaCl ₂	57	780	CaBr ₂	760	CaI ₂	740
MgCl ₂	51	708				
BeCl ₂		600	BeBr ₂	601		
PbCl ₂	28	447				
HgCl ₂	18	290	HgBr ₂	244	HgI ₂	241
CuCl ₂	17	498				

(C) TRI-HALIDES.

Substance	A.H.F.	m.p.	Substance	m.p.	Substance	m.p.
BiCl ₃	23	227	BiBr ₃	215		
SbCl ₃	23	73	SbBr ₃	93	SbI ₃	167
AsCl ₃		-18				
PCl ₃		-112				
FeCl ₃	24	301				
AlCl ₃	24+10 ³	301	AlBr ₃	93	AlI ₃	185
GaCl ₃		73				
TiCl ₃		25				

(D) ALKALI, ETC., SULPHATES, CARBONATES AND NITRATES.

Substance	A.H.F.	m.p.	Substance	A.H.F.	m.p.	Substance	A.H.F.	m.p.
K ₂ SO ₄	49	1070	K ₂ CO ₃	47	880	KNO ₃	24	345
Na ₂ SO ₄	47	884	Na ₂ CO ₃	45	849	NaNO ₃	22	313
Li ₂ SO ₄	48	853	Li ₂ CO ₃		710	LiNO ₃	22	258
Tl ₂ SO ₄	32	632						
H ₂ SO ₄	27	10.4				HNO ₃	8	-47
Ag ₂ SO ₄	24	676				AgNO ₃	6	218

(E) ALKALI-EARTH, ETC., SULPHATES, CARBONATES AND NITRATES.

Substance	A.H.F.	m.p.	Substance	A.H.F.	m.p.	Substance	A.H.F.	m.p.
BaSO ₄		infus.	BaCO ₃		795	Ba(NO ₃) ₂		575
CrSO ₄		dec. w.ht.	SrCO ₃	dec.	1160	Sr(NO ₃) ₂		645
CaSO ₄	53	v. high	CaCO ₃	54 dec.	r. ht.	Ca(NO ₃) ₂	27	561
PbSO ₄	38	937				Cu(NO ₃) ₂	9	114.5

(F) OXIDES.

Substance	A.H.F.	m.p.	Substance	A.H.F.	m.p.	Substance	A.H.F.	m.p.
MgO	71.5 × 10 ³	over 2000	Cu ₂ O	14	rd. ht.	SO ₃	26	14.8
SiO ₂	60	1600	NO ₂	- .6	-10	H ₂ O	23	0
P ₂ O ₅	53	subl. r. ht.	N ₂ O	-6.3	-102	CO	14.5	-207
Al ₂ O ₃	30	wht. ht.	CaO	70	infus.	Bi ₂ O	4	84
PbO	25	rd. ht.	B ₂ O ₃	55	577	Cl ₂ O	-6	-19
SO ₂	23	-76	CO ₂	32	-65	NO	-11	-167

(G) OXIDES AND SULPHIDES.

Substance	m.p.	Substance	m.p.	Substance	m.p.
Sb ₂ O ₃	rd. ht.	H ₂ O	(23) 0	Bi ₂ S ₃	decomp.
Sb ₂ O ₅	300	ZnO	V. high	CS ₂	(-6) -110
Bi ₂ O ₃	860	Sb ₂ S ₃	fusible	H ₂ S	(1) -86
CO ₂	(32) -65	Sb ₂ S ₅	fusible	ZnS	1050

The heat of formation used is that of a gramme-molecule, divided by the number of atoms, thus giving what may be called the "atomic heat of formation." It will readily be seen, by a glance at the tables, that in general the higher the heat of formation the higher the melting-point of a substance. There are a few exceptions to the rule, but the discrepancies are small, and there can be no doubt that the rule holds in general. For instance, if we take the alkali chlorides, the decrease in melting-point is regular, except for a slight variation in sodium, and so, also, as we pass from the chlorides to the bromides and iodides; similarly with the sulphates, carbonates, and nitrates. Among the oxides there are a great number of exceptions, but the predominance of high melting-points at the head of the list and of low melting-points at the foot shows that the general rule holds. Moreover, when the sulphides and the oxides are compared, the former invariably have the lower melting-point, as they should. In order to show that these uniform results are not confined to elements of the same periodic group, Table II and the graph with it have been made, showing all the compounds in the order of their

TABLE II.

The Melting-points of Different Substances in the Order of Their Atomic Heats of Formation.

—Substance	A.H.F.	Authority	m.p.	—Substance	A.H.F.	Authority	m.p.
			C°				C°
ThO ₂	110 × 10 ³	3	infus	B ₂ O ₃	55	1	577
UO ₂	85	5	2176	TiO ₂	54		1500
Al ₂ O ₃	79	1	2040	CaCO ₃	54	2	1289
MgO	72	1	>2000	CaSO ₄	53	2	>1000
CaO	70	1, 2	1995	P ₂ O ₅	53		*850
BaCl ₂	66	2	960	KCl	53	1, 2	770
SrO	65	1, 2	3000	MgCl ₂	51	2	708
V ₂ O ₅	63	5	658	K ₂ SO ₄	49	1, 2	1070
SrCl ₂	62	1, 2	825	NaCl	49	1, 2	801
SiO ₂	60	1	1600	LiSO ₄	48	2	853
ZrO ₂	59	7	2500	WO ₃	48	7	*800
CaCl ₂	57	2	780	Na ₂ SO ₄	47	1, 2	884

*=approximate value.

TABLE II. (Continued)

—Substance	A.H.F.	Authority	m.p.	—Substance	A.H.F.	Authority	m.p.
			C°				C°
LiCl	47	2	600	CuO	19	2	1148
K ₂ CO ₃	47		880	HgCl ₂	18		290
MnO	45		*1500	CuCl ₂	17		498
Na ₂ CO ₃	45	1, 2	849	HgCl	15		500
MoO ₃	45	5	759	CCl ₄	15	1	— 24
As ₂ O ₅	42	2	960	Cu ₂ O	14		*800
Fe ₃ O ₄	40	4	1538	Tl ₂ O	14		*700
Fe ₂ O ₃	39	18	1458	AgCl	14	1, 2	460
PbSO ₄	38	2	937	PbI ₂	14	6	373
CdSO ₄	37	2	>1000	CO	14		—207
LiOH	37		*850	C ₂ H ₅ COOH	11	2	— 22
KOH	35	1, 2	360	HCl	11	2	—111
NaOH	34	1, 2	318	Cu(NO ₃) ₂	9		114
FeO	32	18	1419	AgI	8	13	500
K ₂ O	32		*800	HNO ₃	8	1	— 47
Na ₂ O	32		*800	CH ₃ OH	8	2	— 95
Tl ₂ SO ₄	32	2	632	Trifluorocresol	7	17	— 5
ZnCl ₂	32	1, 2	375	C ₂ H ₅ OH	7 × 10 ³	2	—112
CO ₂	32	1, 2	—65	CH ₃ CHO	7	2	—120
TeO ₂	29	5	*600	AgNO ₃	6	1, 2	218
Co ₃ O ₄	28	5	750	Nitrofluorophenol	5	17	74
PbCl ₂	28	2	447	CHCl ₃	5	2	— 70
Ca(NO ₃) ₂	27	1	561	(C ₂ H ₅) ₂ O	5	2	—117
SnCl ₂	27	2	249	Fluoronitracetani-	4	17	96.5
H ₂ SO ₄	27	2	10	lide			
SO ₃	26		15	Bi ₂ O ₃	4		84
SnCl ₄	26		—33	Parafluorphenol	4	17	28
PbO	25	2	*800	Orthofluorphenol	4	17	16
Ag ₂ SO ₄	24		676	Metafluorphenol	4	17	14
TiCl	24	2	407	HBr	4	2	— 86
KNO ₃	24 × 10 ³	1, 2	345	CH ₄	4	1, 2	—184
FeCl ₃	24	2	01	Metafluoracetani-	3	17	85
BiCl ₃	23	2	227	lide			
SbCl ₃	23	2	73	Diffuorethylnitra-	3	17	45
SO ₂	23		—76	mine			
NaNO ₃	22	1, 2	313	Nitrofluorphenetol	3	17	14
LiNO ₃	22	2	258	Metatrinittrotoluol	3	17	— 2.4
CdCl ₂	21	2	568	Parafluorphenetol	3	17	— 8.5
Tl ₂ O	21	2	300	C ₂ H ₄	3	1, 2	—171
SeO ₂	21	5	> 260	C ₃ H ₂	3	2	—195
AlCl ₃	20		190	NH ₃	3		— 75
NOCl	— 2	9	— 60	Parafluornitroben-			
HI	— 3	1, 2	— 51	zol	2	17	27
H ₂ Se	— 5		— 64	Ethylenitramine	2	17	6
N ₂ O ₃	— 5	1	—106	SiH ₄	2		< 0
Cl ₂ O	— 6		— 19	Fluornitraniline	1	17	96
CS ₂	— 6	1	—110	Dinitrofluorbenzol	1	17	26
N ₂ O	— 6		—112	Metafluornitro-	1	17	4
AsH ₃	— 9		—113	benzol			
HCN	— 10		— 14	H ₂ S	1	2	— 86
NO	— 11	2	—167	Metacresol	+ .3	17	4
C ₂ H ₂	— 12 × 10 ³	2	— 82	C ₇ H ₈	— .1	2	— 97
C ₂ N ₂	— 19	1	— 35	C ₂ H ₄	— .3	2	—169
SbH ₃	— 22	1	— 91	NO ₂	— .6	1	— 10
H ₂ O	19	1	0	C ₆ H ₆	— 1	2	5
(NH ₄) ₂ SO ₄	19	1, 2	140	Aniline	— 1	2	— 8

* = approximate value.

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"atomic heats of formation." Here there is no chance for any other factor, such as atomic weight or place in the periodic table, to affect the melting-points consistently. I have not made any selection, but have used all the compounds for which the required data are available. In spite of occasional rather large discrepancies in this table, there can be no doubt that in general the melting-point rises with an increase in the atomic heat of formation.³

I have given so much space to this demonstration of the connection between the heat of combination and the melting-point because this seems to be a definite proof that the forces which bind the atoms of different molecules together in the solid state, measured by the melting-point, are similar to those which bind a chemical molecule together, measured by the atomic heat of combination. The similarity must be not only a likeness in nature, but also comparability in magnitude, since if the magnitude of the forces were not comparable there would be no reason to expect the relative melting-points to be comparable with the relative heats of formation.⁴ We may consider it established,

³ Table II and the graph representing it (Fig. 7) are more complete than those given in the original paper. They were shown in their present form before the American Physical Society at its meeting October 30, 1915.

⁴ A calculation of the energy required to raise the temperature of a substance from absolute zero to its melting-point and melt it shows that, on the average, this energy is about one-fourth of its heat of formation. Thus the energy required to remove the atoms of a "molecule" in the solid form from the atoms of the neighboring "molecule" is of the same order of magnitude as that required to separate the atoms of the same molecule from each other.

FIG. 7.

therefore, that in a solid the forces affecting an atom due to neighboring atoms of other molecules are both of the same nature as and comparable in magnitude with the forces due to the other atoms of its own molecule.

It thus appears that the forces of cohesion which hold the molecules in positions of stable equilibrium must be the mutual attractions of the atoms of neighboring molecules. In order, however, that each molecule should be in the most stable position with respect to the other molecules, it is evident that it must orient itself in such a manner that the atoms of different molecules which attract each other most strongly shall be next to each other. One result of this is that the molecules must evidently all be oriented and arranged in a definite, repeating order, which means a crystalline structure. Thus we see that the structure of all true solids must be crystalline. If this is true, the molecules in the so-called "amorphous solids" must not be in positions of most stable equilibrium under the atomic forces, and these substances should therefore have neither a definite melting-point nor perfect elasticity even for small forces. It seems probable that the "near solid state" in which these substances exist is caused by the agglomeration of large numbers of molecules into minute crystalline groups, similar to liquid crystals, which are so large compared with their distances apart that the viscosity is very great.

A second result of this arrangement of the molecules is that since an atom is nearest the other atoms of its own molecule which attract it most strongly, and since it comes next to the atoms of the neighboring molecules which attract it most strongly, it seems probable that, wherever possible, the arrangement of the atoms on all sides of it shall be similar. So if an atom should escape from the other atoms of its own molecule it would be held just as strongly by the atoms of the other neighboring molecules.

The forces on an atom due to the atoms of its own molecule and to those of other molecules, on the average, equal.

The next step in the argument to prove that there is no true molecular structure in the solid state will be to show that the forces between the atoms of the different supposed molecules are as great as those between the atoms of the same molecule. The first part of this proof is to show that the distance between the atoms in a solid is small compared with the "diameters" of the atoms themselves. That is, if the atoms are considered as spheres,

the distance between the surface of two neighboring spheres is small compared to their diameters.

Possibly the most direct way to show this point is to compare the size of the molecules as deduced (1) from the viscosity of a gas, (2) from the thermal conductivity, and (3) from Van der Waals's equation, with the size of the molecules as deduced from the density of the densest known form of the substance, assuming the molecules to be spheres arranged in the order of closest packing. As we saw above, according to the Staigmüller-Boltzmann theory, the atoms of a molecule in the gaseous state are in such close contact that there is no freedom for motion along a chemical bond. So if it can be shown that the molecules are very nearly in contact, the atoms of different molecules must also be very nearly in contact. The following figures are taken from Kaye and Laby's tables, page 33:

Molecular diameter deduced from

	Viscosity	Thermal Conductivity	Van der Waal's Equation	Limiting Density
	2.47 times 10^{-8}	2.40 times 10^{-8}	2.32 times 10^{-8}	2.92 10^{-8}
H ₂	2.18		2.30	4.34
He	3.50	3.31	3.53	2.97
N ₂	3.39	3.31		2.79
O ₂	3.36		2.86	4.43
A			3.14	4.93
Kr			3.42	4.88
Xe	4.55	4.68		5.26
C ₂ H ₄	4.18	4.32	3.40	4.42
CO ₂	4.27	4.20		4.58
N ₂ O	4.09			3.49
H ₂ O				

These data assume that the molecules are spherical, which undoubtedly introduces some error, but the uniformly close agreement of the values in the fourth column with those in the other three can leave but little doubt that the molecules in the solid state, and hence the atoms also, must be very nearly in "contact."

In support of this evidence for the proximity of the atoms in a solid we may mention the evidence which comes from the X-ray spectra from different crystals that the distance of the thermal motion is small compared with the diameter of the atoms themselves. This evidence comes from a consideration of the relative intensity of the different orders of spectra. At first the rapid falling off in intensity of the higher orders for such crystals as

rock salt when compared with crystals like potassium ferrocyanide was explained as due to the greater heat motion of the lighter atoms in the former case. But the Laue photographs which de Broglie obtained at great extremes of temperature—from liquid air to red heat—showed a surprisingly small difference in the intensity of the spots, showing that the heat motion has very little effect. Apparently the only remaining explanation is that the X-rays are not reflected from single points in the atoms, but by electrons distributed throughout the atoms. Thus it is the size of the atom compared to the distance apart of the reflecting atoms which accounts for the decrease in intensity of the higher orders of spectra. (If a large proportion of the electrons are in the central ring about the nucleus, the intensity should not diminish as rapidly as if they are uniformly distributed throughout the sphere. It should be possible to test this point.⁵) But since the heat motion of the atom does not materially affect the intensity of the higher orders of spectra, while the diameter of the atoms does so affect it, the distance of the heat motion, and hence the distance between the atoms, must be small compared with the diameter of the atoms.

A more definite confirmation comes from the arrangement of the atoms in those simple crystals whose structure has been worked out. If we assume here the existence of molecules, the distance between the atoms within a molecule is the same as that between neighboring atoms of different molecules. The atoms of the same molecule are certainly very near together, however, so for these simple compounds, at least, any two neighboring atoms are very close together.

One further line of evidence toward this same point may be valuable. The expansion of solids on heating is due, of course, to the lengthening of the paths of the molecules as the temperature

⁵ It was this fact that suggested the writer's study of the distribution of the electrons in atoms as indicated by the intensity of X-ray reflection (cf. *Nature*, May 27, 1915, and *Phys. Rev.*, 9, 29, 1917). In the latter paper it was shown that the distance of the outer electrons from the atomic centres was comparable with the distance between the atoms. According to Debye's theory of the effect of heating on the intensity of X-ray spectra (*Ann. d. Phys.*, 43, 49, 1914), which has been verified experimentally by Professor Bragg (*Phil. Mag.*, 27, 881, 1914), the thermal motion is relatively small, and reduces to practically zero at very low temperatures, as is here suggested.

rises. It seems natural to suppose that at absolute zero the length of these paths would decrease until the molecules come in contact. Even if the coefficient of expansion were constant the volume of a solid would not decrease enough to indicate at ordinary temperatures a free path comparable with the diameter of the atoms. As a matter of fact, at low temperatures the coefficient of expansion approaches zero, which indicates an "agglomeration" into groups in which the atoms are all in contact. This is the same theory of agglomeration as the one used to explain the decrease of specific heat at low temperatures. If this theory is correct, at low temperatures all the atoms, whether of the same or of neighboring molecules, are held in "contact" with each other.⁶ We may conclude, then, with considerable certainty that the atoms of neighboring molecules are very nearly in contact with each other, and that they are probably as near together as the atoms of the same molecules.

We showed above that the forces between atoms are of the same nature, whether due to atoms of the same molecule or to those of different molecules. It seems evident, therefore, that the attraction between atoms should be some function of the distance such that if the distances are equal the forces should also be equal. This is confirmed by the evidence of chemical action which we considered above. But, since we know that the distances between atoms of the same molecule and atoms of neighboring molecules are approximately equal, the forces should likewise be very nearly equal. Thus we see that the forces on all sides of an atom must, on the average, be at least very nearly the same.⁸

We can go still farther and show it to be probable that the forces on an atom due to the atoms of neighboring molecules are, on the average, exactly equal to the forces from the other atoms of its own molecule. From the discussion in the last paragraph we see that an atom is as strongly attracted to another atom with which it is in contact, though of a different molecule, as it is to a similar atom in its own molecule. When, therefore, due to the heat motion of a molecule in the solid, one of its atoms comes in contact with an unlike atom of a different molecule, there are even chances that it will remain fast to the other molecule. So

⁶ The theory referred to is that suggested by C. Benedicks (*Ann. d. Phys.*, **42**, 133, 1913).

in a very large number of collisions it will belong just as much of the time to one molecule as it will to the other, and so cannot be said to be a part of either. As a matter of fact, since we know, from a study of the Dulong-Petit law, that an atom has three degrees of freedom in a solid, and since an atom cannot remain joined to another without losing a degree of freedom (Staigmüller-Boltzmann Theorie), it is evident that an atom cannot remain in contact for more than an infinitesimal interval with another atom, but must continually oscillate back and forth, exerting equal attractions on all the neighboring atoms.

The fact that Dulong and Petit's law is not accurately followed—*i.e.*, that the atoms of solids do not always have three degrees of freedom, is a support rather than an objection to our hypothesis; for as the temperature decreases, the time interval during which an atom remains in contact with a neighboring atom will, on the average, increase, thereby decreasing the total number of degrees of freedom at any one instant. In the gaseous state, as we have just seen, each atom has three degrees of freedom minus the number of its chemical bonds. But if the gas is heated to a sufficiently high temperature it becomes ionized; that is, the chemical bonds become loosened so that parts of the molecule occasionally separate (Meyer, "Kinetic Theory of Gases," p. 132). According to our hypothesis, when a molecule assumes the solid state, the attractions of the neighboring atoms loosen the chemical bonds sufficiently to give each atom three degrees of freedom. Even in the solid state, however, each atom is strongly bound to the neighboring atoms, so that if the kinetic energy of the atom should become sufficiently low, one would expect it to be held in contact with some of the other atoms thus taking away its degrees of freedom, until it should be moved from its place by a sufficiently violent collision. This would be exactly analogous to the binding of the atoms together in a gas molecule until there is a sufficiently violent collision to ionize the gas. The only differences are that, since the atom in the solid state is not held so strongly by other atoms, the collisions would not have to be so violent, and that, since the atom in the solid state is surrounded by other atoms, it might have either zero, one or two degrees of freedom when held in contact with other atoms. It is easy to see that on this hypothesis, when the kinetic energy becomes sufficiently low, large numbers of the atoms will

be held in contact with each other, thus losing their degrees of freedom, so that as absolute zero is approached the specific heat should also approach zero. This is, I believe, about the same as the "Agglomeration Theorie" on which Dean Magie reported to Physics Colloquium last winter.⁷

CONCLUSION.

THE STRUCTURE OF SOLIDS IS NOT MOLECULAR.

Since, therefore, each atom of a substance in the solid state exerts equal forces on all the neighboring atoms, it cannot be said definitely to belong or not to belong to the same molecule as some other one atom.⁸ In other words, the atoms of a solid are so intimately intermingled that particular molecules cannot be definitely defined. Thus we can no longer speak of solid

⁷ These were the considerations which led to the development of the theory of specific heat presented by the writer in the *Physical Review*, 6, 377, 1915, where it was found that this agglomeration hypothesis is capable of explaining in a fairly satisfactory manner the variation of the specific heat of solids with temperature. It may be pointed out that the theories of the temperature variation of specific heat based on the quantum hypothesis (Einstein, Nernst-Lindemann, Debye) lead to the same conclusion as that here arrived at concerning the rigidity with which atoms are held in a solid. According to these theories, the energy corresponding to a degree of freedom depends upon the corresponding frequency of vibration. In the case of gases this frequency is very high, while in the solid state the frequency of the natural vibrations of the atom is relatively low. This means that the rigidity with which the atom is held in position is much less in the solid state than in the gaseous state, due doubtless to the fact that the forces due to the surrounding atoms are nearly equal on all sides.

⁸ On account of the selective nature of the forces between atoms, we can state these forces as a function of the distance only when we consider but a single arrangement of the atoms. This argument therefore proves that the "bonds" on the different sides of an atom are of the same strength only for those atoms which have similar atomic groups arranged symmetrically about them. For this reason it is probable that there are some complicated compounds in which certain groups of atoms may retain their identity in the solid state. The writer has been unable to think of any substance, however, which could crystallize in such a manner that some one atom would not be equally strongly bound to two or more similar atomic groups. The molecule is therefore indeterminate, inasmuch as this particular atom cannot be said to belong to one atomic group rather than to another.

matter as having a molecular structure, but must consider it to be purely atomic, which is the thesis we started to prove.⁹

A CONSIDERATION OF OBJECTIONS.

As an immediate result of our hypothesis it must follow that matter in the solid state can have no properties which depend upon a molecular structure as distinguished from an atomic structure. It is important, therefore, to consider those explanations of properties of solid matter which involve a molecular structure. All

FIG. 8.

such explanations which I have been able to find are those which consider solid matter to be made up of electric or magnetic doublets. For instance, there is the common explanation of electric strain as due to molecules in the dielectric which are made up

FIG. 9.

each of two portions, one positively, the other negatively electrified, and that the two portions are shifted by the forces accompanying the strain. Of course, in making this assumption chemical and electric attraction are identified, as we have assumed

⁹ Langmuir's conclusion from similar considerations is rather that the crystal is a single molecule. The difference depends chiefly upon whether the molecule is defined as the smallest portion of a substance which has the characteristics of the substance or as a group of atoms held together by chemical forces. The above argument is based on the former definition, contending that these smallest portions cannot be definitely defined. Langmuir concludes, on the basis of the latter definition, that, since all the atoms in a crystal are similarly bound together, the whole crystal is a single molecule. Since, however, the forces of cohesion and adhesion are essentially identical with chemical forces, a similar argument would show that the whole earth, and perhaps even the whole universe, is a single molecule. The writer therefore prefers the former conception of the molecule as having a more definite meaning.

above. Following Poynting and Thomson ("Electricity and Magnetism," p. 59): "We may, for our present purpose, . . . conventionally represent a molecule as in the figure (Fig. 8) . . . If the dielectric is in a neutral condition, we must suppose that the molecular axes are distributed equally in all directions, . . . and

FIG. 10.

there is no resultant electric action outside." When an electric field is imposed, these molecules arrange themselves as in Fig. 9, which has the same effect as placing a charge on the surfaces of the dielectric.

FIG. 11.

If this means that the molecules are capable of rotation through any angle, then in a crystal such as a KCl crystal, if the electric field were perpendicular to the (111) planes, as in Fig. 10, the supposed molecules would arrange themselves as in Fig. 11. Thus the (111) planes would become cleavage planes, which is evidently absurd, since there is no apparent change in the crystal

structure. But if the theory means only that a molecule can be turned slightly from its stable position, there is nothing which requires a true molecular structure, since a slight shift in the position of the atoms will produce the same result. (If this shift in position is great enough, it should be possible to detect it in crystal dielectrics by obtaining X-ray spectra from them. For example, if the electric field is perpendicular to a cleavage plane of a KCl crystal, we might expect the atoms to be displaced as in Fig. 12. It may be shown that such a displacement would reduce the comparative intensity of the higher orders of

FIG. 12.

spectra, and this, by careful measurement, might be noticeable.)

Another explanation of electric phenomena which apparently depends upon a true molecular structure in a crystal is Lord Kelvin's explanation of pyroelectricity, which is also extended to piezoelectricity. As explained in Poynting and Thomson ("Electricity and Magnetism," p. 150), this explanation is: "The molecules are set in the crystal with their electric axis

FIG. 13.

parallel to a certain direction, and there will therefore be a definite amount of strain passing from each positive element of a doublet to the negative element of the doublet next to it. The crystal, as a whole, will be the seat of an electric strain along the direction of the axis. The constitution corresponds to that of a saturated permanent magnet on the molecular theory of magnetism. The electric strain will manifest itself almost entirely at the ends of the crystal if the doublets are near enough together; and the crystal will produce a field outside equal to that which would be produced by charges respectively positive and negative at the two ends. . . . But . . . charges will in time gather on

the surfaces at the ends of the axis, . . . entirely masking the existence of the strain, so that there is no external field. This is the ordinary condition of a neutral crystal.

"We have now to suppose that the electric strain passing forward from molecule to molecule depends on the temperature, and that it alters nearly in proportion to the change in tempera-

FIG. 14.

ture. Then when the temperature changes there will be an unbalanced strain proportional to the change, producing the same effect as a positive charge at one end and a negative charge at the other until conduction again does its work in bringing up masking charges."

FIG. 15.

The mechanical model which Poynting and Thomson suggest as an illustration is a series of molecular doublets, arranged as illustrated in Fig. 13, which, when heated, assume the arrangement shown in Fig. 14 as the molecules become separated. Here certain of the lines of force combine, giving the effect of a free charge at either end. This model would explain pyroelectricity as due merely to molecular separations, and we ought to get a

similar effect if the molecular separation is produced by tension, which is the piezoelectricity found by Curie.

An objection to this model is that it assumes that as the temperature rises the parts of the molecule come relatively closer together, while experiments in specific heat seem to indicate that with rising temperature the parts of a molecule become farther separated. A model to which this objection does not apply, which does not assume any molecular structure, and which accords fully with Kelvin's explanation, may easily be imagined. Suppose the atoms in a crystal to be arranged as in Fig. 15. It will be seen at once that such an arrangement will correspond to the "saturated permanent magnet on the molecular theory of magnetism." The left end will have the equivalent of a positive charge and the right end that of a negative charge. There will evidently be in this model three different axes along which there will be such an effect, which might correspond to the three electric axes of a quartz crystal. As the atoms move farther apart with a rise in temperature the strength of the doublets is increased, and, if the ends were neutralized before, a new charge will now appear.

Of course, the same result would occur here also if the atoms were separated by tension, which would explain piezoelectricity. If the structure of a quartz crystal can be determined as the Braggs are now trying to do, it will be an easy matter to see whether a true molecular structure is required for the explanation of pyro- and piezo-electricity.

There are, however, some difficulties with a complete explanation of the magnetic properties of solids, without assuming a molecular structure, that are not so easily met. One of the arguments for a molecular structure from magnetic properties comes from a consideration of the Heusler alloys. In these alloys no element by itself is very strongly dia- or para-magnetic, but when the different elements are alloyed the mixture is almost as paramagnetic as iron. From this it might be concluded that atoms from two different slightly magnetic substances can combine to form a molecule that is ferromagnetic.

We have, however, strong indications that magnetism is a purely atomic property. A good experimental indication of this comes from depositing iron electrolytically in a magnetic field. For instance, if a varnished silver wire with a thin scratch through the varnish is placed in a solution of ferric chloride, when the

iron is deposited electrolytically an extremely small magnetic field will make of the deposited iron a saturated magnet. This indicates that the elementary magnetic doublets are easily turned around while the iron is being deposited. The iron is deposited, however, atom by atom, and, since the position taken by each atom is determined by the crystal form and not by the magnetic field, it must be the atoms and not the molecules which are oriented by the magnetic field.

Perhaps the strongest evidence that the magnetic effects are not molecular but atomic phenomena is the fact that the structure of the atom which the most generally accepted theories suggest offers an excellent explanation of magnetism as due to atomic properties. I refer to the theory that the atom consists of electrons revolving in orbits, held together by the appropriate positive charge. This, of course, makes each atom an elementary magnetic doublet. Langevin and Weiss have developed a complete theory on this assumption (Professor Richardson's lectures on "Electron Theory"), explaining both dia- and para-magnetism, which seems to be as satisfactory as any yet proposed. The fact that a theory based on this assumption explains magnetic phenomena so well without any reference to a molecular structure would indicate that these effects have no dependence on molecular structure.

However, we have good reason to believe that the environment of an atom greatly influences its magnetic properties. For instance, different samples of iron vary greatly in their magnetic properties, according to their temper, per cent. of carbon, amount of alloy, temperature, etc. The explanation of Heusler alloys would therefore seem to be that the environment of the atoms of the different elements is changed in such a manner by being alloyed that they are free to turn under a magnetic field.

There is another difficulty, however, which results from a purely atomic explanation of magnetism. This is an explanation of the heating effect when a piece of iron is placed in an alternating magnetic field. This alternating magnetic field, if intense enough, is supposed to turn the elementary doublets completely around. If these doublets are molecular, it is easy to see how their turning can impart kinetic energy to the system and so raise the temperature; but if they are atomic, since only the translational degrees of freedom of an atom are supposed to

possess heat motion, any amount of rotation of the atom would not affect the temperature of the substance. Two possible explanations may be offered. In the first place, it is possible that, since an atom can no longer be considered to be a sphere, its rotary degrees of freedom actually do enter into the thermal motions. Or, in the second place, though the rotary degrees of freedom may not themselves enter into the heat motion, it is possible, since the atoms are not spheres, that their rotation may displace other atoms translationally, which would account for the heating effect. It must be confessed, however, that neither of these explanations appears wholly satisfactory, and that this heating effect presents a real difficulty to any non-molecular explanation of magnetic phenomena.

A test for this point would be to take Laue photographs through a crystal such as pyrrhotite, which shows magnetic effects, and see if there is any change in the internal structure when the crystal becomes saturated.¹⁰

SUMMARY.

To sum up our argument then: It is shown, in the first place, that the arrangement of the atoms in certain crystals, as determined by their X-ray spectra, indicates definitely that in these crystals there is no molecular structure.

In extending the argument to all solid matter it is pointed out, from the dependence of crystal form on chemical composition, from a consideration of the Dulong-Petit law and of the nature of cohesion, and from the evidence of X-rays as to certain crystals, that each atom in a solid oscillates about a definite position of stable equilibrium.

From a further examination of the nature of cohesion and of the forces concerned in chemical combination and especially from the general relation found between the atomic heat of formation of a substance and its melting-point it is found that the forces

¹⁰ This test was suggested by my brother, K. T. Compton. It has been made by K. T. Compton and E. A. Trousdale (*Phys. Rev.*, 5, 315, 1915) and repeated with greater care by the writer and Oswald Rognley (*Science*, N. S., 46, 415, 1917). These experiments show that when magnetic crystals are saturated magnetically the atoms are not displaced by as much as $1/250$ of the distance between the atoms. Magnetic effects are therefore not due to rotations of the molecules, but must be due to the atoms or something within the atoms.

holding the atoms in their positions of stable equilibrium are of the same nature and comparable in magnitude with the forces binding together a chemical molecule.

It is seen further that the atoms in a solid are very close together, so that they often come in contact. And, since an atom attracts equally all atoms of another kind which are in contact with it, an atom cannot remain combined for more than an infinitesimal interval with any other particular atom at ordinary temperatures.

Finally, it was shown that, since in the solid state each atom has three degrees of translational freedom and is strongly attracted by atoms other than those of its own "molecule," it must, on the average, exert equal attractions on all the neighboring atoms.

From this the conclusion is drawn that in the solid state the atoms are so intimately intermingled that particular molecules cannot be definitely defined.

When those properties of solid matter which have been explained by molecules are considered, nothing is found which indicates at all definitely a molecular structure.

We feel justified in concluding, therefore, *that the structure of solid matter is not molecular.*

July 25, 1914.

Largest High-head Francis Turbine. ANON. (*Electrical Review*, vol. 72, No. 10, p. 417, March 9, 1918.)—The Puget Sound Traction, Light and Power Company, of Seattle, Wash., is installing a new turbine unit of 25,000 horsepower capacity in its White River hydro-electric plant in the vicinity of Sumner, Wash. The two original units, which were installed in 1911, have a rated capacity of 36,000 horsepower, but in actual practice have carried a load of 44,000 horsepower. This equipment, which includes Francis turbines, was built by the Allis-Chalmers Manufacturing Company, the plant having been designed and installed under the supervision of Stone & Webster, engineers. The new installation is being made primarily to supply the power required by the Chicago, Milwaukee and St. Paul Railway Company to operate passenger and freight trains over the Cascade Mountain division in Washington.

The new unit being installed consists of equipment similar to that of the two units now in use; the new Francis turbine, however, having a capacity of 25,000 horsepower, is the largest of this type ever built. The turbines of the two original units are of the double-discharge horizontal type with spiral case, operating at 360 revolutions per minute under a head of 440 feet. These turbines have shown very high efficiency under test.