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Andrew A. Cochran

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THE APPLICATION OF QUANTUM-MECHANICAL CONCEPTS TO BIOLOGICAL SYSTEMS

BY

ANDREW A. COCHRAN

A

THESIS

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Approved by

Louis W. Lund (Advisor) W. J. James

Harold Q. Fuller C. A. Johnson

ABSTRACT

The relation between quantum-mechanical concepts and biological systems is explored by studying the relation of both to the concepts of heat capacity and entropy. It is shown that the most important substances in living matter have extremely low heat capacities and entropies at ordinary temperatures. A critical analysis of the two types of quantum-mechanical interactions between particles and the interactions occurring in low-entropy systems shows that the wave properties of matter are strongly predominant in the chemical elements that constitute 99 percent of living matter. It is concluded that the wave aspects of matter are strongly predominant in biological systems. Predominance of the wave aspects of matter appears to be a necessary, but not a sufficient, condition for the existence of life.

Evidence is cited indicating that biological systems are condensates in momentum space in the same sense as superconducting electrons and helium II. The evidence indicates that the wave-functions of pi electrons in proteins, nucleic acids, and porphyrins extend over relatively long distances by means of quantum-mechanical resonance, and it is suggested that this is the physical basis of the extension of biological organization into macroscopic dimensions. Quantum-mechanical resonance can be regarded as a specific example of the predominance of the wave aspects of matter in the essential chemical structures of living organisms.

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I. INTRODUCTION

A. Biological Phenomena as a Physical Problem.

The fundamental nature of biological phenomena has long been considered one of the most important scientific problems of all time. The complex phenomena of life have been only partially elucidated in terms of the present-day concepts of science, and many mysteries of a fundamental nature remain. Whether the conceptual structure of modern science will prove adequate to encompass living organisms is at present not clear; it is possible that this conceptual structure will have to undergo modifications.

Since the development of quantum theory in the last half-century, there have been many hints that this relatively new tool will have important applications in the understanding of biological phenomena. While many physicists have noted this fact, attempts to implement this idea have been vague and speculative. What is needed are specific proposals leading to new areas of contact between quantum concepts and biological phenomena. When such contacts are found, it may be possible to test the proposals by useful experiments. Only when specific concepts are proposed and experiments are performed can real progress be made in this difficult field. The discovery of a specific relationship between quantum concepts and living matter would undoubtedly stimulate further developments in both biology and quantum physics.

B. Review of Literature.

A considerable number of modern physicists have believed that it will eventually be necessary to apply the concepts of quantum theory to the fundamental problems presented by biological systems.

> According to MARGENAU (1) "The advance has also led physics to higher ground from which new and unexpected approaches to foreign territory can be seen. Not too far ahead lies the field of biology with its problems of organization and function, and one is almost tempted to say that modern physics may hold the key to their solution."

JORDAN stated that living organisms must eventually be studied by means of the concepts of quantum physics, for these reasons: The entire behavior of living organisms is directed from amazingly tiny centers. The gene molecules which are found in the nucleus of each cell transmit all the hereditary characteristics and control many aspects of cellular metabolism. A few 'organizers' control the entire development of the tiny zygote to an adult organism. A few cells of the brain of man contain the powers which direct all intellectual, emotional, and voluntary activity. Because of these facts, JORDAN believed that living things belong to the microscopic world in a very real sense. Since man's directive centers belong to the atomic realm, JORDAN believed that man must eventually be studied by the physical concepts of this dimension, which belong to quantum physics (2).

BOHR pointed out that the dual aspects of the fundamental particles of matter are analogous to the dual aspects of man, and showed that Heisenberg's Uncertainty Relations apply to both material particles and living things (2). Material particles exhibit the dual aspects of both particles and waves, while living things exhibit the dual aspects of both a collection of physico-chemical processes, and an evolutionary dynamism which transcends physico-chemistry. BOHR applied the Uncertainty Relations to man in the following way: If the physico-chemical aspect of a man were to be studied exhaustively, all his tissues would have to be examined, dissected, and analyzed. But this would cause the death of the man, and then his vital dynamism could not be studied at all. Conversely, if we are to study the dynamic or mental aspects of a man, we must have great regard for the soundness of his tissues, which leaves us with incomplete knowledge of his physico-chemical aspects. BOHR further suggested that certain key processes in the brain, controlling mental activity, are so delicate and sensitive that they must be described in a quantum-mechanical way, and that these key processes are amplified until they result in a bodily movement involving vast numbers of quanta and are capable of being described by classical methods (3). In this connection, BOHM (3) pointed out that a very close analogy exists between quantum processes and the processes of conscious thought in men's brains.

SCHRÖDINGER (4) has discussed in considerable detail the application of quantum concepts to biological systems.

> Concerning mutations, SCHRÖDINGER says "The significant fact is the discontinuity. It reminds a physicist of quantum theory--no intermediate energies occurring between two neighbouring energy levels. He would be inclined to call de Vrie's mutation theory, figuratively, the quantum theory of biology. We shall see later that this is much more than figurative. The mutations are actually due to quantum jumps in the gene molecule." (4, p. 34)

Several more quotations from SCHRÖDINGER'S book follow:

> "...incredibly small groups of atoms, much too small to display exact statistical laws, do play a dominating role in the very orderly and lawful events within a living organism. They have control of the observable large-scale features which the organism acquires in the course of its development, they determine important characteristics of its functioning; and in all this very sharp and very strict biological laws are displayed." (4, p. 19)

> "...living matter, while not eluding the 'laws of physics' as established up to date, is likely to involve 'other laws of physics' hitherto unknown, which, however, once they have been revealed, will form just as integral a part of this science as the former." (4, p. 68-69)

> "We must therefore not be discouraged by the difficulty of interpreting life by the ordinary laws of physics. For that is just what is to be expected from the knowledge we have gained of the

> structure of living matter. We must be prepared to find a new type of physical law prevailing in it. Or are we to term it a non-physical, not to say a super-physical, law? No. I do not think that. For the new principle that is involved is a genuinely physical one: it is, in my opinion, nothing else than the principle of quantum theory over again." (4, pp. 80-81)
>
> "The physicist is familiar with the fact that the classical laws of physics are modified by quantum theory, especially at low temperature. There are many instances of this. Life seems to be one of them, a particularly striking one... To the physicist--but only to him--I could hope to make my view clearer by saying: The living organism seems to be a macroscopic system which in part of its behaviour approaches to that purely mechanical (as contrasted with thermodynamical) conduct to which all systems tend, as the temperature approaches the absolute zero and the molecular disorder is removed." (4, pp. 69-70)

SCHRODINGER (4) also applies the concept of entropy to living things. He points out that a living organism is a chemical system with a high degree of order and organization, and therefore low entropy. Living things are not in chemical equilibrium (a state of maximum entropy) until death, and they avoid the decay to equilibrium by eating low entropy material and discarding high entropy material as wastes. Many investigators have further developed the idea of low entropy or negative entropy in living things, and important use of this concept will be made in this thesis.

C. Basis of Thesis Work.

In this thesis, the lines of thought represented by the preceding references have been extended into new territory and a specific relationship between quantum concepts and living matter is shown to exist. The reasoning process is based on consideration of the following facts:

1. Carbon is the basic chemical element of living matter; and carbon, hydrogen, nitrogen, and oxygen make up more than 99 percent of living matter.

2. Carbon has the lowest entropy and heat capacity of all the chemical elements at ordinary terrestrial temperatures; and hydrogen, nitrogen,

and oxygen have very low entropies and heat capacities in the solid state at these temperatures.

3. The low heat capacities and entropies of these four elements at ordinary temperatures can be explained only on the basis of quantum theory.

These three facts suggest that the elucidation of biological systems in terms of quantum physics involves such familiar physical quantities as heat capacity and entropy. This raises the hope that a specific application of quantum concepts to living matter may be made by studying the relationship of both to these familiar physical quantities. The rest of this thesis is concerned with this task.

II. ENTROPY AND HEAT CAPACITY DATA

A. The Entropies of the Chemical Elements.

What are the principal chemical elements found in living matter? As mentioned in the Introduction, the elements carbon, hydrogen, nitrogen, and oxygen are by far the most plentiful, and together they constitute more than 99 percent of living matter (5, 6). Of these four elements carbon can be singled out as having unique properties which make it suitable for living matter. EDSALL and WYMAN (6, p. 23) state, "The fact that carbon compounds occupy a key position in life as we know it is so obvious as to need no comment."

> According to SIDGWICK (7) "Carbon is unique among the elements in the number and variety of the compounds which it can form. Over a quarter of a million have already been isolated and described, but this gives a very imperfect idea of its powers, since it is the basis of all forms of living matter. Moreover, it is the only element which could occupy such a position. We know enough now to be sure that the idea of a world in which silicon should take the place of carbon as the basis of life is impossible; the silicon compounds have not the stability of those of carbon, and in particular, it is not possible to form stable compounds with long chains of silicon atoms."

No other element approaches carbon in the ability to form molecules in which a large number of like atoms are joined together. The number of permutations and combinations possible with carbon and hydrogen alone is great, and this number is enormously increased by the presence of other elements, especially oxygen and nitrogen. It is obvious that the complexity of living matter depends to a great extent on the ability of carbon to form long chains and rings, and many compounds with other elements. Because of these unique properties, carbon is generally regarded as the basic chemical element of living matter.

The chemical substances of greatest importance and interest in living organisms, such as nucleic acids and proteins, are true solids, held together by Heitler-London bond forces, even though they may form highly flexible structures (4, p. 58-61). In the present consideration of biological systems we will, therefore, confine our attention to the solid state.

Many writers have noted and discussed the fact that living matter has a high degree of order and, therefore, has a low entropy. It will be helpful if we pause at this point long enough to gain some idea of how low the entropy is. Although living matter is not in thermodynamic equilibrium, living systems may be thought to exist in a steady state over short intervals of time, as matter is conveyed through them and metabolism occurs (8). However, living matter involves certain complexities that make simple calorimetry inapplicable in the determination of entropy. One difficulty is that of measuring the amounts of the different kinds of work performed in living systems: chemical work of synthesizing proteins and other compounds, mechanical work of muscle contraction, electrical work of nerve impulses, and absorption or secretion against an osmotic gradient. Another difficulty is that any living cell contains, in addition to the essential chemical structures of life, a higher-entropy substrate of water and simple raw materials for chemical synthesis that would mask the entropy of the actual living matter. Therefore, quantitative entropy data will be presented by indirect methods.

The entropies of the solid chemical elements in the first three rows of the Periodic Table are shown in Figure 1. (The transition elements Scandium through Zinc, in which the inner 3d electron shell is progressively filled with electrons, have not been included in the graph.) Inspection of the entropies of all the chemical elements that are solids at 25 degrees C. show that the following elements have the lowest entropies:

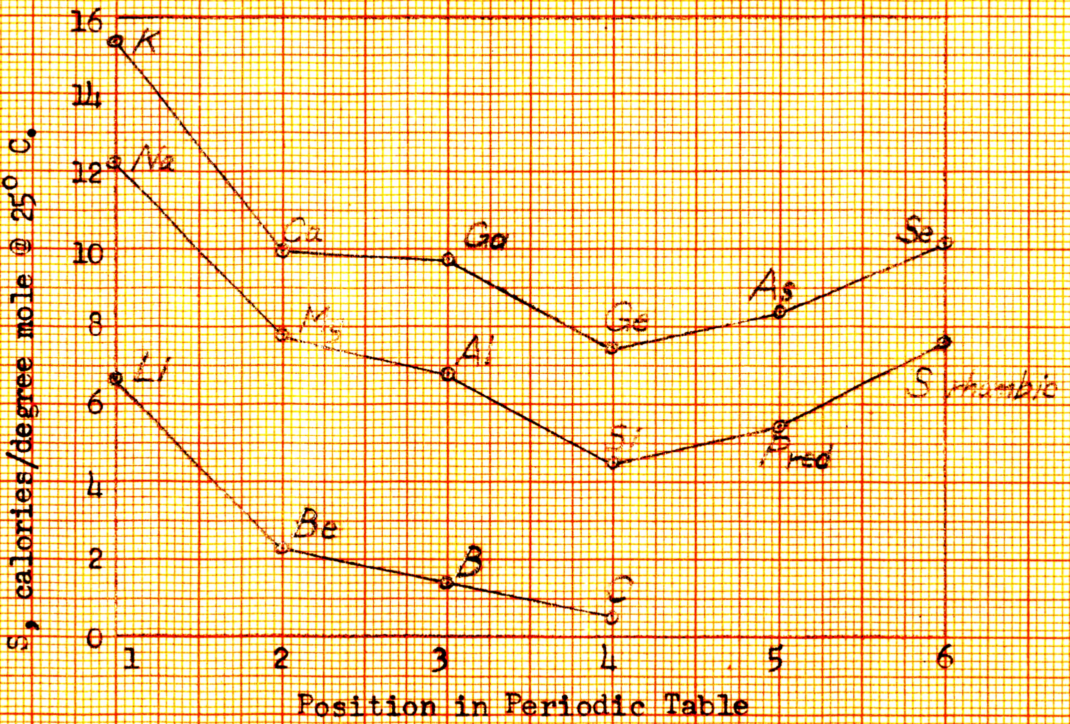


Fig. 1. Atomic Entropies of Elements in the First Three Rows of the Periodic Table. (9)

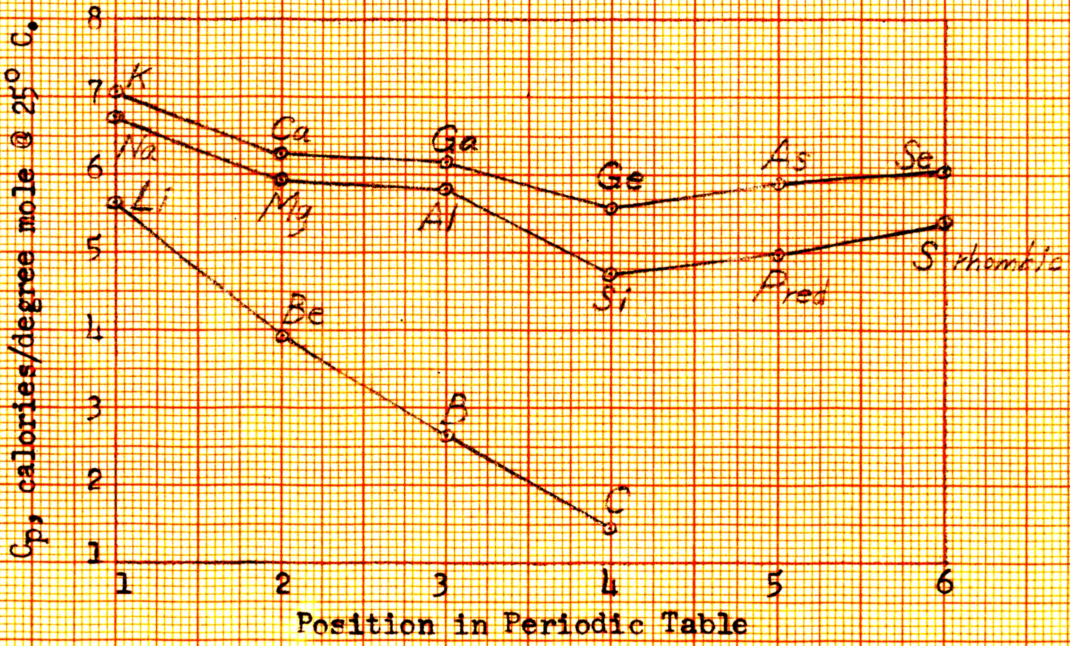


Fig. 2. Atomic Heat Capacities of Elements in the First Three Rows of the Periodic Table. (9)

Element:	C(diamond)	B	Be	Si	P(red)
S, cal./deg. mole (9)	0.58	1.40	2.28	4.51	5.46

In either diamond or graphite form, carbon has the lowest entropy of all the chemical elements.

B. The Heat Capacities of the Chemical Elements.

Entropy and Heat Capacity are closely related mathematically and conceptually. The mathematical relation is:

$$S = \int_0^T \frac{C_p\,dT}{T} = \int_0^T C_p\,d(\ln T)$$

where S is the entropy at Absolute Temperature T, and C_p is the heat capacity. In crystalline solids at ordinary temperatures, C_v and C_p, the heat capacities at constant volume and constant pressure, are so nearly equal that the difference between them is often neglected. The entropy of a system may be considered to be the total accumulated disorder, or degraded energy, while the heat capacity may be considered to be the instantaneous rate at which disorder is added to (or subtracted from) a system. The exact relation between entropy and disorder is:

$$S = k \log D$$

where k is the Boltzmann constant and D is a quantitative measure of the atomic disorder of the body in question. (4, p. 73)

The heat capacities at constant pressure of the solid chemical elements of the first three rows of the Periodic Table are shown in Figure 2. Inspection of the heat capacities of all the chemical elements that are solids at 25 degrees C. shows that the following elements have the lowest values (9):

Element:	C(diamond)	B	Be	Si	P(red)
C_p, cal./deg. mole	1.45	2.65	3.93	4.73	4.98

Note that the same elements are found in the same order as in the low-entropy series.

Of the different methods of obtaining entropies, that based upon low-temperature heat capacity data is of the greatest importance. (9, p. 3) Curves of C_v versus T are similar in appearance for nearly all solid elements, since C_v increases from zero at zero degrees K. to approximately 5.9 cal./deg. mole at some temperature which is characteristic of the substance, and then remains almost constant (10). Two such curves for different elements can be made to almost coincide by suitable adjustment of one of the temperature scales (10). In view of these facts, and the fact that the same elements were found in the same order in both the low-entropy and the low-heat-capacity series, we suspect that if a solid has a low entropy at a given temperature, it will in general also have a low heat capacity at that temperature. We can check the validity of this reasoning by means of Kopp's Law of heat capacities, which states that the molar heat capacity of a solid can be calculated approximately by adding together atomic heat capacity values for the elements composing the solid. Lists of Kopp's Law heat capacity values for the chemical elements have been compiled for this purpose (11, 12), and are shown in Figures 3 and 4 for the first three rows of the Periodic Table. Values of 6.35 cal./deg. mole are to be used for all the other chemical elements. One of the important features of Kopp's Law is that it provides solid-state heat capacity values for the gaseous elements that did not appear in Figures 1 and 2.

It can be observed in Figures 1 and 2 that in each case the Group IV element (C, Si, and Ge) has the lowest value in each row of elements. The decrease in the heat capacities of the first row elements Li through C is

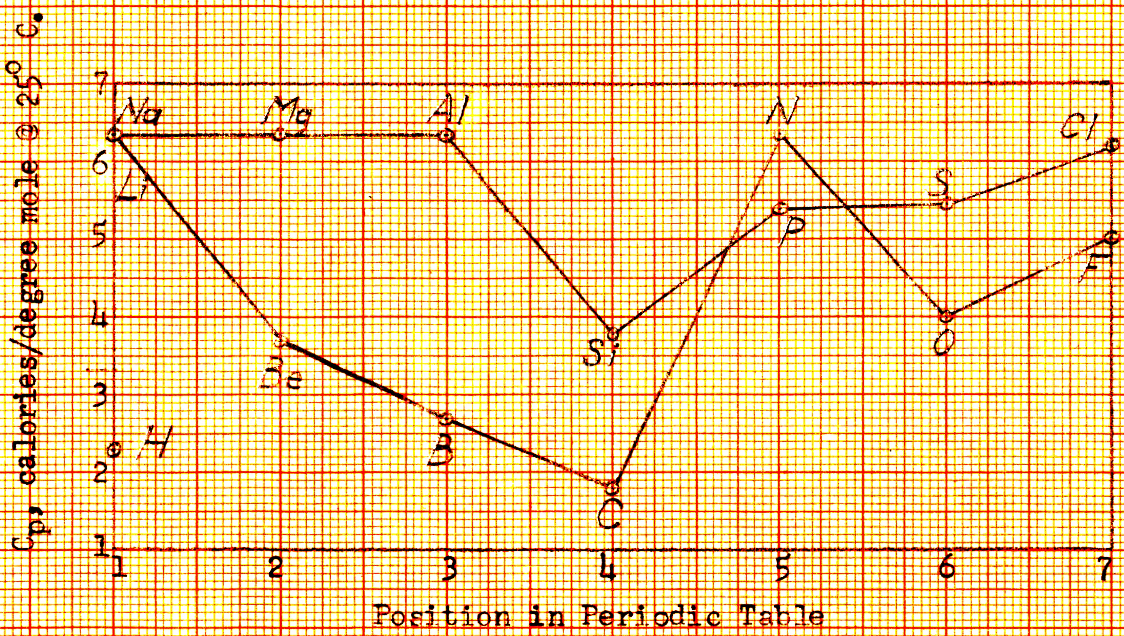


Fig. 3. Kopp's Law Heat Capacities of Hydrogen and Elements in the First Two Rows of the Periodic Table. (11, 12)

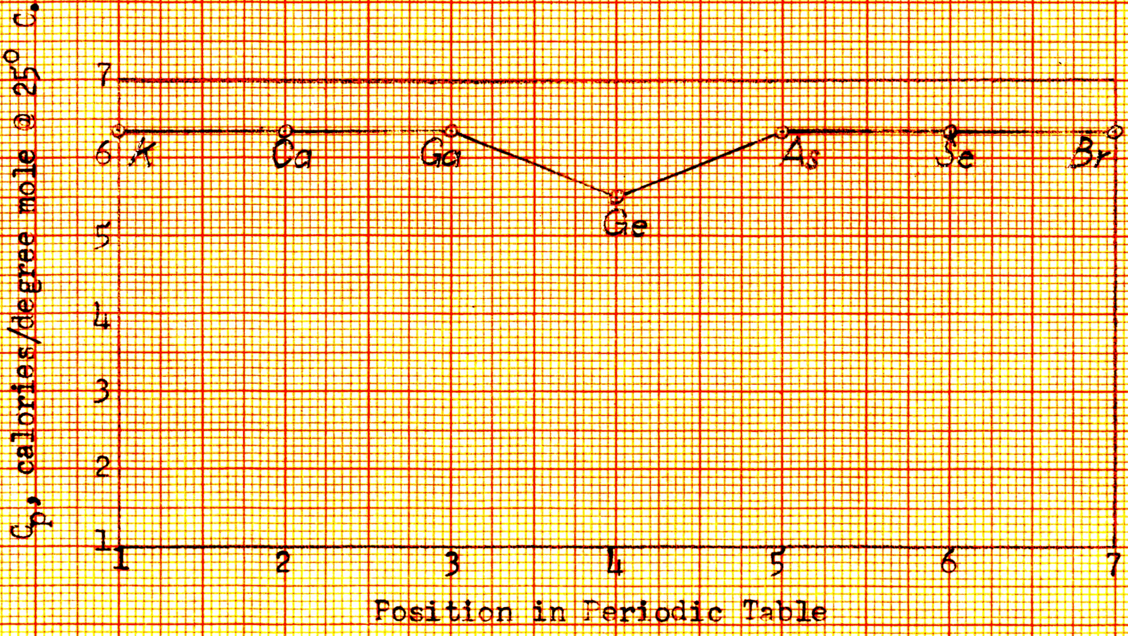


Fig. 4. Kopp's Law Heat Capacities of Elements in the Third Row of The Periodic Table. (11, 12)

especially sharp. In addition, the entropy and heat capacity values increase in the step-wise manner as we go in either direction from the Group IV element to the end of the row. Although the effect is less pronounced in the fourth row of the Periodic Table (Rb through I, not shown), the Group IV element, Sn, again has the lowest entropy in the row. Reference to the Kopp heat capacity values in Figures 3 and 4 shows that the Group IV element is again the lowest in each row, and with one obvious exception, N, the values either increase in a step-wise manner or remain constant in either direction from the Group IV element. The value shown for Nitrogen is the only exception to the latter rule in all nine curves.

C. Calculation of Kopp's Law Heat Capacity Value for Nitrogen.

A study of all the data suggested that the Kopp value shown for N is erroneous, and that the true value probably lies between 1.8 (C) and 4.0 (O). This suspicion was tested objectively by calculating the Kopp's Law value for N in various solid nitrogen compounds. The Kopp values of all the elements except N were subtracted from the true molar heat capacities, thus determining N by difference. Since compounds containing a high percentage of N are more valuable for this purpose, only compounds with at least 10 atomic percent of N were included in the calculations. Data were not accepted unless the molar heat capacities were given to a precision of at least 0.1 cal./deg. mole.

The data are shown in Table I. All the solid nitrogen compounds (containing at least 10 percent N) listed by KELLEY and KING (9), ROSSINI et al (13), and TIMMERMANS (14) were included in the calculations.

The mean Kopp value for N in the 59 compounds shown in Table I is 3.4 ± 0.7 cal./deg. mole; this value shows that our suspicion was justified and makes Figure 3 look much more reasonable.

TABLE I

Kopp's Law Heat Capacity Values for Nitrogen in Solids

No.	Compound	C_p in Cal./deg. mole @298.15°K.	Kopp C_p For N in Cal./deg. gram atom
1	BN	4.78	2.08
2	TiN	8.86	2.51
3	VN	9.08	2.73
4	ZrN	9.66	3.31
5	$K_3Co(CN)_6$	74.00	6.30
6	$K_3Fe(CN)_6$	75.60	6.58
7	$NaNH_2$	15.80	4.85
8	$AgNO_2$	19.17	4.82
9	$Ba(NO_3)_2$	36.18	2.92
10	$Ca(NO_3)_2$	35.70	2.67
11	$Mg(NO_3)_2$	33.92	1.79
12	NH_4NO_3	33.31	6.05
13	$TlNO_3$	23.78	5.43
14	$NaNO_3$	22.24	3.89
15	KNO_3	23.01	4.66
16	$AgNO_3$	22.24	3.89
17	NH_4Cl	20.71	5.31
18	NH_4F	15.60	1.40
19	$(NH_4)_2SO_4$	44.81	2.48
20	NH_4VO_3	30.91	3.36
21	P_3N_5	35.6	3.88
22	$(NH_4)_2HPO_4$	43.5	0.70
23	NH_4CN	32.0	10.50

No.	Compound	C_p in Cal./deg. mole @298.15°K.	Kopp C_p For N in Cal./deg. gram atom
24	Urea, CH_4ON_2	22.26	3.63
25	$CH_3NH_2 \cdot HCl$	21.75	-0.05
26	CH_3CONH_2	15.9	-3.20
27	Glycine, $C_2H_5O_2N$	24.0	0.90
28	Zn_3N_2	25.7	3.33
29	Cu_3N	21.7	2.65
30	$Ni(NO_3)_2 \cdot 6NH_3$	96.0	3.03
31	$CoCl_3 \cdot 6NH_3$	76.7	1.72
32	$CoI_2 \cdot 6NH_3$	69.2	1.46
33	$CoI_3 \cdot 6NH_3$	74.3	1.25
34	Fe_2N	16.8	4.10
35	Fe_4N	29.3	3.90
36	Mn_5N_2	43.8	6.03
37	Mn_8N_2	61.0	5.10
38	TaN	9.7	3.35
39	AlN	7.67	1.32
40	$AlCl_3 \cdot 6NH_3$	94.2	4.64
41	$ScF_3 \cdot 3NH_4F$	90.0	8.68
42	$Y(NO_3)_3$	75.7	11.12
43	CeN	11.2	4.85
44	LaN	11.1	4.75
45	Th_3N_4	37.3	4.56
46	Mg_3N_2	24.99	2.97
47	Ca_3N_2	22.5	1.72
48	$Sr(NO_3)_2$	38.3	3.98

No.	Compound	C_p in Cal./deg. mole @298.15°K.	Kopp C_p For N in Cal./deg. gram atom
49	Li_3N	18.4	-0.65
50	NaN_3	19.1	0.02
51	$K_4Fe(CN)_6$	80.3	6.29

TABLE I (Continued)

Kopp's Law Heat Capacity for Nitrogen in Solids

No.	Compound	C_p, cal./deg. gram	Temperature, degrees K.	Molecular Weight	C_p, cal./deg. mole	Kopp C_p For N cal./deg. gram atom
52	Creatine Hydrate $C_4H_{11}O_3N_3$	0.3423	298.4	149.15	51.05	2.18
53	dl-Citrulline $C_6H_{13}O_3N_3$	0.3176	300.8	175.19	55.64	0.98
54	Glycylglycine $C_4H_8O_3N_2$	0.2927	294	132.12	38.67	0.54
55	Alanylglycine $C_5H_{10}O_3N_2$	0.2973	296.4	146.15	43.45	-0.28
56	Guanidine Carbonate $C_3H_{12}O_3N_6$	0.3434	298	180.17	61.87	2.81
57	d-Arginine $C_6H_{14}O_2N_4$	0.3188	296.8	174.20	55.53	1.13
58	m-Nitroaniline $C_6H_6O_2N_2$	------	298.15	------	40.2	3.80
59	p-Dinitrobenzene $C_6H_4O_4N_2$	------	298.15	------	45.9	4.95

Average of 59 Kopp's Law C_p values for N: 3.38 ± 0.66
(For a 95 per cent confidence level)

References: (9) for compounds 1 through 20
(13) for compounds 21 through 51
(14) for compounds 52 through 59

The chemical elements with the lowest Kopp heat capacity values at room temperature in solid compounds now become:

Element:	C	H	B	N	Be	Si	O	F	P	S
Kopp C_p, cal./deg. mole:	1.8	2.3	2.7	3.4	3.7	3.8	4.0	5.0	5.4	5.45

It can be seen that the order of the chemical elements is the same as previously listed in the low entropy series and the low heat capacity series; the difference in the above series is that Kopp's Law permits us to include various elements that are gases at 25° C. We see from the Kopp heat capacity series that the basic chemical elements of living matter have very low heat capacities. Carbon, *the* basic chemical element of living matter, has the lowest heat capacity of all the chemical elements, while hydrogen is second, nitrogen is fourth, and oxygen is seventh. By Kopp's Law, then, it follows that the most important substances in living matter have very low heat capacities.

In the substances of greatest importance and interest in biological systems, proteins and nucleic acids, the most plentiful chemical elements besides C, H, N, and O are phosphorus and sulfur. All nucleic acids and some proteins contain phosphorus, and phosphate esters are of vital importance in energy transfer reactions. From the centers of respiration in animal cells and photosynthesis in plant cells the same molecule--adenosine triphosphate--carries the free energy extracted from food or from sunlight to all the energy-expending processes of the cell. Sulfur is an essential constituent of proteins, coenzyme A, glutathione, and many other important biological compounds. These two important elements, P and S, are found in positions 9 and 10 in the Kopp heat capacity series. Obviously there is a strong suggestion of a correlation between low heat capacity and importance to life.

D. Entropies and Heat Capacities of Some Amino Acids.

Another indication of the low entropy and heat capacity of living matter can be gained as follows: Proteins are made up of amino acids that have been joined together in long peptide chains. Table II gives entropy and heat capacity data for some amino acids that were reported to have been hydrolyzed from proteins (15). The molar entropy and molar heat capacity values have been divided by the number of atoms in the molecule to obtain the average entropy per gram atom, and the average heat capacity per gram atom. When these values are compared with the corresponding gram atom values in the preceeding sections, it can be seen that the entropies and heat capacities of these amino acids are amazingly low. Only three elements have lower entropies than the average entropy value of 2.4 cal./degree gram atom in Table II, and only one element has a lower heat capacity than the value of 2.2 cal./degree gram atom in Table II.

These considerations indicate that the entropy and heat capacity of living matter are surprisingly low; so low that it would be difficult to imagine any substance as complex as living matter which has lower values of these quantities.

Why are the particular elements C, H, N, and O so plentiful in living things? At the first level of insight into the problem, the results suggest that it is because these elements are capable of forming complex solid compounds of very low entropy and heat capacity, and consequently compounds with a high degree of order. Apparently this is a necessary condition for the orderly processes of life to take place.

TABLE II

Entropies and Heat Capacities of Some Amino Acids (14)

No.	Amino Acid	S, cal./deg. mole	Average S, cal./deg. gram atom	C_p, cal./deg gram	Temp. Degrees K.	Molecular Weight	C_p, cal./deg. mole	Average C_p, cal./deg. gram atom
1	dl-Alanine $C_3H_7O_2N$	31.6	2.43	0.3265	297.5	89.10	29.09	2.24
2	d-Arginine $C_6H_{14}O_2N_4$	59.9	2.30	0.3188	296.8	174.20	55.53	2.14
3	dl-Leucine $C_6H_{13}O_2N$	49.5	2.25	0.3540	296.6	131.17	46.43	2.11
4	l-Tyrosine $C_9H_{11}O_3N$	53.0	2.21	0.2827	294.6	181.19	51.22	2.13
5	Glycine $C_2H_5O_2N$	26.1	2.61	------	298.1	------	24.0	2.40
6	dl-Citrulline $C_6H_{13}O_3N_3$	60.8	2.43	0.3176	300.8	175.19	55.64	2.23
7	dl-Ornithine $C_5H_{12}O_2N_2$	46.2	2.20	0.3460	298.1	132.16	45.73	2.18
8	l-Proline $C_5H_9O_2N$	40.8	2.40	0.3096	300.4	115.13	35.64	2.10
9	Glycylglycine $C_4H_8O_3N_2$	45.4	2.67	0.2927	294	132.12	38.67	2.27
10	dl-Alanylglycine $C_5H_{10}O_3N_2$	51.0	2.55	0.2973	296.4	146.15	43.45	2.17

TABLE II (Continued)

Entropies and Heat Capacities of Some Amino Acids

No.	Amino Acid	S, cal./deg. mole	Average S, cal./deg. gram atom	C_p, cal./deg. gram	Temp. Degrees K.	Molecular Weight	C_p, cal./deg. mole	Average C_p, cal./deg. gram atom
11	dl-Leucylglycine $C_8H_{16}O_3N_2$	67.2	2.32	0.3246	297.1	188.22	61.09	2.11
		Average of column:	2.40			Average of column:		2.19

III. THE PHYSICAL MEANING OF LOW ENTROPY AND HEAT CAPACITY

What is the physical meaning of the fact that biological systems have low entropy and heat capacity? This cannot be explained by the law of Dulong and Petit, or indeed by any classical theory. The theories which do explain this successfully are all based on quantum theory. The development of heat capacity theories will be briefly outlined:

The classical theory of Dulong and Petit states that for any solid element the atomic heat capacity $C_V = 3R$, where R is the gas constant and equals 1.98 calories per degree C. per mole. Therefore

$$C_V = 3 \times 1.98 = 5.94 \text{ cal. per degree mole}$$

This theory is based on the concept of equipartition of energy between all the degrees of oscillatory freedom possessed by the system. While this theory was in fair agreement with the observed values for most of the solid elements, a number of exceptions were found (see the elements listed on p. 10), and it was soon discovered that the theory fails for all solids if the temperature is sufficiently low.

An important advance in heat capacity theory was made in 1907, when Einstein applied quantum theory to atomic vibrations. Einstein's basic assumption was that the atoms of a solid vibrate individually and harmonically about their equilibrium positions with a single frequency v, which is characteristic of the solid (10); his heat capacity equation is:

$$C_V = 3R \frac{Z^2 e^z}{(e^z - 1)^2}$$

where $z = \frac{hv}{kT} = \frac{\theta}{T}$. This equation made C_V a function of temperature, and it can readily be shown that C_V approaches zero when T approaches zero, and that C_V approaches the classical value of 3R when T becomes large compared to θ. For intermediate temperatures, Einstein's equation predicts approximately the correct variation of atomic heat with temperature, but at low temperatures it yields values that are too low (see Figure 5).

A further advance in theory was made by Debye in 1912. Debye treated a vibrating crystal as though it had no structure, but was an isotropic homogeneous mass (16). The structure of the crystal entered the calculations only through the value of the maximum frequency of harmonic vibration possible. He further assumed that the velocity of the different frequencies of vibration were equal (no dispersion), and were not affected by temperature. In reality, the velocity is dependent on the frequency, and some dispersion inevitably results. Debye also assumed that the maximum frequency of the transverse vibrations is equal to the maximum frequency of the longitudinal vibrations, which again is not true. In spite of these poor assumptions, the Debye theory approximates the experimental data for all solids with remarkable accuracy (see Figure 5). It is believed that the important assumptions which make the theory valuable are: 1) Each vibration mode, or state, has an energy given by Einstein's theory. 2) In addition to the independent vibrations of the individual atoms, a crystal has many other modes of vibration, which can be thought of as involving various groups of atoms vibrating dependently. The latter assumption represents an improvement over Einstein's theory because it gives better agreement with experimental data at low temperatures, where the vibrations of low frequency are more important. Debye's equation is:

$$C_v = 9R\left(\frac{T}{\theta}\right)^3 \int_0^{\frac{\theta}{T}} \frac{e^x x^4 dx}{(e^x-1)^2}$$

where $x = \frac{hv}{kT}$, $\theta = \frac{hv_m}{K}$, v_m is the maximum frequency possible, and θ again has a different value for each element.

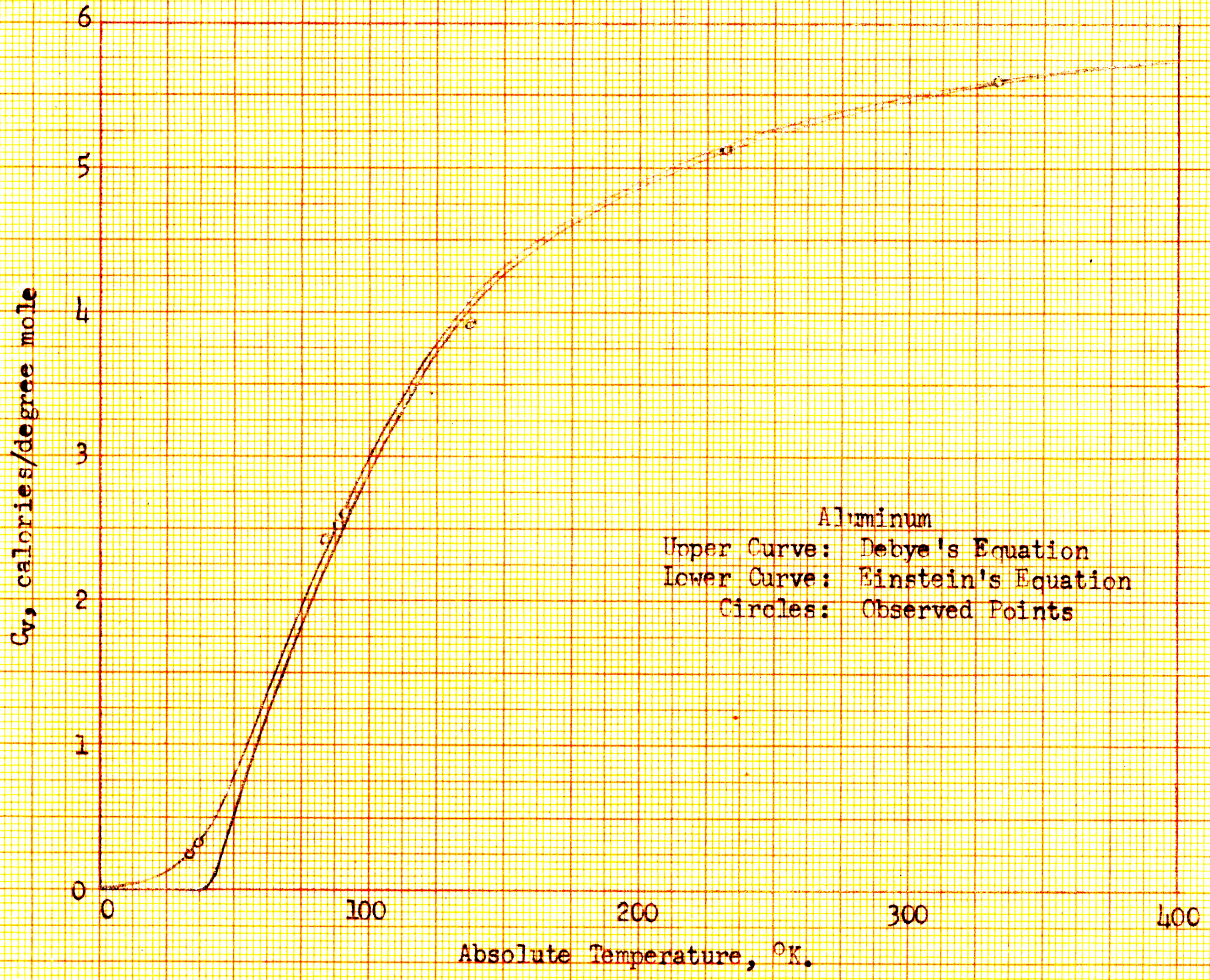


Fig. 5. Comparison of the Heat Capacity Theories of Einstein and Debye. (10)

The quantized oscillatory energy E of an atom or a group of atoms in the lattice is given by the equation:

$$E = (n + \tfrac{1}{2})hv_0,$$

where n is the number of quanta of vibratory energy (called phonons), and v_0 is the classical frequency of the oscillator (17). (Note that at temperatures near absolute zero, when n = 0, $E = \frac{1}{2}hv_0$.)

$$v_0 = \frac{1}{2\pi}\sqrt{\frac{K}{m}}$$

where K is the ratio of the displacing force to the displacement of the atom in the lattice and m is the atomic mass. The quantity K is proportional to the bonding strength of the atom in the lattice. When the vibration frequency is low, the energy of a phonon is low. In living matter, however, the combination of light atoms and strong crystal forces (low m and high K in the above equation) causes the possible frequencies of vibration to be very high, and therefore the energy of a phonon is high. Since the energy necessary to transfer even one quantum to an atom in living matter is far more than the amount usually available from the surroundings, the result is that only a small fraction of the atoms are absorbing and emitting quanta at any given time. Quantum exchanges of energy are relatively infrequent. This low rate of exchange of energy with the surroundings is the basic reason why the entropy and heat capacity of living matter are so low at ordinary temperatures. Most of the atoms are in their lowest quantum state--the state they occupy at absolute zero--and are not participating in the energy exchange.

IV. THE WAVE PROPERTIES OF MATTER

Classical physicists believed that, in principle at least, matter could be completely described in terms of the positions and velocities of its constituent particles. The progress of physics in the twentieth century has made it evident that classical physics is inadequate for atomic-scale phenomena and for the interaction between electrons and electromagnetic fields (18). Physicists have found that the complete description of matter, which is provided by quantum mechanics, involves both descriptions in terms of particle properties and descriptions in terms of wave properties (sometimes called wave nature, or wave aspects). Material particles undergo diffraction as though they have the properties of waves, and the wavelength of electrons, atoms, molecules, and neutrons can be accurately measured (17, p. 1-7).

Under what conditions is the wave nature of matter most prominent? Quantum physics has a clear answer to this question: Whenever we measure the position of a particle, its particle aspects are clearly revealed at the expense of its wave aspects, and the latter become vague and inexactly defined as a result of the measurement (3, p. 132-133, 137-139, 157). Heisenberg's Uncertainty Relations demand this result. On the other hand, whenever we measure the momentum of a particle, its wave aspects are clearly revealed, and its particle aspects become poorly defined.

> BOHM (3, p. 132) states, "To demonstrate this concept we consider, first, an electron with a broad wave-like packet, of definite momentum and, therefore, of a definite wavelength. Such an electron is capable of demonstrating its wave-like properties when it interacts with a suitable measuring apparatus, such as a metal crystal. The same electron, however, is potentially capable of developing into something more like a particle when it interacts with a position-measuring device, at which time its wave-like aspects become correspondingly less important. But even while it is acting more like a particle, the electron is potentially capable of again developing its wave-like aspects at the expense of its particle-like aspects, if it is allowed to interact with a momentum-measuring device. Thus, the electron is capable of undergoing continual transformation from

> wave-like to particle-like aspect, and vice versa. At any particular stage of its development, it may further transform, while keeping its same general aspect; or it may emphasize the opposite aspect instead. The kind of apparatus with which the electron interacts determines which of these potential aspects prevails."

Ordinarily, both of these types of interaction are continually occurring in matter, whether a scientist is present to observe them or not. We are more interested in the momentum-measuring type of interaction, which reveals the wave properties of matter, but first we will pause and examine the fundamental difference between the two types of interaction.

The position of a particle is usually measured by having it interact with, and scatter, either lighter particles or photons. The lighter particles (or photons) are then brought to a focus and the position of the scattered particles in the image reveals the position where the scattering occurred (3, p. 104, 108-109, 118-120). In this type of measurement there must be an interaction between the two particles in which at least one quantum is exchanged, or else there can be no measurement. The exchange of the quantum in general changes the energies and momenta of the two interacting particles. The position of a particle may also be measured by having the particle come through a small hole in a screen at a given time. However, some kind of detector device (such as photographic film, the human eye, or a counting device) must be used to prove that a particle actually did come through the hole (1, p. 372). Without the detector there is no measurement, and the detector of course changes the energy of the particle.

The momentum of a charged particle may be measured by finding the potential drop necessary to bring the particle to rest (3, p. 94-95). In this type of interaction the total energy of the particle does not change. In coming to rest in the imposed field, the particle loses kinetic energy but gains an equal amount of potential energy with respect to the field. Momentum may also be measured by allowing particles to undergo diffraction at a grating and measuring the angles of diffraction (3, p. 94-95). In this case the diffraction itself does not change the momentum or the energy of the particle. When light is diffracted, for example, its direction of propagation changes, but its energy, momentum, and frequency do not change. (To be exact, the measurement of momentum by diffraction involves both kinds of interaction mentioned: 1) the diffraction of the photons, which changes their direction of travel but does not change their energy, and 2) position measurements, when the photons strike the film or eye, which of course changes the photon energies. The position measurements reveal the angles of diffraction, and the angles of diffraction reveal the momentum of the particles).

Apparently the fundamental difference between the two types of interaction (which BOHM calls position-measuring and momentum-measuring interactions) is that in one case the total energy of the particle is conserved, while in the other case the total energy changes. In order to consider the wave nature of matter we are therefore primarily interested in interactions in which the total energy of a particle remains constant.

At first glance, one might think that there are interactions in which the energy of a particle is changed, yet which yield a value for the momentum of the particle. The Compton Effect might be cited as such a case. However, careful consideration shows that this is not true. The quantities actually measured in the Compton Effect are the momentum of the incident photons, and the angles of deflection and the momenta of the deflected photons. The reflection of a photon from a crystal lattice in an x-ray spectrometer does not change its energy, and, therefore, measures its momentum. This momentum information is then used in calculations concerning the initial collision of photon and electron. The initial collision is the type of interaction that reveals particle nature, since the energies of the two particles are changed by the collision.

V. THE RELATION OF WAVE PROPERTIES AND ENTROPY

An atom in a solid will in general possess some particle properties and some wave properties, since it is undergoing both types of interaction described in the previous section. (However, if one aspect is well defined at any given time the other aspect must be correspondingly vague, in accordance with the Uncertainty Relations). The atom is exchanging photons and phonons with its surroundings, which reveals its particle nature, since energy quanta are being emitted and absorbed. The same atom is oscillating harmonically about its lattice position of minimum energy. This oscillation is an electromagnetic field interaction in which the total energy is conserved, even though kinetic and potential energy are continually exchanged; therefore, the interaction is the type that reveals wave nature. A given atom will exhibit its wave properties except when interrupted by the absorption or emission of a quantum, which reveals particle properties at the expense of wave properties.

If a solid is heated to a high temperature (a temperature such that C_V is near 5.9 cal./deg. mole) its particle nature will predominate, since nearly all of its atoms are exchanging quanta. If a solid is cooled nearly to absolute zero its wave nature will predominate, since relatively few of its atoms are exchanging quanta with the surroundings. An atom in a solid at absolute zero still possesses a half-quantum of vibration energy (when $n = 0$, see equation on p. 23) and this vibration reveals the wave aspects of the atom, since its energy is conserved.

It has already been mentioned (p. 23) that in low-entropy substances the exchange of quanta is a relatively infrequent occurrence that involves the independent oscillation of only a small fraction of the atoms at any given time. A low-entropy material then has only a small fraction of atoms whose particle aspects are predominant, while it has a large fraction of atoms whose wave aspects are predominant. Therefore, substances with low entropy (and low heat capacity) have a high degree of wave nature. Wave properties, which are strongly predominant in all matter at absolute zero, are strongly predominant even at room temperature in substances that have low entropy and heat capacity, such as living matter.

It follows from the preceding argument that the low-heat-capacity series of elements on page 17 also represents the chemical elements exhibiting the highest degree of wave nature, in decreasing order. From this series we see that the elements that are important to life have very high degrees of wave nature under ordinary terrestrial conditions. Carbon (the element that is basic to life) has the highest degree of wave nature of all the elements; H, N, and O (the elements that, with carbon, constitute 99 per cent of living matter) are in positions 2, 4, and 7; and P and S (which are important constituents of proteins and nucleic acids) are in positions 9 and 10.

VI. STATISTICAL ANALYSIS OF RESULTS

We have seen that the chemical elements most important to life are bunched at the high end of the wave-nature series. What is the probability that this result occurred by chance? Our question will be stated in the following form: What is the probability that C will be first in the series; H, N, and O will be found in positions 2 through 7; and P and S will be found in positions 8 through 10? In terms of statistics we have divided the 92 natural chemical elements into four groups: $N_1 = 1$(C), $N_2 = 3$ (H, N, and O), $N_3 = 2$ (P and S), and $N_4 = 86$ (all the other elements). The total number of ways that these six elements can be distributed throughout the 92 elements (total number of permutations of the 92 elements taken all at a time) is then:

$$\frac{N!}{N_1!\,N_2!\,N_3!\,N_4!} = \frac{92!}{1!\,3!\,2!\,86!} = 4.278 \times 10^{10}$$

The number of permutations that satisfy the conditions of the problem is:

$\frac{1!}{1!} = 1$ for C; $\frac{6!}{3!\,3!} = 20$ for H, N, and O; and $\frac{3!}{2!\,1!} = 3$ for P and S.

Since the permutations for each group of elements are independent, the total number is 1 x 20 x 3 = 60. The probability of occurrence by chance is then:

$$P = \frac{60}{4.278 \times 10^{10}} = 1.402 \times 10^{-9}$$

or approximately one out of a billion.

For comparative purposes we will calculate the probability of occurrence by chance of an alternative hypothesis; namely, that the chemical elements of lowest atomic number (or of lowest atomic weight) are most important to living matter. In this case the series of elements is the familiar one found in the Periodic Table, and elements C, H, N, and O are found in positions 6, 1, 7, and 8, respectively, while P and S will be found in positions 15 and 16. Since carbon is not in position 1 in this series, the statement of the problem must be changed to the following: What is the probability that C, H, N, and O will be found in positions 1 through 8, and P and S will be found in positions 9 through 16? The total number of permutations is:

$$\frac{92!}{4!\,2!\,86!} = 1.070 \times 10^{10}$$

The number of permutations that satisfy the conditions of the problem is:

$\frac{8!}{4!4!} = 70$ for C, H, N, and O; and $\frac{8!}{6!2!} = 28$ for P and S;

which makes a total of 70 x 28 = 1,960. The probability of occurrence by chance is:

$$P = \frac{1{,}960}{1.070 \times 10^{10}} = 1.833 \times 10^{-7}$$

or roughly 2 out of ten million. Since

$$\frac{1.833 \times 10^{-7}}{1.402 \times 10^{-9}} = 130.7$$

we see that the correlation of atomic number and importance to life is 131 times more likely to occur by chance than is the correlation of a high degree of wave nature with importance to life.

Another approach is to calculate coefficients of correlation based on the average position of C, H, N, and O (for example) in the two series of elements. (To continue the example, the average position of these four elements in the wave nature series of the 92 elements is $\frac{1+2+4+7}{4} = 3\frac{1}{2}$. An average position of $\frac{1+2+3+4}{4} = 2\frac{1}{2}$ would correspond to a perfect correlation coefficient of 1.000, and an average position of $46\frac{1}{2}$ would correspond to a coefficient of zero. The observed coefficient of correlation in this case is $\frac{46\frac{1}{2} - 3\frac{1}{2}}{46\frac{1}{2} - 2\frac{1}{2}} = \frac{43}{44} = +0.977$). The results of these calculations are shown in Table III.

TABLE III

Comparison of Coefficients of Correlation For Two Cases

	For C	For C,H,N, & O	For C,H,N,O,P, & S
Coefficient of Correlation between wave properties and importance to life.	+1.000	+0.977	+0.954
Coefficient of Correlation between low atomic No. and importance to life.	+0.890	+0.932	+0.876

Not only does the atomic number series give much higher probabilities of chance occurrence and lower coefficients of correlation in every case, but it fails completely to explain why carbon is the basic chemical element of living matter. Since the chemical elements with a high degree of wave nature are in general elements of low atomic number (and low atomic weight), there is some correlation between the latter and importance to life, but all the data indicate that the more fundamental relationship is between predominance of wave properties and importance to life. The data show that the probability of this correlation occurring by chance is vanishingly small.

The results indicate that predominance of the wave properties of matter is a necessary, but not a sufficient, condition that must be met in living matter in order to preserve the high degree of order existing therein. That it is not a sufficient condition is evident from a consideration of simple substances in which the wave aspects of matter are predominant. A diamond crystal, for example, does not exhibit the phenomena characteristic of life.

VII. THE RELATION OF BIOLOGICAL SYSTEMS TO OTHER PHYSICAL SYSTEMS

A. Condensates in Momentum Space.

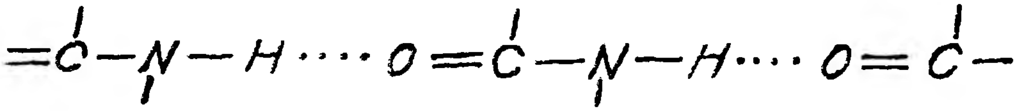
The preceding sections have shown that the wave aspects of matter are highly predominant in biological systems. To the author's knowledge, this interesting and significant fact has not been previously pointed out. This fact is significant because it means that the physicist may be able to classify biological systems with other macroscopic physical systems in which the wave properties of matter are highly predominant, such as electrical conduction in metals, superconductivity in metals, and the peculiar behavior of helium near absolute zero. The latter two systems are the only two known cases of superfluidity, and involve an ordering in momentum space rather than in co-ordinate space. In the case of ordinary electrical conduction, the conduction electrons are highly degenerate at room temperature and much higher, and the Fermi-Dirac quantum restrictions on their momenta are of controlling importance. How can biological systems be physically related to these other macroscopic systems?

According to MENDELSSOHN (19), the characteristic properties of a momentum condensate are: 1) very low entropy, and 2) some essential feature of the system is spread over the whole volume of the momentum condensate. In the case of a superconducting ring, the essential feature is the electric current that goes on indefinitely throughout the ring without any source of electromagnetic force to drive it. The wave-functions of the superconducting electrons are spread over the entire ring. Even for ordinary electrical conduction, the wave-functions of the conduction electrons have extents of the order of hundreds of times the distances between atoms (16, p. 239-240).

In the case of helium II, a somewhat similar situation exists (20). Heisenberg's Uncertainty Relations state that the uncertainty in the position of a particle (Δx), multiplied by the uncertainty in the momentum of the particle (Δp), will always be at least of the order of magnitude of $h/2\pi$. In helium II, the degenerate atoms are in the lowest momentum state, and therefore the uncertainty in their momentum is very small. Consequently, the uncertainty in their position is so large that they cannot be located at all, except that they are confined to the given volume of the liquid. The wave-function of such an atom must be spread uniformly over the whole volume. If a crystal lattice for helium II has any meaning at all, the lattice points must mark a series of maxima in the wave-function of <u>every</u> atom.

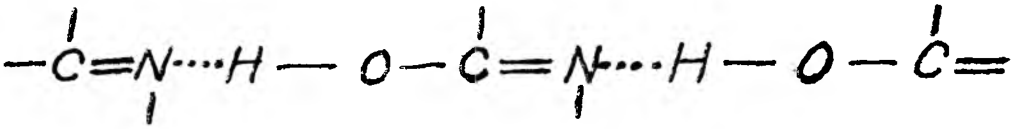
B. Quantum-Mechanical Resonance.

Living matter meets Mendelssohn's requirements for a momentum condensate, and belongs to this class of physical systems; it has very low entropy, and it has an essential feature--the phenomena of life--spread over its entire volume. The problem is to treat biological phenomena in physical terms analogous to the treatment of other macroscopic momentum condensates. How this will be done is a matter of speculation. It is highly improbable that the wave-functions of individual atoms in a protein molecule, for example, are spread over the entire molecule, since, unlike the helium II system, the atoms are strongly bonded together. It is much more likely that the wave-functions of some of the valence electrons extend throughout the protein molecule by means of quantum-mechanical resonance, since suitable molecular orbitals exist throughout proteins. In the alpha helix of a typical protein, the most probable location of such orbitals would be along the following atomic chains (21):



$=\overset{|}{C}-\underset{|}{N}-H\cdots O=\overset{|}{C}-\underset{|}{N}-H\cdots O=\overset{|}{C}-$

and so on, where .... indicates hydrogen bonding. These orbitals do not follow the spiral of the helix, but jump between the coils of the helix by following the hydrogen bonds. Three such atomic chains that are roughly parallel exist in every alpha helix. Another important resonance structure for these atomic chains is illustrated as follows:



$-\overset{|}{C}=\underset{|}{N}\cdots H-O-\overset{|}{C}=\underset{|}{N}\cdots H-O-\overset{|}{C}=$

The C-N bond has approximately 40 percent double bond character (21). Quantum-mechanical resonance occurs between these (and other) structures, with the probable result that the wave-functions of the pi electrons (electrons forming the second and third valence bonds when multiple bonds occur between atoms) will extend over the entire chain. The same chains of atoms with the same resonance structures also occur in the pleated sheet arrangements of proteins. Energy migration through proteins has been reported to take place (22, 23); the molecular orbitals suggested above represent probable routes for this migration.

The basic principle of quantum-mechanical resonance (sometimes called mesomerism) will be briefly summarized. If two or more valence-bond structures can be written for a given molecule, corresponding to two or more wave-functions for the system, the true wave-function is found by a linear combination of the two or more wave-functions as follows (21, p. 11-12):

$$\Psi = a_1\Psi_1 + a_2\Psi_2 + a_3\Psi_3 + \ldots\ldots = \sum_n a_n\Psi_n$$

This is known as the principle of superposition of quantum states. The true wave-function Ψ is found by adjusting the coefficients (a_1, a_2, and so on) so that the energy of the system is a minimum, and Ψ is to be regarded as a hybrid of the contributing wave-functions. The true valence structure of the molecule is also regarded as a hybrid, or weighted average, of the contributing valence-bond structures. The physically significant probability function is proportional to Ψ^2, and it can be seen from the above equation that Ψ^2 will involve interaction terms such as $a_1a_2\Psi_1\Psi_2$, $a_2a_3\Psi_2\Psi_3$, etc. These interaction terms are responsible for the decrease in energy below that of any of the contributing wave-functions Ψ_1, Ψ_2, etc. (24).

Resonance also occurs in the deoxyribonucleic acid (DNA) that makes up the chromosomes of living things--the substance that controls the heredity of all forms of life. The nitrogenous bases found in DNA (adenine, thymine, guanine, and cytosine) have aromatic ring resonance structures as well as hydrogen bond resonance structures between opposing pairs of bases (21, p. 304-308, 502-504). In chlorophyll (the green pigment of plants that is of great importance in photosynthesis) and in the very similar heme group in the red blood cells of mammals, there are ring systems of conjugated double bonds in which resonance occurs. In these conjugated rings the pi electrons can not only oscillate, as in a straight-chain conjugated system, but they can also circulate around the ring (25). In the modern concept of photosynthesis, energy-rich pi electrons are led away from the chlorophyll molecule by electron carrier molecules and are handed around a circular chain of reactions, where they give up their energy bit by bit (26). They then return to the chlorophyll molecule, which is now ready to absorb another photon.

In the same way that the wave-function of a pi electron in the benzene molecule is spread over the entire ring, the wave-functions of large numbers of pi electrons in protein molecules could be spread over the vast extent of these much more complex molecules. Such resonance phenomena may be the quantum-mechanical basis of the extension of biological phenomena into macroscopic dimensions. For comparison, the wave nature of matter is strongly predominant in a diamond crystal, but the wave-functions of the sigma valence electrons (electrons that form the valence bond of lowest energy between atoms) do not extend much beyond the region between two adjacent carbon atoms. There are no electrons in the conduction band at ordinary temperatures, and therefore no mechanism by which wave-functions can extend over long distances.

The most numerous and most important examples of quantum-mechanical resonance occur in atomic systems having one or more multiple valence bonds between atoms.

> In this connection, PITZER (24, p. 167) says "Another interesting property of multiple bonding is its almost complete localization to the first row of eight in the Periodic Table (Li to Ne). This implies effectively the elements O, N, C, B, and possibly Be, since univalent elements could not normally form multiple bonds. There are very few examples of multiple bonding in the stable form of substances involving heavier atoms."

In addition, PAULING (21, p. 452-453), HINE (27), and others consider resonance important in explaining the stability of the very important hydrogen bond between two atoms. It is, therefore, interesting to note that resonance is of greatest importance in describing the chemical bonding of the elements C, H, B, N, and O; which are in general the elements with the highest degree of wave predominance and the elements of greatest importance to biological systems. It should not be surprising to find that there is a relationship between resonance and phenomena of life; resonance can be regarded as the mechanism by which the wave-functions of the pi valence electrons can extend over relatively long distances, with the result that living organisms can extend into macroscopic dimensions. Quantum-mechanical resonance is a specific example of the predominance of the wave properties of matter in these elements at ordinary temperatures.

VIII. SUMMARY AND CONCLUSIONS

A Kopp's Law heat capacity value for nitrogen in solid compounds was calculated from heat capacity data for 59 compounds containing at least 10 atomic percent nitrogen. The result was 3.4, compared to the value of 6.3 or 6.4 in present tables. Further evidence is given showing that the latter values are too high.

Kopp's Law and literature data were used to show that the essential structures of biological systems have very low heat capacities and entropies, and the development of modern quantum theories of heat capacity was outlined. The fact that all living things have low entropies and low heat capacities suggests that the disorderly effect of heat is diametrically opposed to the orderly processes of life, and that the processes of life require some sort of protection against the disruptive bombardment of radiation quanta and neighboring atoms. The protection results from the following situation: Since the atoms of the most important substances in living matter are light and are held together by strong bonding forces, most of the energy quanta available at ordinary temperatures have insufficient energy to set these atoms into oscillation, and therefore are not absorbed by living matter. The result is that living matter is largely untouched by the pelting hail of thermal disorder surrounding it.

An analysis of the two types of quantum-mechanical interactions between particles (which BOHM calls position-measuring and momentum-measuring interactions), and the interactions occurring in low-entropy systems, indicates that the wave aspects of matter are strongly predominant in the chemical elements that are most important to biological systems. The correlation between the predominance of the wave properties of chemical elements in solids at ordinary temperatures and the importance of these elements to living matter is strong, and statistical analysis shows that the probability of this correlation occurring by chance is infinitesimal. The evidence indicates that the wave aspects of matter are strongly predominant in living organisms, and suggests that wave predominance is a necessary, but not a sufficient, condition for the existence of life. This is probably the fundamental reason the particular chemical elements carbon, hydrogen, nitrogen, and oxygen constitute more than 99 percent of living matter.

From an analysis of the available data it appears that biological systems belong to the same class of physical systems as do helium II and superconducting electrons--all three of these macroscopic systems are condensates in momentum space, the wave properties of matter are strongly predominant in all three systems, and all three have very low entropies. By means of quantum-mechanical resonance, the wave-functions of many pi valence electrons in the most important structures of living matter can spread over relatively long distances. This appears to be the mechanism by which biological organization can extend into macroscopic dimensions, and resonance can be regarded as a specific example of the predominance of the wave properties of matter in biological systems.

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VITA

The author was born September 28, 1919, in West Plains, Missouri, where he received his primary and secondary education. His college education was received at Kemper Military School, Boonville, Missouri; Washington University, St. Louis, Missouri; and the University of Missouri School of Mines and Metallurgy. He received a Bachelor of Science Degree in Chemical Engineering from the University of Missouri School of Mines and Metallurgy in May, 1941.

He was employed at the Kansas City refinery of the Phillips Petroleum Company from 1941 to 1946. From 1946 to 1952 he worked in the Organic Research and Development Division of Mallinckrodt Chemical Works in St. Louis, Missouri, where he developed processes for the production of synthetic papaverine, thebaine, and dihydrocodeinone, and made many improvements in the refining of opium. Since 1952 he has been employed as a Supervisory Research Physical Chemist and Project Co-ordinator at the Rolla Metallurgy Research Center of the U. S. Bureau of Mines, where he has supervised a variety of metallurgical and physical chemistry research projects.

As a result of reading the book "What is Life?" by the famous physicist Erwin Schrödinger, he became interested in the application of quantum mechanics to biological systems, and entered the Graduate School of the University of Missouri School of Mines and Metallurgy to study Physics on a part-time basis.