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THE ADDRESS OF THE PRESIDENT

ATOMICITY IN PHYSICAL NATURE

LeRoy D. Weld

From the earliest times men have been curious about the makeup of material things and the mechanism of visible processes. When Empedocles reasoned that all change is merely a rearrangement of permanent, unchangeable parts — an idea which the Atomists and Anaxagoras later elaborated in greater detail — he merely gave expression to what seems to be an intuitive conviction about Nature in general. Anaxagoras recognized the existence of atoms and the fact that there are different kinds of atoms; and he furthermore introduced the grotesque idea of atoms endowed with intelligence, by way of accounting for the order existing in Nature.

Leucippus, regarded by some as the founder of Atomism, conceived atoms to be in motion, with empty spaces between them; while Descartes, many centuries later, could admit no gaps in matter, and no discontinuities in motion. The names of Locke and Leibnitz still later enter this philosophical controversy, with views favoring the idea of empty spaces between atoms, but the latter postulating indivisible or ultimate units of force or energy.

In analogy to the atomistic views which had developed with regard to inanimate Nature was the discovery by Hooke, in the seventeenth century, of what may be regarded as an atomicity of life, namely that living organisms are composed of units or cells capable of some measure of independent, vital existence.

The atomicity of matter remained, however, a mere philosophical speculation until the beginning of the nineteenth century, when Dalton attacked the problem in definite, quantitative fashion. Though quite elementary to the modern student, the reasoning is so typical of what is to follow that we shall find it useful to review it very briefly here. Consider the following easily verified facts:

In 1 liter of hydrochloric acid	gas at NTP	there are	45 mg of H
In 1 liter of hydrogen sulphide	gas at NTP	there are	90 mg of H
In 1 liter of ammonia	gas at NTP	there are	135 mg of H
In 1 liter of methane	gas at NTP	there are	180 mg of H

No gas is known, containing hydrogen, in which the amount of hydrogen is less than 45 mg. per liter, or is anything but an exact multiple of 45 mg. Pure hydrogen itself weighs 90 mg. per liter. The natural, and almost inevitable, conclusion is that this 45 mg. per liter in some way corresponds to the atom of hydrogen in gaseous compounds, and that the hydrochloric acid molecule has one atom of hydrogen, the hydrogen sulphide molecule two atoms of hydrogen, and so on. It was by making such a study with reference to all the elements occurring in compounds that the familiar chemical formulas, HCl, H_2S, NH_3, CH_4, etc., were arrived at.

But in all this reasoning the atom itself, and even the molecule, remained only a hypothesis. Dalton and his contemporaries were not able to isolate individual atoms or molecules or to demonstrate their existence. The first direct evidence of the identity of molecules grew out of the discovery by Brown, about 1820, of the agitation of microscopic particles suspended in a fluid — the well known Brownian movement — which, together with evidence based upon the compressibility and the viscosity of gases, led to the computation of absolute data as to the masses and dimensions of the molecules and atoms of matter. It will be sufficient to recall here that the number of molecules in one cubic centimeter of any gas at N. T. P. was found, through these agencies, to be approximately equal to 30 millions of millions of millions, or more conventionally, 3×10^{19}; from which figure, and the known densities of gases and vapors, the absolute masses of various kinds of molecules and atoms are readily calculated.

During the third decade of the nineteenth century, Faraday obtained the first intimations of the existence of an electric atomicity in chemical electrolysis. When a silver solution is electrolyzed, each silver ion is found to have given up to the corresponding negative ion about 16×10^{-20} coulombs of negative electricity. This is found simply by dividing the measured amount of electricity transferred in the plating of one gram of silver by the approximately known number of silver atoms in one gram. Again, in the electrolysis of copper, each copper ion loses 32×10^{-20} coulombs of negative electricity. For aluminum, the figure is 48×10^{-20} and for germanium, it is 64×10^{-20}, coulombs per ion. *In no case does the process of electrolysis exhibit any other quantity of electricity per ion than* 16×10^{-20} *coulombs or some exact multiple of it.* It thus appears that this quantity represents some sort of natural and indivisible electric unit.

Meanwhile, as these data accumulate in the chemical laboratory, we find J. J. Thomson and others, toward the close of the century, studying the electric particles which fly from the negative terminal or cathode in current-bearing tubes filled with rarefied gases. Thomson obtained the first crude estimates of the quantity of electricity composing these particles and concluded that they are all equal. This work was perfected in America about a dozen years later by Millikan. He sprayed oil into air which had been ionized by x-rays or radium between two parallel, oppositely charged metal plates, and then watched the minute droplets through a microscope. Normally, they settled gradually downward; but now and then one would give a jump and move upward or downward in a manner indicating that it had picked up one of the electrified ions of the air and was thus being propelled by electric attraction. The speed observed in the known electric field gave the value of the captured electric charge. After thousands of these observations, Millikan came to the conclusion that *without exception the charges carried by the droplets were all multiples of the same elementary charge, the value of which was* 15.9×10^{-20} *coulombs.*

Could there be any reasonable doubt that this value, and the 16×10^{-20} coulombs revealed in electrolysis, are one and the same natural quantity? Here, in short, is the atom of electricity, the familiar *electron* of modern physical science.

While considering ionized gases, it is interesting to note, in passing, a recent discovery by Aston. By projecting ionized atoms across a strong magnetic field and observing their curved paths, Aston was able to demonstrate that atoms even of the same element may be of two or more different kinds, having different masses. For example, there is a chlorine of atomic weight exactly 35, and another of exactly 37; in natural chlorine they are mixed in such proportion as to give an *average* atomic weight of 35.46. We are thus introduced to the *isotopes* now known to exist in nearly one-third of the chemical elements.

In any great drama, it is not unusual, as the story progresses, for some totally new scene or character to appear suddenly upon the stage, and by means of fresh and unexpected developments, taken in connection with what has gone before, to open the eyes of the audience to the real significance of the whole plot. The setting for this critical scene in the drama of Nature's atomicity may be described as a tiny, hot, stifling dungeon without door or windows, in which are confined, darting hither and thither in vain efforts to escape, waves of radiant energy from the heated walls. To the physicist, this enclosure is known as the "black body," and the restless prisoners as "cavity radiation."

What has this to do with atomicity? It is a long story at best, and will have to be abridged somewhat here. The gist of the matter is as follows:

The distribution of the energy of black-body radiation along the spectrum of frequencies has proved to be a problem susceptible to statistical analysis, and has been intensively studied during the past forty years. In 1895, Wien developed a theory based upon the statistical equilibrium between molecules and their radiations in the interior of the black-body enclosure, and set forth certain conclusions regarding the relations between temperature and maximum intensity, temperature and the wave length having maximum intensity, and the spectral distribution of the energy for different temperatures. These laws were immediately subjected to the most searching experimental tests by many observers, using the radiation which escaped from a small opening in the wall of the heated enclosure. Lummer and Pringsheim, in particular, persevered in these tests, and their work finally established small but persistent discrepancies in Wien's laws, which became systematically greater as the observations were carried to higher temperatures. Paschen and Planck attempted to defend the laws by fresh theoretical arguments, but to no avail; theory and experiment simply refused to agree.

It was a case which recalls the anomalous motions of the planet Uranus, which finally led Adams and Leverrier to the discovery of Neptune. For, in 1900, Max Planck tore his own reasoning and that of Wien, Paschen, Boltzmann and others, to shreds, and launched forth upon a fundamentally different concept of radiation. It had occurred to him that the theories then current as to cavity radiation were inconsistent with the principle of equipartion of energy, in that, if radiation were composed of a continuous emission of energy, as had long been assumed, practically, all the energy in a black-body enclosure would presently be taken over by short-wave radiation and the walls would cool off to absolute zero.

Planck's revolutionary postulate was nothing less than the assumption of a discontinuous structure for radiation — an atomicity of radiant energy. Thus a molecule of heated matter may not yield its energy gradually, but only in separate rushes or spurts, like water flowing from a jug. By applying this idea to the processes going on within a heated cavity, he found that Wien's laws are satisfied for long waves, and that the discrepancies observed by Lummer and Pringsheim no longer develop as the temperature is raised and the wave length becomes shorter.

An essential feature of Planck's hypothesis is that the "spurts" or *quanta* of energy of which radiation is composed are directly proportional to their wave frequency; that is, that the ratio of the quantum to the frequency is

$$\frac{q}{n} = h,$$

a natural constant, now universally known as Planck's constant, the value of which was at first calculated by Planck to be about 6.5×10^{-27} erg sec. Thus for infra-red radiation having wave length 3 microns, $n=10^{14}$ per sec., and each quantum of this radiation would be 6.5×10^{-27} erg sec. $\times 10^{14}$ per sec.,$=6.5 \times 10^{-13}$ erg.

It is not likely that Planck's astounding proposition, with all the difficulties which are obviously involved in its conflicts with the electromagnetic wave theory of radiation, would have been taken seriously by physicists, had it not been for fresh evidence in its favor which, bit by bit, has been piling up ever since. It will be useful to cite some of this evidence.

When a heterogeneous stream of electrons (cathode rays) is projected into a tube containing a monatomic gas, such as mercury vapor, it gives rise to radiation made up of several distinct frequencies, represented by lines of the spectrum. Now if we limit the stream to a single speed, and gradually increase the speed by increasing the voltage, these spectrum lines abruptly appear one at a time in the order of their frequency. Here are some interesting data as to ultra-violet lines from a mercury tube:[1]

Wave Length of Spectrum Line	Corresponding Frequency n	Voltage	Corresponding Electron Energy q	Ratio q/n
2537.0 A	1.183×10^{15} per sec	4.9	7.8×10^{-12} ergs	6.59×10^{-27} erg sec
1849.6	1.622×10^{15} per sec	6.7	10.6×10^{-12} ergs	6.57×10^{-27} erg sec
1435.6	2.090×10^{15} per sec	8.6	13.7×10^{-12} ergs	6.54×10^{-27} erg sec
1402.7	2.139×10^{15} per sec	8.8	14.0×10^{-12} ergs	6.54×10^{-27} erg sec

It thus appears that each spectral frequency of mercury is emitted when, and not until, the energy supplied by the ionizing electron reaches a critical value, and that this value bears a practi-

1 Compton and Mohler, *Critical Potentials* (National Research Council Bulletin No. 48).

cally constant ratio to the frequency emitted, the average of which is about 6.548×10^{-27} erg sec. It is very difficult to believe that the approximate identity of this ratio with Planck's h can be accidental.

Now let us substitute a tube without gas, but with a metallic target for the cathode electrons to strike; and instead of the low potentials applied in producing ultra-violet radiation in the gas, let us operate the tube on thousands of volts. The result is an emission of x-rays many hundred fold more frequent than the radiation excited in the gas. As the speed of the cathode stream increases with rising voltage, special radiations develop, increasing in frequency and intensity until a certain maximum frequency is reached, when the radiation suddenly dies out. That is, the typical spectrum line is a diffuse band, but it has a sharply defined upper frequency limit. The following are data from the "K series" for various metals composing the target: [2]

Element	Minimum Wave Length	Corresponding Frequency Limit n	Voltage on Tube	Corresponding Electron Energy q	Ratio q/n
		per sec		ergs	erg sec
Magnesium	9.535 A	3.146×10^{17}	1,300	20.67×10^{-10}	6.57×10^{-27}
Zinc	1.281	23.419×10^{17}	9,650	153.44×10^{-10}	6.55×10^{-27}
Silver	0.485	61.856×10^{17}	25,500	405.45×10^{-10}	6.55×10^{-27}
Tungsten	0.179	167.600×10^{17}	69,300	1101.90×10^{-10}	6.57×10^{-27}
Platinum	0.158	189.870×10^{17}	78,100	1241.80×10^{-10}	6.54×10^{-27}

The mean of these values of q/n is 6.556×10^{-27}. The analogy to the results with slow electrons in gases is obvious. The number 6.556×10^{-27} tells the story.

Finally, let us reverse the matter. When ultra-violet light falls upon a negatively charged metal plate in a vacuum, the metal gives off electrons, called photoelectrons, moving with a definite speed which increases with the frequency of the radiation. Following are a few early data with cadmium: [3]

Wave Length of Incident Radiation	Corresponding Frequency n	Energy of Photoelectrons q
2967 A	1.010×10^{15} per sec	2.35×10^{-13} ergs
2537	1.182×10^{15} per sec	14.26×10^{-13} ergs
2257	1.329×10^{15} per sec	22.69×10^{-13} ergs
1849	1.623×10^{15} per sec	39.43×10^{-13} ergs

Here q does *not* bear a constant ratio to n. But if we plot the data with n and q as coördinates, the result is a straight line, the equation of which turns out to be approximately

$$q = 6.5 \times 10^{-27} n - 64 \times 10^{-13}.$$

2 Siegbahn, *Spectroscopie der Röntgenstrahlen.*
3 H. S. Allen, *Photoelectricity.*

This result is consistent with the explanation that each escaping electron has been given a "wrench," the energy value of which is 6.5×10^{-27} times the radiation frequency; but that before it can get away, 64×10^{-13} ergs of its energy must have been given up, perhaps in breaking through some barrier. The significant thing, however, is the value of this wrench or quantum, and the number 6.5×10^{-27} appearing in it — Planck's h again beyond reasonable doubt. Photoelectric emission is thus evidently a quantum phenomenon.

And so we might proceed.

A. H. Compton has made another strange discovery. We learned as younsters that if a small marble hits a larger one, the former will in general glance off in some direction with a different speed, while the latter moves more leisurely in another path, in obedience to simple mechanical laws. Now Compton's observations showed that when x-rays plunge into a swarm of loose electrons, as those in the atoms of the light element carbon, they are scattered in all directions, as a stream of small marbles would be upon entering a group of heavier ones. But the significant thing is that though the incident x-rays may be of perfectly uniform wave length, *the scattered rays are of different wave lengths.* And if we take as the energy of the incident quanta the value 6.57×10^{-27} n (in which n is their frequency), the frequency n′ of the rays reflected in any direction, multiplied by this same factor 6.57×10^{-27}, or Planck's h, gives for their energy precisely that value which it should have if they were little balls having the original quantum of energy, and were to strike larger balls, having the mass of an electron, in such a way as to be reflected in the direction observed.

Can it be, then, that light, thermal radiation, and x-rays are, after all, made up of tiny projectiles, and that the advocates of the corpuscular theory were right?

The suggestion of such a possibility has precipitated a struggle perhaps more desperate than any other in the history of physics, but which differs from former controversies in that it is not so much between the opinions and reasonings of different men as between one set of facts which says that radiation is composed of waves, and another which asserts that radiation contains flying particles having momentum and concentrated energy. Physicists are now about ready to concede that it is made up of both, and are endeavoring, as yet without success, to visualize the mechanism of their relationship. Thomson [4] indeed, goes so far as to construct a theory of quanta which reminds one of the vortex atom of the nineteenth century, but scant attention has apparently been paid to it.

It is interesting to note a recent discovery by Davisson and Germer, that electrons, impinging upon a crystal of nickel, are reflected at definite angles, as if they were like x-rays, the angles depending upon the speed of the electrons. The results indicate that moving electrons have something about them of the nature of waves, and that the frequency of these waves increases with the speed, and hence with the energy, of the moving particles.[5]

Who knows where these discoveries may lead in the realms of science? There are astronomers here present, who know that the spiral nebulae, already at fathomless distances from the earth, are all apparently moving away from us, as indicated by the Doppler effect upon the spectral wave lengths, with speeds almost unheard of elsewhere in material creation. This is a most astounding phenomenon. Can it be that the spectroscope deceives us, and that the observed reduction in frequency may be explained by supposing that the quanta, during the aeons of time since they left their source, have become senile and weak, and that their energy, and hence the corresponding wave frequency, has thus been reduced to an anomalous value?

From such vague speculations we may allow ourselves to be led off into other fields, and to wonder, for example, whether the property of atomicity is confined even to matter, electricity and radiant energy. How about other entities, such as space and time? The cinema suggests atomistic possibilities for both of these magnitudes. We know that what appears to be motion upon the screen is merely a succession of discrete positions, with nothing existing between them. What proof have we that the actual motions of actual bodies may not likewise be a succession of small but finite jumps, or that time may not alternately proceed and stand still, just as the hands of a watch can be seen to do through a microscope? Jeans [6] denies this possibility; Rougier [7] advocates its reality.

Furthermore, the atomicity of matter defines a smallest particle of any given kind of matter. If a surface having the area of the earth's orbit were to be uniformly plated with a gram of

[4] J. J. Thomson, *The Structure of Light.*
[5] Davisson and Germer. Phys. Rev. 30 (II), 705, 1927.
[6] J. H. Jeans, *Atomicity and Quanta.*
[7] Louis Rougier, *Philosophy and the New Physics.*

pure gold, how thick would the layer be? This would seem to be a mere matter of geometry; but the truth is that there would be only about 114 atoms of gold to the square mile, and all semblance of continuity would have disappeared. You cannot roll out atoms into thin sheets. One could lay out whole city blocks of this area which would have no gold at all upon them, while other similar areas might boast of one atom each.

Now the significance of such facts is that it suggests other questions; for example, this one: How much attraction exists between each atom of nitrogen in this room and each atom of nitrogen in the interior of the star Aldebaran? Give me the distance to Aldebaran, and the mass of the nitrogen atom, and I can make a theoretical calculation of that force by means of the inverse square law; but does such an infinitesimal attraction really exist in nature? Again, we are told that the dropping of a grain of sand causes the earth to rise to meet it. The laws of classical mechanics imply as much, to be sure; but is the inference valid, or is there a *smallest* momentum and a *smallest* potential energy, just as there is a smallest particle of gold or of electricity?

One might criticize such inquiries as being metaphysical; but physics has been encroaching upon metaphysics for generations, and the time is long past when scientific inquiry must be confined to the orders of magnitude which are within the scope of human observation.

Some day these questions will be answered. Some day we shall know whether atomicity and continuity can coexist, or whether the one of necessity excludes the other.

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