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# The Emergence of the Macromolecular Paradigm In the World of Chemistry

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The community of scientists devoted to the study of macromolecules is now large and vibrant. However, before 1920, there was no such community. The present paper traces the ideas associated with matter from the early days of Greek natural philosophy through the ages of the mechanical philosophy, the electrochemical period, the rise of structural chemistry and the rise of physical chemistry. A detailed analysis of the work of Boscovich and of van't Hoff is presented. Reasons for the delay in the formation of a coherent community of polymer scientists are discussed.

## Introduction

The world in which we live is filled with macromolecules. However, the recognition that this is so is of fairly recent origin. A macromolecule is defined as a covalent assembly of atoms of high relative molecular mass with a definable composition and structure containing a large number of subunits of relative low molecular mass. In order for macromolecules to be recognized as a normal part of our world, it was necessary to have a compelling theory of molecules that was accepted by the worldwide community of chemists. In addition, the conditions under which such covalent assemblies could attain large sizes needed to be elucidated. The story of macromolecules started in antiquity, herein an account is given of the era prior to 1920.

The present community of scientists devoted to the study of macromolecules is very large. It includes chemists, physicists, biologists, mathematicians, chemical and mechanical engineers, materials scientists and engineers, physicians, dentists, and even people with formal degrees in polymer science and engineering. The present account considers the period before there were such communities, and concludes at a time when there were no compelling reasons to believe that such a community would soon form. However, the growth of natural philosophy that preceded and key moments in this history will be discussed in anticipation of an eventual ontology of matter that included macromolecules.

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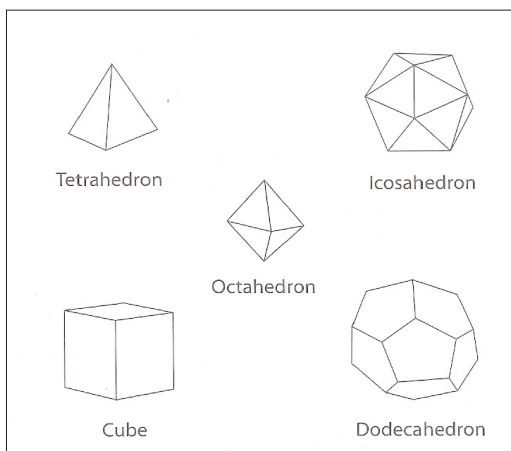
## Science in Antiquity

Communities of philosophers developed at several places and times in the ancient world, such as Croton, Elea, Miletus, Byblos and Athens. The world was observed and critical thought was brought to bear on the description and explanation of the natural environment. There was no lack of observations to feed this process and the terrestrial world was divided into animals, vegetables and minerals. Part of philosophy was learning to distinguish things that differed.<sup>1</sup> To a human observer, the air seemed continuous, as did the sea and the land. It was perfectly reasonable to conclude that everything on earth was a mixture of continuous elements. This continuum paradigm still survives as the best choice for many phenomena on earth.

Philosophical intuition is not often content to rest with the most obvious explanation of physical reality. Considerations of the ultimate divisibility of matter led to the notion of “indivisibles” or *ατομος*. But, what were the atoms like? Some thinkers reasoned that at some level, all matter must be identical, and hence the atoms were all the same. Thus if they were all the same they must be spherical, the perfect shape.<sup>2</sup> This material idealism is very attractive until one tries to explain the incredible heterogeneity of our actual world. The intellectual pressure to elaborate the fundamental particles of our world is and was then strong, and other noble shapes were invoked: the so-called Platonic solids (tetrahedron, cube, octahedron, dodecahedron and icosahedron). (See Figure 1).<sup>3</sup> The question of the interactions of the fundamental particles was much harder to envision. But, Greek thinkers like Democritus did suggest that there were many different intrinsic

shapes associated with the fundamental particles.<sup>4</sup> This crude model could have led to a science of macroparticles, but there was no evidence for it, and it languished in favor of the continuous model, favored by Aristotle.

The structure and dynamics of the particle world were also discussed. Since the earth was at the center of the universe, and all matter sought its natural place, the particles were assumed to be falling towards the earth. If the particles were not presently in contact, and if they did



**Figure 1. The Greek fundamental particles**  
(From Scerri, *The Periodic Table*).

not interact at a distance, then they would fall independently towards their ultimate destination. The raw determinism of this view offended philosophers like Epicurus, and he proposed that the particles occasionally underwent “swerves” in order to preserve free will. The ability to elaborate a fictional account of reality in order to satisfy philosophical preferences is one of the signs of creativity in humankind. But, these “solutions” did not compel adherence and are now largely, but not completely, forgotten.

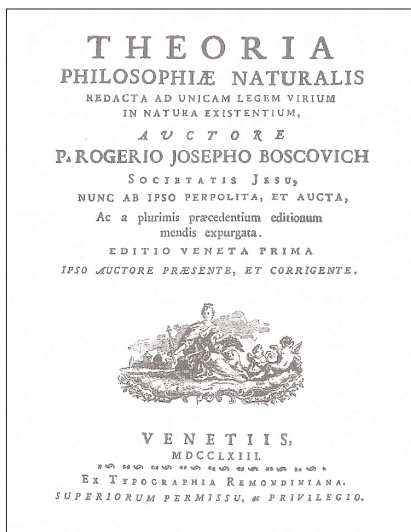
### **The Age of Gassendi**

The corpuscular paradigm returned to “polite discourse” in the time of Gassendi, Descartes and Boyle. The “mechanical philosophy” demanded that the material universe be described entirely in terms of the structure and dynamics of the particles of which it was composed. Since the particles were viewed as hard spheres, this research program was developmentally challenged from the start. Even the ingenious invention of “vortices” as the fundamental structural and dynamic units of material reality by Descartes was largely stillborn.

Robert Boyle carried out quantitative measurements on gases and showed that they behaved as “elastic” bodies: they resisted compression with a predictable force. Isaac Newton explained this pressure in terms of the intrinsic repulsions between otherwise static gas particles.<sup>5</sup> This “triumph” is a good example of the underdetermination of science. Not all successful explanations are a faithful representation of the microscopic reality of matter. The invocation of repulsion, when the only widely accepted interaction between particles of matter was gravitational attraction, was brave on Newton’s part, but he was pilloried for asserting both attraction and repulsion by those who viewed such talk as superstitious. The “fundamentalism” of Newton’s day rejected both his science and his religion.

Apparently, there needed to be at least two kinds of matter: the kind that was attracted to itself and produced liquids and solids, and the kind that repelled itself and produced gases. Clearly, there could be no macroparticulate gases. And liquids and solids could not be represented in terms of well-defined compositions and structures. There could only be aggregations of matter in this conceptual world.

The Golden Age of “Atoms and Powers”<sup>6</sup> (Thackray, 1970) flowered especially well in the work of Roger Joseph Boscovich (1711-1787). He was a truly multidisciplinary thinker with an allegiance to the Society of Jesus and to Nature. He combined a rare excellence in many fields and was “at once philosopher, astronomer, physicist, mathematician, historian, engineer, architect and poet”.<sup>7</sup> He was an



**Figure 2.** Title page from “*Theoria Philosophiae Naturalis*” R.J. Boscovich, 1763.

independent thinker who tried to take the best of 17<sup>th</sup> century thought, wherever he found it. He tried to mediate between the followers of Newton and Leibniz and produce a theory that would satisfy both. His system was presented in a magisterial work “*Theoria Philosophiae Naturalis*”. It is available in English translation.<sup>7</sup>

Boscovich’s approach was to combine all known empirical knowledge with a careful philosophical and mathematical analysis. On philosophical grounds, he believed, strongly in the “continuity of Nature.” While “hard spheres” might be useful for illustrative purposes, he believed correctly that all real materials must avoid “discontinuities.” He also believed in the “impenetrability” of the fundamental particles of matter.

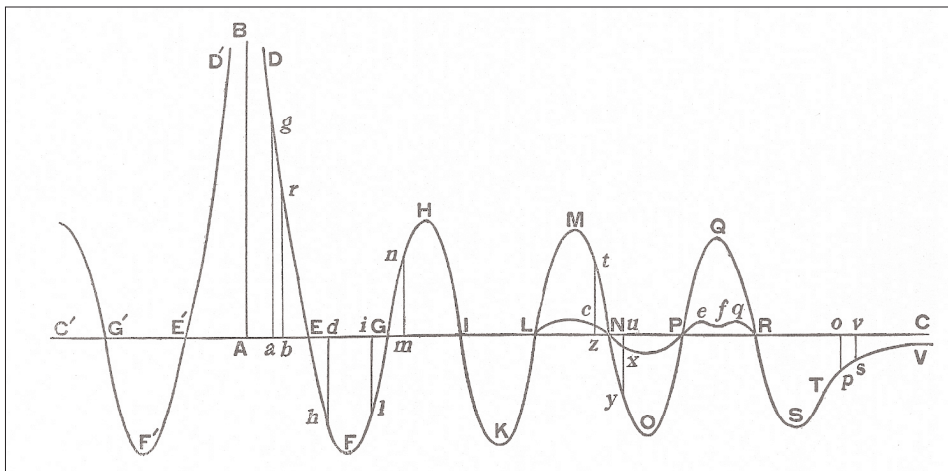
Another philosophical preference he had was for the identical nature of the primary particles of matter. With these philosophical assumptions, how could he produce a theory that would explain the richness of the actual world of observation? His “solution” was to propose an interparticle force function that was sophisticated enough to yield a great variety of composite particles. The famous graph of this function is shown as Figure 3.

Boscovich reasoned that the fundamental particles had no intrinsic size and could best be represented as points. He followed Leibniz and the theory of “monads” in this regard. Lest we think this view is antiquated, modern electrons are often viewed as points with no intrinsic size. For example, the limiting de Broglie wavelength for an electron is,

$$\lambda = h / m_e c = 2.43 \times 10^{-12} \text{ m}$$

a very small size. As two of these points approached along their line of interaction, the force of repulsion increased continuously and without bound. However, the range of this ultimate repulsive potential is very small. At very large separations, two mass points interact by gravitational forces and the final portion of the curve reflects this attractive force. The intermediate oscillations are required to reproduce the properties of macroscopic matter. There must be both repulsions and attractions in order to allow the formation of composite particles with more complicated force curves.





**Figure 3. The force between two primary particles in the theory of Boscovich.**

Boscovich proposed that these primary particles combined to form “tenacious compound particles” (TCP). These TCP entities were then proposed to be the basis of the chemical elements. These compound particles could be described by a well-defined mass, a well-defined structure, and a well-defined force function with themselves and with other tenacious compound particles. In particular, he proposed that the surface of these TCP entities could have regions of attraction and repulsion with very regular patterns. His thinking was very geometrical and he reasoned from the observed shapes of single crystals to the shapes of the underlying TCPs and to the regular arrangements of the compound particles.

Such a model is complex enough to produce TCPs with multiple attractive sites that could lead to either linear or branched chains of TCPs. Unsaturated surface sites could be covered with univalent TCPs or be available for further interactions. Boscovich had a profoundly geometrical mind, and could have easily developed a theory of macroTCPs, but with so many other natural phenomena to explain, he focused his attention on materials that were important in his world, for example gel-like materials such as rennet. Most of the observable materials that were formed by aggregation of TCPs were also viewed as reversible. The theory of Boscovich looks similar to modern colloid science where one of the most celebrated interparticle potentials (DLVO) contains multiple repulsive and attractive regions.

The spirit of Boscovich is well-expressed in two of his comments from the conclusion of the “Theoria”:

“Although we cannot peer into the intrinsic nature of bodies, the endeavour to investigate Nature must not be abandoned. Many things can be detected daily from those external properties”.

“But what if, partly by observation and partly by using deduction, it should finally be established that matter is homogeneous, and that all distinctions between bodies comes from form, connection, forces and motions of the particles, such as may be the fundamental origin of all sensible properties? These escape our senses for no other reason than the exceedingly small volume of the particles; nor are they beyond the powers of our intelligence, except on account of their huge number, and the very complicated, though general, law of forces. Owing to these, we cannot hope to obtain an intimate knowledge of the composition of each species. I consider that the attainment of a knowledge of the structure of particular bodies in the future will be difficult; that it will be altogether impossible, I will not dare to assert.

### **The Age of Franklin**

The existence of gravity and the proposed existence of gaseous repulsion was not enough to produce a satisfactory natural philosophy of chemistry. The extensive studies of electrical phenomena carried out by Benjamin Franklin and others<sup>8</sup> and chronicled by Joseph Priestly<sup>9</sup> provided an opportunity to further elaborate the theoretical description of matter. Macroscopic particles displayed both attraction and repulsion under the right conditions, and the strength of this force was much larger than the gravitational attraction. Perhaps electricity was the key to the understanding of chemistry. Berzelius certainly thought so! He even coined the word “polymer” to describe the aggregation of smaller “mers” to form more extended objects.<sup>10</sup>

The physical description of electricity in the 18<sup>th</sup> century was as a fluid; it flowed from one place to another. Boscovich proposed that his compound particles could absorb many different fluids: light, heat (caloric) and electricity. After all, some materials absorb light, and some even give it off. The belief in the existence of “elements” in addition to the current chemical atoms is well-documented.<sup>11</sup> In particular, it was believed that each compound particle was filled with just the right amount of electricity under isolated conditions. Manipulations of these particles could lead to either an excess or a deficit of electric fluid. Particles with an excess of electricity attracted those with a deficit. In addition, “neutral” tenacious compound particles had different “affinities” for electricity, so that, when two par-

ticles were near one another, electricity could flow from one particle to another, leading to attraction. Identical particles would not interact in this way since there was no tendency to exchange electricity. The modern notion that electricity is exchanged one electron at a time was completely unknown. Dalton lived in this netherworld where even the boldest chemists believed in some continuous fluids. Phlogiston may have been banished, but other tenuous substances would continue to be important until the 20<sup>th</sup> century.

### **The Age of Dalton**

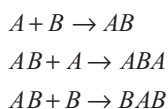
“The New System of Philosophical Chemistry” envisioned gaseous entities as composed of a small, unique number of chemical atoms. Exactly what these atoms were was unknown and exactly why these atoms stuck together was not understood, and it was usually asserted that homonuclear diatomic or polyatomic molecules were forbidden. Even though Dalton was lionized during his lifetime, his philosophy was often denigrated, even by those, such as Davy, who were in a position to award the medals and national honours! The Law of Definite and Multiple Proportions was a major advance in understanding, and the atomic paradigm is essential for the development of a science of macromolecules, but Dalton could never convince his contemporaries why elements needed to be discussed in terms of chemical atoms.

As the number of known chemical substances increased, it became more and more clear that stable polyatomic structures were the most useful way of representing many chemicals. Gerhardt and Laurent in France took the lead in promoting this perspective.<sup>12</sup> More detailed thinking about the proposed structures led to the concept of valency.<sup>13</sup> Some atoms appeared to be routinely bound to more than one other atom. The source of the chemical bond was vaguely described in electrostatic terms, but the utility of valency was becoming apparent to many chemists. Once Kekulé had established the tetravalency of carbon atoms, it appeared that the notion of macromolecules was inevitable. Kekulé even promoted a generic formula for the n-alkanes of the form:  $C_n H_{2n+2}$ , however he was uneasy with the notion that  $n$  could be very large.

Part of the genius of the paradigm of structural formulas was that the lines drawn on paper represented logical relationships between the atoms. The connectivity of each atom could be discussed without knowing exactly what the nature of the connection was. For the geometrically minded chemist, geometry was indeed the royal road to chemistry. Even in the 21<sup>st</sup> century, most chemists draw lines on

paper without any thought of quantum mechanics. With the concept of multivalency and the visual aid of atomic structural formulas, a science of macromolecules should have been inevitable, but there are many chemical reactions that are inevitable but rarely happen.

The reticence in the mind of Kekulé and many others at this point in history is quite understandable. In the absence of detailed knowledge about the nature of the chemical bond, it is most reasonable to assume that atoms bind according to some equilibrium expression. In the simplest case of an alternating binary chain polymer,  $(AB)_n$ , a chemical reaction scheme can be presented in the form:



If these chemical reactions are reversible and the equilibrium constant for all these reactions is the same, the probability distribution of chain lengths ( $n$ ) can be given as:

$$\wp(n) = p^{n-1}(1-p)$$

where  $p$  is the probability that an  $AB$  bond is formed. The number average degree of polymerization is then given by:

$$\langle n \rangle = 1/(1-p)$$

For a bond probability of 90%, the mean chain length is only 10. The notion that average degrees of polymerization in the thousands could be obtained was extremely implausible in the 19<sup>th</sup> century. Reversible polymerization is inherently inefficient if large molecular weights are desired. Every linear polymer can be decomposed by heating it to the range where the entropy gained by depolymerization drives the equilibrium back towards smaller units; the phenomenon known as the ceiling temperature. Since the principles of chemical equilibrium were only just beginning to be formulated in a precise way, and the principles of chemical kinetics were also in their infancy, most chemists continued to think in terms of reversible aggregation as the best paradigm for producing larger, but not too large, entities.

The strengths of chemical bonds were not known, nor was the actual basis for a chemical bond understood. Nevertheless, the geometry of structural formulas did provide a sound conceptual basis for the discussion of molecules. The pinnacle of clarity in structural chemistry was reached in the work of J.H. van't Hoff, "Chemistry in Space" (1891).<sup>14</sup> This English translation was also an updated and highly expanded version of the original French pamphlet, "La Chimie dans L'Espace" (1875).

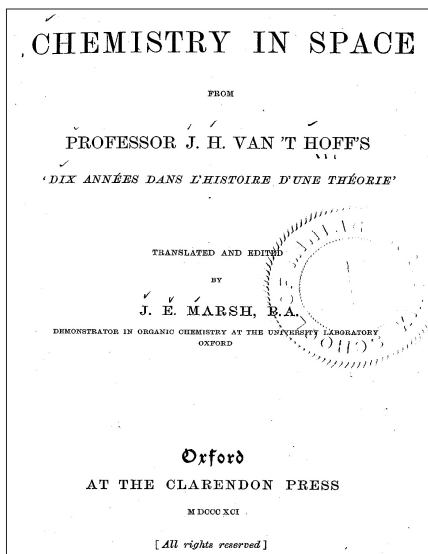
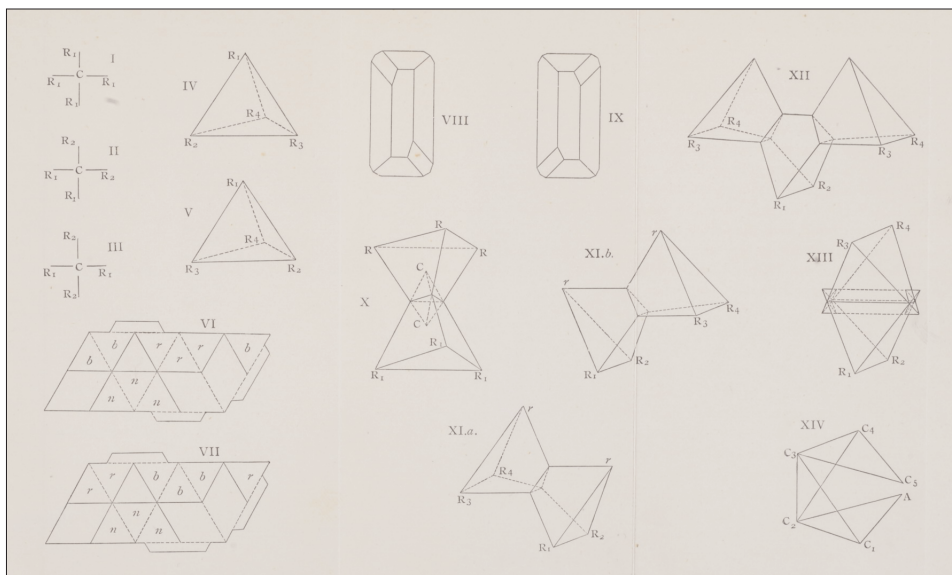


Figure 4. J. H. van't Hoff, *Chemistry in Space*, Oxford, Clarendon Press, 1891.

The tetravalency of carbon was further elaborated in terms of the tetrahedral geometry associated with carbon compounds. All of the known optically active organic compounds were explained in detail by the theory that the presence of an asymmetric carbon with four distinct substituents was necessary for the creation of optical rotatory power. Hundreds of specific compounds were discussed in detail. The field of Stereochemistry was completely consolidated and a vibrant research community was created that persists to the present. The book concluded with a folding sheet of line diagrams similar to that to be found in any modern organic chemistry textbook.

Among the many types of organic compounds containing asymmetric carbons, homologous series of chain molecules were discussed. Chemical formulas of the form:  $E_1-(CR_1R_2)_n-E_2$  occur frequently in the chapter on molecules with multiple asymmetric carbons. van't Hoff understood completely that each asymmetric carbon needed to be considered and the overall optical activity would depend on the actual sequence of centers. For example, a molecule with two asymmetric carbons would have three distinguishable optical isomers: Using *r* and *s* notation, there would be two optically active forms, *rr* and *ss*, with opposite rotation, and two indistinguishable forms, *rs* and *sr*, with zero optical rotation. No limit was placed on the value of the chain length, *n*, but only known compounds that had structures that were considered reliable were discussed in detail. These included the hexose sugars, so loved by Emil Fischer.

The progress of the field of stereochemistry was often obfuscated by the presence of impurities in commercial samples of either natural or synthetic products. An especially interesting case involving styrolene (styrene) was discussed in detail. The structural formula definitely ruled out optical activity, but commercial samples routinely yielded optical rotation. The degree of rotation could be varied by repeated distillation, but it was difficult to eliminate entirely. Of more interest in the present context, it was observed that freshly distilled styrene polymerized on its own, a fact that has been verified many times. The concept that unsaturated



**Figure 5. J.H. van't Hoff diagrams from "Chemistry in Space". Photos by Douglas A. Lockard. The Donald F. and Mildred Topp Othmer Library of Chemical History, Chemical Heritage Foundation, Philadelphia, PA.**

compounds were capable of polymerization was treated as perfectly natural by van't Hoff. The stereochemical consequences of polymerization of unsymmetrical-substituted alkenes were discussed. In view of the clarity of this exposition, it is astonishing that the existence of macromolecules was often denied by leading organic chemists. But leading lights such as Berthelot even denied the existence of chemical atoms. Ultimate progress in the science of macromolecules needed to wait for the death of a generation of anti-atomists and anti-structuralists such as Berthelot and Kolbe.

### The Rise of Physical Chemistry

The first Nobel Prize in Chemistry was awarded to van't Hoff (1901). If his masterpiece, "Chemistry in Space", was not enough, he also contributed major work to the theory of chemical thermodynamics, chemical kinetics and solutions. He is the father of the field of physical organic chemistry. To the lifeless structural formulas, he added a dynamic view of molecules; they vibrated, rotated and even underwent internal conformational changes. He discussed chemical reactions in

terms of the mechanism of the transformation. He considered the breaking and making of chemical bonds to be the key to understanding reactions.

One of the most important steps in the establishment of the molecular paradigm in the 19<sup>th</sup> century was the measurement of accurate molecular weights. Application of the gas theory of Avogadro (and later by Ampere) to measurements of gas density by Dumas led to accurate molecular weights for many molecules. Since most macromolecules are either nonvolatile or have very low vapor pressures below their ceiling temperature, another way of measuring molecular weight was necessary. Major advances in the understanding of solutions were made by Raoult and van't Hoff. van't Hoff reasoned that if it was the kinetic motion of gas molecules that gave rise to gas pressure, the kinetic motion of solute molecules would give rise to osmotic pressure (Jones, 1899).<sup>15</sup> The importance of the kinetic theory of matter for the rise of modern chemistry must be stressed. However, the self-proclaimed father of physical chemistry, Ostwald, was unwilling to consider solutions of large particles of matter to be "true" solutions, and proposed that they were merely physical mixtures with zero osmotic pressure, like glass marbles in a fish-bowl! Even the authority of van't Hoff was not enough; it took the kinetic theory of solutions by Einstein<sup>16</sup> and the Brownian motion measurements of Perrin<sup>17</sup> to clarify the matter. The van't Hoff Law of Osmotic Pressure can be stated as:

$$\Pi = (N/V)k_bT$$

where N is the number of solute molecules in volume V, and the kinetic theory term includes the Boltzmann constant and the absolute temperature. A knowledge of the mass concentration of the solution, c, then leads directly to the molecular weight, M, since  $N/V = cN_A/M$ . Perrin is famous for his dogged pursuit of an accurate value for the Avogadro number (Perrin, 1913).<sup>18</sup> Actual measurements of many particles in solution yielded values in excess of 10,000 for the molar mass, either by osmotic pressure or by melting point depression, another equivalent colligative technique discussed by Raoult and van't Hoff. Mere measurements were insufficient to convince scientists who were committed to a paradigm of physical aggregation as the source of the large masses for the particles. The science of colloidal particles was already a coherent research community in the late 19<sup>th</sup> century, but its leading lights were committed to a stance that promoted qualitatively different principles for colloids than for other forms of matter: a "new" form of matter, a "new physics." The community of colloid scientists in the 21<sup>st</sup> century is large and vibrant and the unity of physical chemistry has been restored.

Since a truly atomic level method for studying the chemical structure of molecules was still many years away, more mesoscopic techniques were developed to gain new insights. The transport properties of solutions were considered and Einstein



developed a kinetic theory of solutions that included particle diffusion and viscosity. While measurement of the diffusion coefficients of solute particles is now routine, it was hard work in the 19<sup>th</sup> century. Measurement of the viscosity of liquids and solutions was much easier, and the Ostwald viscometer was a precision device. The standard procedure consists of measuring the viscosity of the solution as a function of concentration and then calculating the limiting quantity known as the intrinsic viscosity:

$$[\eta] = \lim_{c \rightarrow 0} ((\eta - \eta_0) / c \eta_0)$$

Einstein showed that the intrinsic viscosity could be related to the hydrodynamic volume as:<sup>19</sup>

$$[\eta] = (((5/2)V_h N_A) / M)$$

It was observed that colloidal particles in the size range 1-1000 nm were common. Just the evidence of large size did not convince many colloid scientists that these particles were macromolecules. Even the observation that very large sizes could be obtained for very small values of  $M$  did not compel adherence to the macromolecular paradigm. After all, reversible aggregation can lead to fractal particles with a low internal density.<sup>20</sup>

Classical physical chemistry was a very successful research community and the three famous “Ionists” (van’t Hoff, Arrhenius, and Ostwald) all received the Nobel Prize during the first decade of the 20<sup>th</sup> century.<sup>21</sup> A flood of disciples followed in their footsteps. The “hot” areas of research included chemical kinetics and colloid science. Macromolecules had not yet attracted enough interest to produce a community devoted to the study of their properties as a full time effort.

## Notes

<sup>1</sup> A good source for the ancient period is Marshall Clagett, *Greek Science in Antiquity* (Salem, Ayer Company, 1985).

<sup>2</sup> Another good philosophically oriented treatment is Ernan McMullin, *The Concept of Matter in Greek and Medieval Philosophy* (Notre Dame, University of Notre Dame Press, 1965).

<sup>3</sup> Eric R. Scerri, *The Periodic Table: Its Story and Its Significance* (New York, Oxford University Press, 2006).

<sup>4</sup> The essential reference for the history of atomism. Bernard Pullman, *The Atom in the History of Human Thought* (Oxford, Oxford University Press, 1998).

<sup>5</sup> Isaac Newton, *Principia Philosophiae Mathematica*, (London, Royal Society, 1686).

<sup>6</sup> Arnold Thackray, *Atoms and Powers: An Essay on Newtonian Matter-Theory and the Development of Chemistry* (Cambridge, Harvard University Press, 1970).



- <sup>7</sup> Branislav Petronievic, "Life of Roger Joseph Boscovich" in Roger Joseph Boscovich, *A Theory of Natural Philosophy*, (Cambridge, MIT Press, 1966).
- <sup>8</sup> I. Bernard Cohen, *Franklin and Newton* (Philadelphia, The American Philosophical Society, 1956).
- <sup>9</sup> Joseph Priestley, *A History and Present State of Electricity, with Original Experiments*. (London, J. Dodsley, J. Johnson and B. Davenport, 1767).
- <sup>10</sup> Herbert Morawetz, *Polymers: The Origins and Growth of a Science* (New York, John Wiley and Sons, 1985).
- <sup>11</sup> Scerri, *The Periodic Table*.
- <sup>12</sup> Alan J. Rocke, *Nationalizing Science: Adolphe Wurtz and the Battle for French Chemistry* (Cambridge, The MIT Press, 2001).
- <sup>13</sup> Alan J. Rocke, *Nationalizing Science*.
- <sup>14</sup> Johannes H. van't Hoff, *Chemistry in Space*. (Oxford, Clarendon Press, 1891).
- <sup>15</sup> Harry Clary Jones, Ed. *The Modern Theory of Solutions* (New York, Harper and Brothers, 1899).
- <sup>16</sup> Albert Einstein, *Investigations on the Theory of the Brownian Movement* (London, Methuen and Co., 1926).
- <sup>17</sup> Jean Perrin, *Brownian Movement and Molecular Reality*. (London, Taylor and Francis, 1910).
- <sup>18</sup> Jean Perrin, *Les Atomes*. (Paris, Alcan, 1913).
- <sup>19</sup> Gary Patterson, *Physical Chemistry of Macromolecules* (Boca Raton, CRC Press, 2007).
- <sup>20</sup> Zhenyu Gu, *et al.* "Self-assembled supramolecular microgels: fractal structure and aggregation mechanism". *Journal of Polymer Science, Part B: Polymer Physics* 41 (2003): 3.037-3.046.
- <sup>21</sup> L.K. James, Ed. *Nobel Laureates in Chemistry 1901-1992* (American Chemical Society and Chemical Heritage Foundation. 1993).