BERTHELOT MEMORIAL LECTURE.

DELIVERED ON NOVEMBER 23RD, 1911.

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(1) *His Career.*

IN this age of extreme specialisation, the life and work of Berthelot teach the world the much-needed lesson that men of science are not necessarily men of one idea, but may be great, not only as experimenters, but great also as thinkers and as citizens. On all that he turned his mind to—and few things were foreign to his interest—Berthelot brought to bear, not only an exact scientific method and an exquisite clearness of statement, but an imagination as foreseeing as it was comprehensive, a patriotism as pure as it was enlightened. In the work of his life—whether as a philosopher or as a Cabinet Minister—Berthelot looked to Science as his guide. He believed in science as an illuminating and humanising force; he believed that in science lay the secret of the progress of France and of mankind. To pursue science was to ensure progress; science was to him a mission, a recreation, a religion. "To the end of my life," he wrote half-sadly to Renan (in 1892), "I shall be the dupe of this desire for progress which you so wisely relegate to the sphere of illusions." But of the reality of the progress achieved by Berthelot no chemist can doubt. In the realm of industry alone what tempting offers were made to him for a monopoly of his synthetic processes in organic chemistry. But Berthelot never bargained with or patented his discoveries. "The man of science," he declared, "should make the possession of Truth his only riches." Not that Berthelot considered the applications of science beneath him; on the contrary, he believed that science should be pursued largely by reason of its service to mankind. "Science has a double aim," he wrote, "an ideal aim which is the search for pure truth, and a positive and human aim which is the good of man and the development of civilisation."

Pierre Eugène Marcelin Berthelot * was born in the heart of the old Paris, in the Place de Grève—now Haussmannised out of recognition into the Place de l'Hôtel de Ville—on October 25th, 1827.

* I am indebted to the kindness of Berthelot's son—Prof. Daniel Berthelot—for exact names and dates, and also for much other valuable information. I desire also to express my obligation to my old student, Mr. A. S. Robinson, for making me a *précis* of Berthelot's papers.

He died in Paris, March 18th, 1907. As he was born and bred, so he lived and died a Parisian.

Through his father, Dr. Jacques Martin Berthelot, the son inherited his scrupulous regard for duty, his serious love for science, his liberal instincts, and his philosophic outlook on life; through his mother, Ernestine Sophie Claudine Béard, he inherited his ardent and responsive nature, his amazing industry, his versatility, and his curiosity. From the Place de Grève his family moved to a house near by in the narrow Rue des Ecrivains, just opposite the Tour Sainte-Jacques. The somewhat delicate and highly-strung boy grew up in sight of those royal ceremonials—the Corpus Christi processions from the Tuileries to Notre Dame—when people in the street were obliged to kneel, under penalty of sacrilege, as the procession passed. As a child the roar of the revolution must have sounded in his ears, for his father's house overlooked the scene of many of those deeds of violence that marked the popular upheaval against the Ordinances of the 25th of July (1830). Then, as again in the later revolutions, the house became a hospital equally for Royalist and for Republican, for Dr. Berthelot made no distinction between his patients, however much his sympathy went out to the suffering people.

Even from the age of ten, Berthelot tells us, he began to ponder on the problems of life, and was troubled by the insecurity of the future. Nevertheless, he was an industrious and brilliant scholar, and made rapid progress at the school he attended—the Collège Henri IV. Sixty years later at the Jubilee Celebration, M. Fouqué, the President of the Académie des Sciences, bore striking testimony to Berthelot's gifts as a boy. "Everyone admires in you your power of work, your spirit of invention, your logic of ideas, your grasp of memory, your skill in experiment. . . . I affirm that these precious gifts you already possessed in the germ when you were still a simple schoolboy. More than half a century ago we sat side by side on the benches of the mathematical class in the Collège Henri IV.; a close comradeship grew up between us. My recollections bring back with pleasure the long talks we had on every kind of question. . . . I still see myself in discussion with you on the muddy road that led to your house at the foot of the Tower of Saint-Jacques. There I met the kindest greeting from your father, and then we climbed to your attic and resumed our interrupted argument—our only distraction being the swallows that built among the sculptures of the old tower."

At the end of his school course in 1846 he took the highest prize in competition with all the best students from the lycées of Paris—

the "prix d'honneur de philosophie." To his sound classical education he attached great value, and his love of ancient literature lasted through life. Two old editions of Lucretius and of Tacitus, preserved from his schooldays, were his constant companions whenever he left Paris. He quoted Horace familiarly, and he has told us that he soon recovered his Greek when he began to decipher the Alexandrine MSS. on Alchemy.

His school studies over, he made up his mind to pursue natural science as a career, and he even mapped out a programme for the methodical study of the principles of *all* branches of science in what he afterwards called the "naïve confidence of youth." But, however much he may have had to curtail his educational ambition, he completed during the next few years a full medical course, he studied chemistry in the laboratory of Pelouze, and passed the University examinations for Bachelier and Licencié-ès-Sciences. To carry out this programme he took a small lodging in the Rue de l'Abbé-de-l'Epée, and attended the school of M. Crouzet. In this school happened that fortunate meeting between Berthelot and Ernest Renan—the beginning of a friendship which became from that day a principal element in the lives of both. Renan, then twenty-two, had renounced his clerical orders, and retired from Saint-Sulpice. Lonely and depressed by his mental struggles, he had become an assistant master in the school, but could not shake off his melancholy. Berthelot spoke to him, the talk became intimate, something in each ardent nature was touched and responded, and the two were drawn together until soul reacted with soul like acid and alkali. "Our friendship," wrote Renan, "was something analogous to that of the two eyes when they fix upon the same object, and from the two images there results a single impression in the brain." Renan and Berthelot would take long walks together, and on Sundays would visit Neuilly, then in the country, where Berthelot's parents had taken a house, and always they discussed the eternal problems that torture the human mind. One day Renan called his young friend a "Revolutionist." But Berthelot had one sure faith, built on the ruins of other beliefs. "I a Revolutionist!" he cried, "clear your mind of that notion; call me rather an 'Evolutionist.'" We must remember that this was said a decade before Darwin gave us the "Origin of Species."

The ideas resulting from their stimulating intercourse took different shapes in the two minds, and though Renan admitted his indebtedness to Berthelot, it is impossible for us, as it was for them, to separate what was due to each. On the monument of Berthelot which is to be placed in the Gardens of the Luxembourg, the sculptor, Saint Marceau, has introduced the face of Renan as a memorial of one of the most notable friendships of our time.

Under Pelouze the experimental skill of the young chemist rapidly developed, and in 1850 he presented his first paper to the Academy of Sciences—"On a simple method of demonstrating the liquefaction of gases." He showed how the gases chlorine, ammonia, and carbon dioxide could be liquefied in the capillary end of a glass tube by the expansion of mercury filling the body of the tube. When oxygen and nitric oxide showed no sign of liquefaction under pressures of 700 to 800 atmospheres he rightly concluded that under certain conditions of temperature it was not possible to liquefy gases by pressure alone. A second paper appeared in the same year, and in January, 1851, Berthelot received his first appointment, that of lecture-assistant to Balard, the discoverer of bromine, then Professor of Chemistry in the Collège de France. Unluckily the stipend was not a living wage—800 francs (£32) a year—and to earn a living Berthelot had to give private lessons. Luckily the official duties of the post were not heavy, and the resources of the laboratory were placed freely at his disposal by Balard, who in proposing him for the post wrote: "Everything allows us to hope that M. Berthelot will know how to utilise for the advancement of science the position I ask for him." In three years from his appointment Berthelot had obtained his doctorate by his remarkable thesis, "On the combinations of glycerine with acids, and on the synthesis of the immediate principles of animal fats." A year later he began to publish his work on the sugars, and the same year (1855) made the memorable syntheses of ethyl alcohol from ethylene, and of formic acid from carbon monoxide, which revolutionised the accepted ideas on the formation of organic compounds. Then followed in quick succession researches on the synthesis of hydrocarbons, of methyl alcohol, and of oxalic acid. After eight years' brilliant work, Berthelot was appointed Professor in the École Supérieur de Pharmacie, where he lectured, but he continued to act as assistant and to research in the Collège de France. This was the first public recognition of his discoveries. Early in the following year (1860) this Society honoured itself and him by electing him a Foreign Member. At the invitation of Alexander Williamson, then President, Berthelot lectured before the Chemical Society "On the synthesis of organic substances," on June 4th, 1863. It is pleasant to think that our Chemical Society set, rather than followed, the fashion.

With the appearance of his first book, "Organic Chemistry founded on Synthesis" (1860), the fame of Berthelot quickly spread.

The Jecker Prize was awarded to him in 1861 by the Academy of Sciences. The professors of the Collège de France, headed by Balard, petitioned the Minister of Public Instruction to found a Chair for Berthelot, and this movement resulted in his being appointed to a Professorship in the College in 1861, and finally (in August, 1865) in the formation of a special Chair of Organic Chemistry, which Berthelot held until his death. But though his early academic promotion was slow, honours came thickly to him in his middle age. The French Academy of Medicine elected him a member in 1863; he was elected to the Academy of Sciences in 1873, and of this body he succeeded Pasteur as Perpetual Secretary in 1889. In 1900 he became one of the forty French Academicians.

I cannot attempt any enumeration of the various learned societies of which he became an honorary fellow; I will only mention that he was elected a foreign fellow of our Royal Society in 1877, and that a Davy Medal was awarded in duplicate to him and to his friendly rival in thermochemistry, Julius Thomsen, in 1883, and that he received the Copley Medal, the highest distinction the Royal Society has to bestow, in 1900.

On his appointment to a Professorship in the Collège de France, Berthelot was enabled to fulfil his engagement to Mademoiselle Sophie Caroline Niaudet, niece of M. Louis Breguet, a French Swiss, whose family had been prosperous manufacturers of scientific instruments for many years, and who himself was the constructor of a well-known telegraph and induction coil. The story goes that the Berthelot and Breguet families had been intimate for some years, but Marcelin had not lifted his eyes to the beautiful Mademoiselle Sophie until one day accident brought them into collision on the Pont-Neuf. She was crossing the long bridge in front of Berthelot, and making her way with difficulty in the teeth of a strong wind, when a stronger gust catching her skirt and Tuscan hat blew Mademoiselle round into the arms of her future husband.

They were married on May 10th, 1861. Never was a happier match, or a more devoted family than Berthelot's. Madame Berthelot was endowed above most women with grace, with tact, and with sympathy; she brought into his life that great gift of serenity which Berthelot regretted he had not inherited from his mother. Well might he have appreciated our homely English saying, "It's an ill wind that blows nobody any good."

Busy in his laboratory by day and in his study by night, Berthelot took little part in public life under the imperial régime until the overthrow of Louis Napoleon and the siege of Paris in 1870. Then he threw himself whole-heartedly into the work of resisting the invaders, and as president of the Scientific Committee of National Defence superintended the manufacture of explosives to be used against the enemy. After the war Berthelot continued the study of explosives, to which he applied all his experimental skill and the knowledge he had acquired in his thermochemical researches. In collaboration with Vieille he began a systematic investigation of the phenomena of explosions, which finally resulted, not only in the invention of a powder that gave to French arms for some years a remarkable superiority, but in the addition to science of a new chemical constant—*l'onde explosive*.

His work on the combination of nitrogen with organic bodies under the influence of the silent electric discharge turned his attention to the fixation of nitrogen by plants in the soil; in 1884 a laboratory was built for him on the heights of Meudon, and here he devoted himself every summer to problems of vegetable chemistry.

Determined to take his share in the government of his country, he was elected a Permanent Senator in 1881, and in 1886 became Minister of Public Instruction in the Cabinet of M. Goblet. Here he found the opportunity of impressing on his generation his strong convictions on the educative and liberalising power of science. But he was no advocate of an illiterate mechanical training; he held firmly that science should be taught on the sound basis of a literary culture. It was in this spirit that he met the demand for "technical education" which swept over Europe. Industry demands two things, according to Berthelot: capable directors and competent workers. To be capable the director must be a judge of men and a judge of things; he must be trained in literature, history, and science; the high school and the university will prepare him for his business. To be competent the worker must be intelligent and skilful; the elementary school and the workshop will fit him for his job. Berthelot saw no need for ordinary technical schools—except as evening schools to help the workman. Can we yet say that Berthelot was wrong? At all events, he knew what he wanted, and he helped France to get it.

In 1895 Berthelot accepted the Portfolio of Foreign Affairs in the Bourgeois Cabinet. In this difficult post he had to negotiate the Anglo-French treaty dealing with the status and boundaries of Siam, which found herself in the uncomfortable position of "buffer" state between the French in Annam and the English in Burmah. Berthelot did not feel the duties of the Foreign Office congenial, and he resigned shortly after signing the treaty with Great Britain. But this, I think, we can say—that as a politician he had a sincere regard for England, and had he continued to guide the foreign relations of France the *Entente*, that has happily smoothed away so many difficulties between the two nations, might have blossomed a decade earlier.

That Berthelot was a man of peace is evident from his book, "Science et Libre Pensée." It contains a strong plea for international arbitration. Of his other books mention must be made of his studies of the Greek and Arabian alchemistic writings. In 1869 Berthelot visited Egypt, where his imagination was struck with the early records of chemical and metallurgical experiments and ideas. He returned to this subject later, and followed it up with his characteristic eagerness. By his influence he obtained the publication of many rare manuscripts on alchemy, which he edited in collaboration with M. Ruelle, "Collection des Alchimistes Grecs," and with MM. Duval and Houdas, "La Chimie au Moyen-Age."

Few more interesting chemical papers have ever been published than the hundred and one preparations and recipes comprised in the Papyrus of Leyden translated by Berthelot. They reveal some of the methods of the Egyptian priesthood, who were the holders of the secrets of chemistry. How pithily is described the conversion of a copper vessel into a beautiful vase of gold (by rubbing it with gold amalgam and heating)—a vase which will stand the regular test of the touch-stone! With what cynical pleasure Berthelot remarks that such a fraud was no doubt quite natural, and even commendable in the eyes of a priest!

In 1880 it was my great privilege to be introduced to Berthelot in his laboratory at the Collège de France by Sainte-Claire Deville and Alexander Williamson. I had just been showing for the first time non-explosive mixtures of dried carbon monoxide and oxygen at the British Association Meeting at Swansea. Deville was enthusiastic over the discovery, since it upset one of our cherished ideas; but Berthelot was more philosophical. Carbon monoxide was a gas, he said, "a little capricious" in its ways. One must repeat and again repeat such experiments. Most sound advice! I had, by the way, been repeating these experiments for four years before I published them; and it was in "again repeating" them that, all unconsciously, I struck across one line of Berthelot's own work—the measurement of the rate of explosion in gases.

But except for this natural attitude of philosophic doubt Berthelot was kindness itself. We were taken to his home in the Institute, and were entertained by Madame Berthelot, whose silver hair heightened the saint-like beauty of her face. Berthelot was full of fire and quick replies. When Williamson rallied him on the rapidity with which his memoirs appeared, Berthelot replied, "Ah! you English are too cautious, too frightened of committing yourselves; what is worth doing is worth publishing!" It was perhaps characteristic of him that an hour before he had given me the opposite and better advice.

Those who met Berthelot in his prime could not but be struck with the intellectual sincerity and the intense enthusiasm of the man. The broad forehead, the brilliant, blue eyes, the clean-cut features, and the thoughtful expression impressed all who saw him; while his musical voice and clear enunciation charmed the ear. It would be impossible to forget that first impression.

Students who attended his lectures speak in the highest terms of the inspiration they drew from his teaching. He gave of his best, and delighted to show his audience the new experiments he was engaged upon. But it was when he forgot the immediate experiment in hand, and began to think aloud, that the inspiration was highest. Here truly was science "in the making."

(2) *His Scientific Work.*

In considering the amazing output of scientific work we owe to Berthelot, it would be useless to enumerate, and hopeless to discuss individual memoirs. Luckily they can be grouped into well-marked divisions, for Berthelot always followed up a train of thought until some logical explanation was reached that satisfied his mind. Then some idea suggested by the first research was followed up experimentally until another generalisation was reached, and other trains of thought could be pursued.

Study of Glycerine.—As soon as he was installed in Balard's laboratory in the Collège de France, Berthelot took up a line of research which led him on to discoveries of the highest interest. He began to study the modes of combination of glycerine with acids, and proved that it was an alcohol capable of combining with acids to form "etherial salts"—thus bearing out the views of Chevreul that fats were "compound ethers," and justifying the modern name "glycerol"; but he also showed that glycerol differed from ordinary alcohol by its ability to combine with three equivalents of an acid instead of with one, just as phosphoric acid differs from nitric acid in combining with three equivalents of a base. By what seems a curious mental slip Berthelot likened the three classes of esters formed by glycerol to ortho-, para-, and meta-phosphates, instead of to their true analogues, the three salts of ortho-phosphoric acid. Wurtz not only made the correction, but by his synthesis of glycol —the "diatomic" intermediate between the "monatomic" alcohol and the "triatomic" glycerol—confirmed the importance of Berthelot's discovery. The work of Berthelot and Wurtz on the polyatomic alcohols must rank in importance with that of Liebig on the organic polybasic acids. I think, also, it is clear that the analogies shown by alcohols to inorganic bases—and I may specially mention the analogy between glycerol and bismuth hydroxide pointed out by Odling—led to the general adoption of the idea of valency which had been given to chemistry by Edward Frankland. The proof that glycerol is an alcohol led Berthelot to prepare and examine many other bodies of a like nature. We are indebted to Berthelot for a considerable number on the list of substances recognised as alcohols, and we constantly employ his method of acetylisation as the means of recognition.

Synthesis of Organic Substances.—I can only make a passing mention of very few of the many compounds of glycerol prepared by Berthelot by submitting it to the action of acids. Hydriodic acid, he found, yielded two substances, *iso*propyl iodide and allyl iodide; from the latter he made for the first time artificial oil of mustard.

The curious reducing power of hydriodic acid, especially at a high temperature, he afterwards made good use of in reducing benzene- to hexane-derivatives (1867). But the most stimulating thing to Berthelot's mind was the discovery that glycerol would combine, if time were given it, with all sorts of different acids, producing new fatty bodies, and that one could predict the formation of an endless number of new substances through a "creative power greater than that realised in nature." This idea, once planted in his mind, grew apace. He sought and found methods for preparing the simpler types of organic compounds, and from these to pass on to the higher and more complicated. To appreciate the boldness of Berthelot's conceptions we must remember the firm conviction that chemists held throughout the first half of the last century, that there was a gulf fixed between inorganic and organic substances; the chemist might build up, or synthesise, inorganic salts, but he could only break down, or analyse, the substances created in plants and animals by the "vital force." This gulf had not been really passed in the eyes of most chemists by the synthesis of urea by Wöhler or the formation of acetic and propionic acids from their nitriles by Kolbe and Frankland, for the cyanides from which these substances were formed were regarded as organic products themselves.

Berthelot's first success on his new path came in 1855. He shook up pure sulphuric acid in a large globe holding 32 litres of ethylene gas until 30 litres of the gas had been absorbed. The liquid was then mixed with water and distilled. The liquid coming over was dried and redistilled until 45 grams of a liquid having all the properties of pure alcohol were obtained. But the original ethylene had itself been obtained from alcohol—so the synthesis might be said to be contaminated at its source. Berthelot next prepared ethylene iodide from coal gas, and from this prepared a sample of ethylene, which he treated as before. It yielded alcohol, which was thus made for the first time without fermentation.

Now since ethyl alcohol on heating with sulphuric acid yields ethylene and water, and formic acid on heating with sulphuric acid yields carbon monoxide and water, if the first process can be reversed, it might be predicted that the second would also:

$$C_2H_6O = C_2H_4 + H_2O.$$
$$CH_2O_2 = CO + H_2O.$$

Berthelot placed 10 grams of potash in a half-litre flask, which he filled with carbon monoxide, sealed, and heated for three days on a water-bath. When the flask was opened under mercury the gas was found to be completely absorbed; on dissolving the potash salt in dilute sulphuric acid and distilling, Berthelot obtained a distillate of formic acid.

In the following year (1856) a more difficult synthesis was effected —that of marsh gas, together with ethylene and acetylene. Formic acid on heating yields all its carbon as carbon monoxide and its hydrogen as water; but if there is present a strong base, which might cling to some of the carbon, a substance containing carbon and hydrogen might be evolved. Berthelot prepared formic acid on a large scale from carbon monoxide, combined it with baryta, and distilled the barium formate at a red heat. He condensed a small amount of liquid, caught the unsaturated hydrocarbons in bromine, and collected the marsh gas over water. The unsaturated hydrocarbons were ethylene and propylene. On decomposing their bromides by means of water and copper foil in thick glass tubes at 275°, Berthelot regenerated the ethylene and propylene, and found about 10 per cent. of acetylene—the result of a secondary action. From this ethylene he again prepared pure alcohol.

Berthelot's next starting point was carbon disulphide. If carbon disulphide were heated with a metal capable of combining with the sulphur, while at the same time hydrogen were liberated in contact with the nascent carbon, the two might combine to form a hydrocarbon. Passing hydrogen sulphide and carbon disulphide vapour through a broad tube packed with copper turnings freshly reduced and heated to a dull red heat, Berthelot condensed a trace of naphthalene, and collected ethylene in bromine and marsh gas over water. Iron acted in the same way as copper, and hydrogen phosphide and steam could be used instead of hydrogen sulphide.

Berthelot regenerated the ethylene as before (finding acetylene produced), and prepared alcohol from it. One cannot help feeling in reading Berthelot's account of this experiment that in his mind the ethylene (with its resulting alcohol) was more important than the marsh gas. But a year later Berthelot chlorinated marsh gas in diffused daylight, separated the methyl chloride from the residual marsh gas and higher chlorides by solution in anhydrous acetic acid, and prepared methyl alcohol from the chloride.

Just as Berthelot had got ethyl alcohol from ethylene and sulphuric acid, so he obtained propyl alcohol from propylene and sulphuric acid. The propylene was prepared from the propyl iodide obtained from glycerol and phosphorus iodide. Again he showed that the higher olefines could be combined with hydrogen chloride and the chlorides turned into the corresponding alcohols—a general method by which he prepared many alcohols; and *vice versâ*, by abstracting the elements of water the olefines could be prepared from the alcohols. Again, as barium formate yielded on distillation several hydrocarbons, so might the acetate of sodium yield other hydrocarbons than marsh gas. Berthelot found that it yielded higher olefines as well, namely, propylene, butylene, and amylene.

But among the most memorable of Berthelot's syntheses was the direct combination of hydrogen and carbon in the electric arc to form acetylene (1862), and the condensation of acetylene into benzene (1866); thus the barrier between inorganic and organic chemistry was broken down at all points, and Berthelot's disciples could exclaim with justice: "There is but one chemistry, and Berthelot is its prophet."

In working on acetylene Berthelot investigated the properties of the acetylides of silver and copper. This work led him in 1866 to make the suggestion that the mineral oils found in the earth might have been formed from acetylene produced by the action of water and carbonic acid on the acetylides of the alkali metals. By reducing the carbonaceous matter found in meteorites he produced some liquid petroleum.

Action of Heat on Hydrocarbons.—Berthelot's work on the hydrocarbons included a study of the mode in which these bodies behave at a red heat. A hydrocarbon, he says, is not directly resolved into its elements, but either polymerises (for example, acetylene into benzene) or by a condensation of two or more molecules forms a denser hydrocarbon with elimination of hydrogen; thus marsh gas gives mainly acetylene and hydrogen, ethane yields ethylene and hydrogen, while ethylene yields mainly acetylene and hydrogen. Acetylene itself is not resolved into its elements, but polymerises, or condenses with hydrogen or other hydrocarbons into compounds of great density—naphthalene, anthracene, etc. When carbon is finally separated, it is therefore not a simple molecule, but in the form of a highly complex group of atoms corresponding with the dense hydrocarbons yielding it. This attractive theory of Berthelot has not, however, been fully borne out by later work. Sir Edward Thorpe showed that the decomposition of a paraffin (under heat and pressure) gave rise to the formation of an olefine and a lower paraffin; and Haber showed that *n*-hexane gave methane and amylene, but confirmed Berthelot's observation that benzene condensed to diphenyl with loss of hydrogen. Bone and his colleagues have shown that methane is formed directly from its elements between 1000° and 1200°, and breaks up again into carbon and hydrogen without forming acetylene. Ethylene, on the other hand, gives acetylene, which itself can either recombine with hydrogen or break down into carbon and hydrogen.

Action of Mass.—The observation made by Berthelot that time was required for the union of glycerol with acids led him, in conjunction with his pupil, Péan de St. Gilles, to investigate the course of the reaction between alcohols and acids, especially that between ethyl alcohol and acetic acid. Here, again, Berthelot was a pioneer in a subject that had hardly been touched experimentally. He found that when equivalent amounts of alcohol and acid are brought together, the reaction proceeds slowly (at a rate depending on the temperature) until a limit is reached, and that the same limit is reached when the corresponding amounts of ester and water are brought together. "An equilibrium is established between the affinity of the acid for the alcohol, which tends to unite them, and the inverse affinity of the water for the neutral ether, which tends to regenerate the acid and the alcohol." We can put the result into an equation:

$$\frac{C_2H_3O_2\cdot C_2H_5 \times H_2O}{C_2H_4O_2 \times C_2H_6O} = 4.$$

It is clear, I think, that Berthelot regarded the equilibrium as a statical, and not as a dynamical, one; he did not see that the two opposite reactions were taking place at the same time; Guldberg and Waage recognised this, and used Berthelot's figures in illustration of their principle. Nevertheless, Berthelot and St. Gilles' memoirs form the starting points of much of the subsequent work on equilibrium and mass action. They showed the effect on the equilibrium of varying the amounts of one of the reacting substances; they showed that an increase of temperature or of concentration greatly shortened the time for the equilibrium to be reached, although pressure alone had little effect. They suggested an equation for the determination of the velocity of a bimolecular reaction similar to that of Harcourt and Esson. Few researches indeed have been more fruitful in physical chemistry than those of Berthelot and St. Gilles.

Of other equilibrium problems Berthelot was the first to investigate the partition of a dissolved substance between two solvents. He showed, for instance, that when succinic acid is dissolved in ether and water, the coefficient of distribution is constant whatever the amounts dissolved; but other substances showed a variation with concentration, an anomaly explained by Nernst in 1891 as due to a difference of the molecular aggregation of the substance in the two solvents. In 1875 Berthelot studied the partition of acids between several bases in solution.

Thermochemistry.—Berthelot's great work on thermochemistry was begun in 1863, and was continued until 1879, when he published the two volumes entitled, "Mecanique Chimique fondée sur la Thermochimie." This and his later book, "Thermochimie, Données et Lois numériques," constitute a monument of elaborate experiment and calculation, which men of science rank alongside the "Thermochemische Untersuchungen," the life-work of Julius Thomsen. It is not at all to the disadvantage of Chemistry that the Frenchman and Dane worked in rivalry. When we want to know the heat of formation of any compound we look up the two authors, and if they agree we are entirely satisfied. I think each respected the other's work. I can point to an instance—the heat of formation of ammonia—where Thomsen corrected his first result, and to another—the heat of formation of ethane—where Berthelot corrected his; in each case as the result of the other's work. They both put forward a theorem, though not quite in the same terms, that every action of a purely chemical nature gives out heat and produces the result that is accompanied with the maximum evolution of heat. Berthelot defended with great skill his "principle of maximum work"; it required the genius of Helmholtz and Boltzmann to prove that the principle required that the heat of reaction should be independent of the temperature, and was only strictly true at absolute zero. But although these limitations must be accepted, and Berthelot finally accepted them, the "law" is nevertheless a useful guide which is often appealed to. Was not Deacon inspired by Berthelot's ideas when he sought and finally found a practical method of liberating chlorine from hydrochloric acid by the oxygen of the air?

Much of the apparatus devised by Berthelot for his thermochemical determinations has come into general use; in particular, I may mention his "calorimetric bomb" for combustions in oxygen under pressure.

Explosions.—Berthelot's experiences in the war led to his systematic work on explosives and on the theory of explosions. In conjunction with Vieille he studied the rapidity of combustion and the heat of reaction of various explosives. In July, 1881, he published his first short paper on the explosion-wave in gases. He states that he would not have published it had not MM. Mallard and Le Chatelier sent him their memoir on the same subject, which they had attacked by a different method. It is a curious coincidence that a few months before I had myself begun to measure the rate of explosion of carbon monoxide and oxygen with different quantities of water-vapour, and found that the accepted rate was altogether too slow.

Berthelot's first paper contains the germ of his theory—the identity of the rate of explosion with the mean velocity of the molecules formed in the reaction before any heat had been lost. Other papers quickly followed. Berthelot made the important discovery that the rate of explosion rapidly increased from the point of origin until it reached a maximum which remained constant, however long the column of gases might be. This maximum Berthelot stated to be independent of the pressure of the gases, of the material of the tube, and of its diameter above a small limit. The rate of explosion thus forms a new physico-chemical constant, having important theoretical and practical bearings. The name "l'onde explosive" was given by Berthelot to the flame when propagated through an explosive mixture of gases at the maximum velocity, and this velocity could be predicted if the heat of combination and the density and specific heat of the products were known. For instance, the total heat given out when hydrogen and oxygen combine is known. If this heat is contained in the steam produced, its temperature may be calculated if its heat capacity be known; and if the temperature of the steam be known, the mean velocity with which the molecules must be moving can be calculated. Now Berthelot supposed that the heat is all contained in the steam produced. He assumed that the heat capacity of steam was the same as the sum of those of its constituents; and he supposed, moreover, that the steam was heated at constant pressure. Making these assumptions, he calculated out the theoretical mean velocity of the products of combustion of various mixtures, and found a close accordance between these numbers and the explosion rates of the same mixtures. He concluded that the explosion-wave was propagated by the impact of the products of combustion of one layer upon the unburnt gases in the next layer, and so on to the end of the tube at the rate of movement of the products of combustion themselves. If this theory be true, it accounts, not only for the extreme rapidity of explosion of gaseous mixtures, and gives the means of calculating the maximum velocity obtainable with any mixture of gases, but it also affords information on the specific heats of gases at very high temperatures, and explains the phenomena of detonation whether of gases or of solid or liquid explosives.

Table I shows the explosion rates found by Berthelot, compared with the theoretical velocity of the products of combustion:

TABLE I.

Gaseous mixture.		Velocity in metres per second. Calculated.	Found.
Hydrogen and oxygen	$H_2 + O$	2830	2810
Hydrogen and nitrous oxide	$H_2 + N_2O$	2250	2284
Carbon monoxide and oxygen	$CO + O$	1940	1090
Carbon monoxide and nitrous oxide	$CO + N_2O$	1897	1106
Marsh gas and oxygen	$CH_4 + O_4$	2427	2287
Ethylene and oxygen	$C_2H_4 + O_6$	2517	2210
Cyanogen and oxygen	$C_2N_2 + O_4$	2490	2195
Acetylene and oxygen	$C_2H_2 + O_5$	2660	2482

Two facts established by these experiments impressed on me the conviction that Berthelot might have found the true theory of explosions: first, the close coincidence between the rates of explosion of hydrogen (both with oxygen and nitrous oxide) and the calculated mean velocities of the products of combustion; and, secondly, the great discordance between the found and calculated rates for carbonic oxide with both oxygen and nitrous oxide, for I had previously discovered that pure carbon monoxide cannot be exploded either with pure oxygen or pure nitrous oxide. The discordance found by Berthelot was what I should have expected from my own experiments. Again Berthelot examined the effect of inert gases in damping down the velocity of the explosion-wave; for instance, on adding nitrogen to different explosive mixtures he found:

TABLE II.

Gaseous mixture.	Velocity in metres per second. Calculated.	Found.
$H_2 + O$	2831	2810
$H_2 + O + N_2$	1935	2121
$H_2 + O + 2N_2$	1820	1439
$CH_4 + 2O_2$	2427	2287
$CH_4 + 2O_2 + 2N_2$	2002	1858
$CH_4 + 2O_2 + 4N_2$	1744	1151
$C_2N_2 + 2O_2$	2490	2195
$C_2N_2 + 2O_2 + N_2$	2334	2044
$C_2N_2 + 2O_2 + 2N_2$	2152	1203

These experiments seemed to Berthelot to show that a small amount of inert gas does not prevent the propagation of the true explosion-wave, but damps it down according to its calculated effect. A large amount of inert gas, on the other hand, destroys the character of the explosion-wave—which must always be regarded as the "*maximum possible*" velocity.

In comparing the rates of explosion determined in his tube with those calculated from his formula, Berthelot, I think, was not justified in his argument that the specific heats of the gaseous products must be reckoned as at constant pressure, since the whole change took place in a closed tube. In the damping experiments with nitrogen he did not allow for the fact that with inert gases a longer run is required before the explosion-wave is set up, and he began to time the flame before it had acquired its maximum pace. In the cyanogen experiments he did not appreciate the fact that in the wave-front the carbon only burns to carbon monoxide. But in spite of these criticisms, which required years of work to establish, I have always thought it one of Berthelot's strokes of genius to identify the maximum velocity of the flame with the mean translational velocity of the molecules themselves, a conception which all later investigators have used in working out the propagation of an intense pressure-wave which preserves its type by being continually reproduced from point to point by the chemical action.

Fixation of Atmospheric Nitrogen.—In Berthelot's synthetic researches we find him using the silent electric discharge to cause nitrogen to enter into combination, for example, as in the direct formation of hydrocyanic acid from acetylene and nitrogen. This fixation of nitrogen led him to investigate its absorption by plants, and generally the action of electricity on vegetable growth in his laboratory at Meudon. Berthelot asserted that free nitrogen could be assimilated by plants, a statement that was vehemently opposed until Hellriegel proved that leguminous plants can take up nitrogen through the agency of bacteria. Berthelot was the first to point out that atmospheric nitrogen was fixed in the soil by micro-organisms, a new departure of supreme interest to agriculture. Among other developments of Berthelot's idea, Dr. E. J. Russell has recently shown how the fertility of a soil might be enormously increased by killing off the infusorial enemies of these bacteria. Four solid volumes, entitled, "La Chimie végétale et agricole," published in 1899, contain the record of Berthelot's work at Meudon.

Looking back at the enormous mass of experimental detail published by Berthelot I am astonished at the small percentage of error that has been detected. The accuracy of his experiments is really marvellous. It is not in his experiments, but in his interpretation of them that Berthelot has to meet criticism. Although Berthelot was a rapid worker, he was a still more rapid thinker. Not once or twice, but almost throughout the range of his researches we see the theoretical conception outstripping the experiment. Sometimes deliberately, sometimes unconsciously, he chooses his experiments to illustrate his theory. It is a question of idiosyncracy; genius must work its own way. The nineteenth century praised Dalton for basing his Atomic Theory on the sure foundation of the Law of Multiple Proportions; the twentieth century knows that Dalton sought for cases of multiple proportion to support his preconceived theory of atoms.

Berthelot's imagination gives a distinction to all his work; his rapidity of generalisation fascinates us, and compels our interest. Can we say which is the better for knowledge—on the one hand, the dashing advance of an explorer into an unknown country, the rapid survey, the approximate location of a great lake and a great mountain range, and the publication of a fascinating sketch-map giving us the possible sources of a Nile or a Congo; or, on the other hand, the deliberate advance of a surveyor with his levels and theodolites? May it not with justice be maintained that had it not been for the pioneer and his map the surveyor would never have started at all? Berthelot might rightly claim that he had pointed out the trend of the country and the possibilities that lay that way, and had stimulated the curiosity of the exploring world. "For myself," he wrote, "I shall be happy if, in the development of science, some of my results are valued some day as the origin of the discoveries of the future." I believe this was no conventional phrase of self-depreciation, but an expression of his thought used in all sincerity.

Again, like other great men, Berthelot found it hard, even when the creatures of his thought had been proved to be "unemployables," to dismiss them from his service. I ventured just now to compare Berthelot's mode of thought with Dalton's. May we extend the parallelism further, and say that the intensity of conception in the mind of each was sometimes too strong to yield to facts? Dalton, firm in his conviction that different elements had atoms of different sizes (the very genesis of his theory), could see neither the relevancy of Gay-Lussac's Law of Volumes nor the beauty of Avogadro's explanation. For him the formula of water was always HO. Berthelot, equally firm in his conviction that in chemical reactions we are dealing with "equivalents," could see the force of Gay-Lussac's experiments, but not of Avogadro's argument. For him the formula of water (the molecule occupying 2 volumes) was H^2O^2.

If we, then, as the result of the steady progress of experiment and thought, can see the limitations of Berthelot's vision, we can also, I hope, appreciate the brilliancy of the conceptions that guided his work, and the intensity of the stimulus given by his ideas to contemporary science.

(3) *The Last Phase.*

Berthelot enjoyed a wonderfully active and honoured old age. To celebrate his seventy-fifth birthday and the jubilee of his first appointment in the Collège de France, his colleagues inaugurated a great meeting of congratulation, and commissioned M. Chaplain to design a medal in his honour.

The Chamber of Deputies and the Senate declared that the occasion demanded a public ceremonial, in which the State should participate. Abroad, all the great societies passed resolutions congratulating Berthelot on his achievements, and sent delegates to present their felicitations in person. The meeting was held in the great hall of the Sorbonne on November 24th, 1901. Berthelot declined the procession and the military escort offered by the State, and went on foot to the hall. He was received by the President of the Republic. Then amid the acclamation of his colleagues, who thronged the hall, he heard perhaps for the first time from the mouths of his most distinguished contemporaries the deep veneration in which the world held his genius and his career. In acknowledging this great demonstration, Berthelot once more insisted on the humanising spirit of science. "It is not," he cried, "for the satisfaction of our private vanity that the world to-day pays homage to men of science. No! it is because it knows that the man of science really worthy of the name consecrates his life disinterestedly to the great work of our age—the amelioration of the lot of all, the rich and the happy, the poor and the suffering. It is this that my friend Chaplain has sought to express on the beautiful medal which the President of the Republic is to offer me. I know not if I have completely fulfilled the noble ideal the artist has drawn, but at least it has brought me strength to have made this the aim that has directed my life."

"*Pour la Patrie et la Vérité*"—the design was well chosen by Chaplain to sum up Berthelot's career.

Berthelot continued to work to the end. Although he ceased to lecture, he seldom passed a day without visiting his laboratory. There and in his home he found his happiness, for husband and wife seemed to grow nearer as the years went by. In his last months he had the sorrow of losing a daughter and then a beloved grandson. The shock preyed on his wife, who developed heart disease. Berthelot, himself a victim to the same disease, watched assiduously at her bedside, and wasted his strength in his nightly vigils over her. A Sunday came when she seemed better, and Berthelot visited his laboratory at Meudon, where he was studying the effects of radium emanations on vegetation. On his work table there was found afterwards an alchemic manuscript from Morocco, written in Hebrew, which he was deciphering, for he had not forgotten the early lessons he had received from Renan.

He returned to find his wife failing, and they both knew the end was near. "What will become of him when I am no longer there?" were the last words she spoke to her daughter. Berthelot was alone with his wife when she died. He called his children, kissed the dead, walked into the next room, and threw himself upon a couch. One of his sons followed him, and hearing him sigh, ran to seize his hand. But the hand was lifeless: he had joined his beloved one.

The pagan poet whom Berthelot loved has perhaps made us feel most keenly the cry of the heart that cannot survive separation:

"Ah! te meae si partem animae rapit
Maturior vis, quid moror altera,
Nec carus aeque nec superstes
Integer? Ille dies utramque

Ducet ruinam. Non ego perfidum
Dixi sacramentum. Ibimus, ibimus
Utcumque praecedes, supremum
Carpere iter comites parati." *

The state procession and military escort which Berthelot had declined alive, were fitting attendants round the hearse that bore the bodies of husband and wife to honourable sepulchre in the Pantheon.

So passed away a great man, full of years and honour. To France and to Science he gave his life, and he was not without reward in the love and veneration of his countrymen. Happy the country that produces such genius; happier still the country that can appreciate and use it.

* At the request of the Publication Committee, I subjoin the English rendering of these stanzas I gave at the Lecture:

"If Death, untimely, snatch away
That half—ah! dearer half—my soul,
Why should this other half delay?
Could life be sweet no longer whole?

The day that strikes thee strikes us both:
Together, when thou goest, we go
Sworn comrades ('tis no idle oath)
To tread the last long path below."

—*Horace* II. xvii.