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THEODORE WILLIAM RICHARDS

1868—1928

A Biographical Memoir by
JAMES BRYANT CONANT

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Biographical Memoir

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T. W. Richards

THEODORE WILLIAM RICHARDS

January 31, 1868–April 2, 1928

BY JAMES BRYANT CONANT

THEODORE WILLIAM RICHARDS was a precocious son of distinguished parents. He was born in Philadelphia on January 31, 1868, the third son and fifth child of William Trost Richards and Anna Matlack Richards, who had been married on June 30, 1856. As strict members of the Society of Friends, the Matlack family looked askance at a young man who earned his living painting pictures. Anna was "read out of meeting." The Quaker marriage ceremony took place in the house of a friend. The first months of the honeymoon were devoted to the composition and illustration of a manuscript volume of poems for the lady who had first brought the young couple together. A mutual interest in Browning and Tennyson had started an acquaintanceship which rapidly became a romance.

An old friend and fellow artist of Philadelphia reminiscing long after W. T. Richards had established his reputation as a landscape painter said, "He amazed me by getting married and resigning his position as designer [in a local firm manufacturing gas fixtures] in order to devote himself entirely to his art. I don't remember which event took place first but I thought the latter extremely unwise—and so it would have been with anyone else, but timidity had no place in his nature." Of the struggle of a largely self-taught artist to support a family in the Civil War years there is little record. By the time the third son,

Theodore, was conscious of his environment, the artist's family was comfortably settled in Germantown (a suburb of Philadelphia); the summers were spent in Newport, Rhode Island (after 1874).

Whether the father or the mother had the greater influence on young Theodore may be argued. But to anyone who examines the few personal documents that are left, there can be no doubt that the future chemist's career was molded at the outset by his two extraordinary parents. In an article prepared for a Swedish journal shortly after he was awarded the Nobel Prize in 1915, Theodore Richards paid tribute to his understanding mother and father:

"Although my parents had no experience with scientific investigation, their tastes and education having been of a very different kind, nevertheless they entered fully into the spirit of my desire to undertake it, and were wise enough to see that a possible future lay ahead for me in the path which so profoundly interested me. From that time my father always advised me to devote myself as much as possible to research. Moreover, he supported this advice in a very practical way (realizing that research in pure science is not a money-getting employment) and offered always to help me, out of his none too plentiful means, in case of a pinch, rather than to permit me to engage in the distracting task of making money by occupations outside of my main interest. Later after my marriage in 1896, when new cares presented themselves, and when he saw there was danger of my overworking, he placed into my hands a sum of money large enough to enable me to feel that I could take a year's rest from academic work, if that should prove necessary. The relief from worry, afforded by this sum in a savings bank, made the vacation unnecessary. There is no question that this generous and thoughtful confidence was a very important factor in the success of a not very optimistic and somewhat delicate young man, then entirely without any capital except his brains; and

it would be impossible to exaggerate my feelings of gratitude.”

Quite apart from the wise advice and the financial assistance, William T. Richards must have influenced his third son by his example. “There was nothing of the pose of his craft about him,” writes his biographer, “the cast of keen observation in his face, and the easy grace of his carriage, denoted the man of original thought and unconstrained opinion, the artist who sees a little deeper into objective life than most people, and whose instincts are, therefore, less confined to convention. . . . He knew he could draw matchlessly, and yet there were elements in the portrayal of a breaking wave that he never achieved to his own satisfaction. If you pressed him with commendation on the side of drawing he would shield his modesty behind his struggles with that miracle of color under the curving wave. He had studied this for years. His son tells us that ‘he stood for hours in the early days of Atlantic City or Cape May, with folded arms, studying the motion of the sea,—until people thought him insane. After days of gazing he made pencil notes of the action of the water. He even stood for hours in a bathing suit among the waves, trying to analyse the motion.’ ”

The words of the son which the father’s biographer quotes demonstrate how much the patience and thoroughness of the artist bent on portraying nature had impressed the boy who so often stood by while the beginnings of a seascape were forming in the painter’s mind. The link between the world of science and the world of art was a pride of both father and son in a capacity to take infinite pains. The chemist who was to become famous for the painstaking accuracy of his experimentations may well have received his inspiration from watching his father standing hour after hour in the surf.

If the influence of the father is largely a matter of conjecture, the role of Theodore’s mother in his upbringing is definite and clear. She provided the formal education at home. Her experience with the schools in Germantown had been unsatis-

factory. Therefore she decided to try the experiment of teaching the younger children herself.

"We used to have regular hours and school was not to be slighted," Theodore Richards reports in an autobiographical fragment. Continuing the description, he notes that "drawing and music were included in this home curriculum and so, of course, were reading, writing, arithmetic and geography as well as much more history than is usually taught to young children. . . . My mother's devotion was tireless and beyond praise. My debt to her (as well as to my father) is inestimable." He might well so write since not only had his mother's instruction prepared him for entry to the sophomore class at Haverford at the age of fourteen but her tutoring in Greek (which she learned for this purpose) a year later enabled him to enroll in the senior class at Harvard after graduation from Haverford.

A typescript composed two years before Richards died is entitled "Early Memories." He ends with an account of his leaving the summer home near Newport to head for college. He was "on his own for the first time," he writes. "With me in my pocket I carried two sonnets written for me by my mother (who was in many ways a very remarkable and brilliant woman)." Then follow the two sonnets, of which the opening lines of the second amount almost to a parental injunction:

Fear not to go where fearless Science leads,
Who holds the keys of God. What reigning light
Thine eyes discern in that surrounding night
Whence we have come, what law that supersedes
The fiat of all oracles and creeds,
Thy soul will never find that Wrong is Right;

At Christmas 1880, when Richards was not quite thirteen, chemistry had entered his life. He was given a large box containing materials and apparatus for 200 experiments "warranted to be safe and instructive." Richards has recorded his progress

as a chemical student as follows: "Soon afterwards, when I had nearly blown off my head with this outfit, I was given Steele's *Fourteen Weeks in Chemistry* so that knowledge might diminish the risk; and when the somewhat limited scope of this book had been outspanned, I advanced to Eliot and Storer's *Elementary Chemistry* which contained a priceless fund of information. . . . Dr. John Marshall of the University of Pennsylvania Medical School was good enough to interest himself in the boy of thirteen who was so eager for sound chemical knowledge. He invited me to Professor Wormley's lectures at the University of Pennsylvania."

Such was Richards's memory in later years of his introduction to chemistry. At Haverford he first studied the subject with a serious purpose under Lyman B. Hall and decided to become a chemist. Looking back to that period in his life he recalls that "except for his somewhat defective eyesight he might have chosen to become an astronomer." At this point Josiah Parsons Cooke, Professor of Chemistry at Harvard, whom the family had come to know during the summers at Newport, Rhode Island, enters the story. He seems to have been instrumental in Richards's decision to spend another year of study and to take a second bachelor's degree at Harvard. Two years later Richards received the Ph.D. degree for important research on the atomic weights of oxygen and hydrogen accomplished under Professor Cooke's guidance. The results were reported in a paper published in 1888 as a joint communication. In the same year Richards printed three other papers based on his independent work on the atomic weights of copper and silver, as well as one dealing with the heat produced by the reaction of silver nitrate with solutions of metallic chlorides. Four publications and the young investigator was not yet twenty-one! Then followed a year abroad.

Two pieces of research were conducted in the chemical laboratory of Göttingen University, one in analytical chemistry

under Paul Jannasch and one on vapor chemistry determination under Victor Meyer. In addition some weeks were spent in Munich and in Dresden studying special chemical methods. As a supplement to what Professor Cooke could teach him, these experiences seemed to place the young American chemist in the mainstream of current investigations. They formed an introduction to a far more important semester spent in Leipzig (with Wilhelm Ostwald) and in Göttingen (with Walther Nernst) in 1895. These two periods spent in German laboratories could be regarded as Richards's training in the then newly developing field of physical chemistry. At that period in history there were no centers of research in physical chemistry in either the United States or England. It is not much of an exaggeration to speak of Richards as a German-trained scientist. His outlook on life, however, was in no sense Germanic. In spite of his early and wide acquaintanceship among German chemists and a half year spent in Berlin in 1907, he seems to have found little to attract him in the empire ruled by the Kaiser. In England, on the other hand, he made lifelong friends. In the summer of 1889 he met one of the outstanding chemists, Sir Henry Roscoe (who was a friend of Professor Cooke), as well as Lord Rayleigh, who was soon to become an internationally famous physicist. With the English investigators he felt very much at home. He admired them and their way of life. It is altogether fitting that the definitive account of his life is the Theodore William Richards Memorial Lecture delivered by Sir Harold Hartley before the Chemical Society of London on April 25, 1929.

Richards was elected to the National Academy of Sciences in 1899. Of all the many honors he received, the award of the Faraday Medal of the Chemical Society of London must have pleased him as much as any. Together with his wife and three children he traveled to England in May 1911 for the occasion. Sir Harold Hartley refers to Richards's pleasure at Professor H. B. Dixon's allusion to him as the Faraday Lecturer who was

fulfilling Canning's prophecy: "I look to the new world to redress the balance of the old." Honorary degrees from Oxford, Cambridge, and Manchester added to the delight of that summer. The Nobel Prize in chemistry awarded in November 1915 may be considered as the climax of Richards's public recognition. World War I, however, prevented his going to Sweden to receive the award at the time of its announcement. Later a projected trip had to be canceled because of the sudden illness of his oldest son, who was to have accompanied him to Stockholm.

As much as Richards loved England, and after the invasion of Belgium in 1914 despised all things German, his career as a teacher followed the pattern of Germany. Indeed, a call to the University of Göttingen in 1902 may be said to have assured his position at Harvard. President C. W. Eliot made him a full professor and agreed to the construction of new laboratory facilities if and when funds could be raised. (The Wolcott Gibbs Memorial Laboratory was built for Richards just before World War I.) Richards desired a few (but only a few) graduate students, the professorship of physical chemistry which involved giving a full course of lectures, and the privilege of continuing a half course of lectures on "Elementary Theoretical and Physical Chemistry, including the Historical Development of Chemical Theory." This course he had initiated in the 1890s when he was still an assistant professor. These teaching tasks Richards thoroughly enjoyed because he did them well. They were based on a full confidence in the lecture method, as it was employed in the German universities. As a young man Richards had been responsible for instruction in quantitative analysis. But by the time he was called to Göttingen he was ready to turn over concern with this phase of practical chemistry to junior professors whom he had trained. The arrangements which Richards entered into in 1902 at the age of thirty-four remained unaltered until his death. Though he became famous because

of his many papers describing his researches, his performance as an excellent and devoted teacher was in itself worthy of high praise.

In 1896 Richards married Miriam Stuart Thayer, daughter of Joseph Henry Thayer, a professor at the Harvard Divinity School and outstanding New Testament scholar. Thanks to the generosity of his father, Richards was able to build a house not far from the Harvard College yard, in which the couple lived their entire married life. There were three children: Grace Thayer, who became the wife of the author of this memoir; William Theodore and Greenough Thayer, both of whom became professors, the one of chemistry at Princeton, the other of design at Virginia Polytechnic Institute. The summer months without fail were dedicated to a vacation, often on Mt. Desert Island in Maine. The health of both father and mother was somewhat precarious but the duties of the professor of physical chemistry were carried out without fail year after year. Only for half a year in 1907 did Richards absent himself from Cambridge in order to function as the Exchange Professor at Berlin. There were no leaves of absence for reasons of health, and Richards never availed himself of the privilege of taking a half year's sabbatical at full salary. He could not bear to be separated in term time from his graduate students whose experimentations he followed almost daily with a discerning yet sympathetic eye. The habit of attempting to foresee all possible contingencies, which was basic to his success as a scientific investigator, placed a heavy strain on his life as a husband and father. To worry about the smallest detail was to be a painstaking chemist setting new standards of accurate measurement. Yet to carry over to daily life the same attitude condemned the scientist to a total life of anxiety. As he approached sixty it became apparent to his close relatives that the nervous load Richards had been carrying for years was too much for the physical organism. Yet he continued his lectures and went to his laboratory on his regular

schedule until within a few days of his death, which occurred on April 2, 1928. He went down with his colors flying as had been his wish.

RICHARDS'S SCIENTIFIC WORK

[Richards left an account of his scientific work up to the year 1914. The first portion of the document deals with his investigations of atomic weights. I have printed it as part of an article on "Theodore William Richards and the Periodic Table" (*Science*, Vol. 168, pp. 425-28, April 24, 1970). For the sake of completeness I reproduce it here and it constitutes the balance of the text of this memoir. The entire autobiographical fragment is written in the third person. The part which has not yet been published starts with his evaluation of his work on chemical thermodynamics. I have to thank my wife for making the manuscript available.]

The scientific work of Theodore W. Richards may be divided for convenience into five categories more or less closely interrelated. The first of these categories includes the study of atomic weights, the second, the investigation of various problems concerning chemical equilibrium, the third, original work upon chemical thermodynamics both practical and theoretical, the fourth, the study of various problems in electrochemistry, and the fifth both practical and theoretical work concerning the significance of atomic compressibility and the changes exhibited by atomic volumes under varying conditions.

During the past twenty-six years Richards has been directly concerned in the study of the atomic weights of twenty elements, and some of his pupils at Harvard have independently studied ten more. Thus far no one has been able to show that any one of the investigations concerning these thirty elements is seriously in error, and the results of all have been accepted as the best heretofore published by the International Committee on

Atomic Weights, which has no Harvard representative upon it. The elements investigated under the immediate direction of Richards or with his own hands are as follows: oxygen, copper, barium, strontium, zinc, magnesium, nickel, cobalt, iron, uranium, calcium, caesium, chlorine, bromine, silver, sodium, potassium, nitrogen, sulphur, and lithium.

The determination of the ratio of oxygen to hydrogen was taken up in collaboration with J. P. Cooke in 1886. They weighed hydrogen directly in large glass globes, and after having burnt it with copper oxide, determined the weight of water. The outcome gave a result for hydrogen only 0.0004 different from the value 1.0078 now generally accepted. This was the first direct determination showing that the ratio of hydrogen to oxygen is distinctly less than 1 is to 16, and the error in the result was one-half as large as the error that was previously considered as the best.

The behavior of copper oxide led Richards to suspect that the atomic weight of copper accepted at that time was in error, and accordingly he commenced an investigation of this element which lasted four years. He discovered that oxides of metals prepared from the nitrate always contain included gases, a circumstance which he found to vitiate the earlier work not only upon the atomic weight of copper but also those of a number of other elements. He showed also that the copper sulphate had much greater tendency to retain water than had been attributed to it, and by means of a number of new methods obtained a series of consistent results for the atomic weight of copper. The relation of copper to silver, of copper to bromine, and of copper to sulphuric acid were all determined with care, and all yielded essentially the same new value, thus leaving no doubt that the old value for copper was nearly one-half a percent too low.

The anomalous behavior of barium sulphate led Richards then to study the atomic weight of barium; both barium chloride and barium bromide were analyzed taking care to drive off all

the water without decomposing the salts. Much time was spent upon the preparation of pure silver and every step of the analysis was tested taking great heed especially of the solubility of silver chloride. The result showed that barium was previously almost as unexact as copper. In this case as in the other not only were new results obtained but also the reasons for the deviations in the old ones were made clear.

Strontium, magnesium, zinc, nickel, cobalt, iron, uranium, and caesium were then taken up in succession, being studied by somewhat similar methods with the help of the experience gained in the earlier researches. In some of these Richards had the assistance of pupils. He was able to show that the old results on zinc and magnesium were in error because of the retention of gases on the oxides, and that most of the other values also had been vitiated by chemical imperfections in the methods employed. Richards not only employed and revised the old methods but devised new ones in the course of this work.

The investigation upon caesium marked the end of the first period of his investigations concerning atomic weights—the time during which the work of Stas had been considered impeccable. In 1904 the investigation of a large number of specimens of sodium bromide while verifying Stas's atomic weight for bromine seemed to indicate that this value for sodium was distinctly too high. Because the sodium bromide underwent transition from the dihydrate to the anhydrous salt at a perfectly definite point, it was evidently very pure. Hence its verdict could not be ignored and a new study of the atomic weight of sodium was undertaken. This investigation began a new period in Richards's work in which he was able to show the errors into which Stas had unwittingly fallen. He proved without question that not only was Stas's value for sodium too high but his value for chlorine was too low, and both of these conclusions have been verified by the subsequent work of others. Because Richards had previously chiefly used bromides, this

discovery of the error in chlorine was not made during his earlier researches.

The discovery of error in two of Stas's most accurately determined results led to the natural suspicion that others also might need revision. Accordingly three determinations of potassium, of sulphur, and of nitrogen were undertaken with the help of able assistants, the last of the three investigations being conducted partly at the University of Berlin during the term of his exchange professorship there. Potassium chloride and bromide were both analyzed with all the care used in the case of sodium. Sulphur was approached by a new method involving the conversion of silver sulphate into the chloride, and nitrogen was attacked both by the synthesis of silver nitrate and by the analysis of ammonium chloride. The work on silver nitrate was in some ways the most convincing of all, because in this case it was possible to prove that the salt was essentially free from water, by decomposing it and passing the products of decomposition, suitably treated, through a phosphorus pentoxide tube. No more concordant results have ever been secured in the Harvard Laboratory than the six successive experiments by which the silver was converted into silver nitrate—the extreme variation between the results being less than one-thousandth of a percent. If any error existed in them, it was an error of amazing constancy.

The most recent finished problem with which he has been concerned was a study of the atomic weights of lithium, and silver. Not only was the ratio of lithium chloride to silver determined but also its ratio to silver chloride and besides this by a new method the amount of lithium chloride contained in lithium perchlorate was carefully determined. The ratio of silver to oxygen was thus directly obtained by this equation.

$$\frac{\text{Ag}}{\text{LiCl}} \times \frac{\text{LiCl}}{\text{LiClO}_4 - \text{LiCl}} = \frac{\text{Ag}}{\text{O}_4}$$

This was entirely a new procedure and for many reasons seems to give one of the very best means of determining the atomic weight of silver. Incidentally the atomic weight of lithium was found to be almost a whole percent less than that obtained by Stas. This seems to have been Stas's most grievous error, and came to pass only because all the defects in his process accumulated on the head of this lightest of all the metals.

Richards has himself said that "the secret of success in the study of atomic weights lies in carefully choosing the particular substances and processes employed, and in checking every operation by parallel experiments so that every unknown chemical and physical error will gradually be ferreted out of its hiding place. The most important causes of inaccuracy are: the solubility of precipitates and of the material of containing vessels; the occlusion of foreign substances by solids, and especially the presence of retained moisture in almost everything. Each of these disturbing circumstances varies with each individual case. Far more depends upon the intelligent choice of the conditions of experiment than upon the mere mechanical execution of the operations, although that too is important." In carrying out these suggestions he has brought into play all the powerful aid furnished by the new science of physical chemistry which has thrown so much light upon the mechanism of the establishment of chemical equilibrium. He has always heeded the advice given in the paragraph above, especially the series of errors caused by the unsuspected presence of water in the salts to be weighed. With this in mind there was evolved in the course of this work a remarkably simple device for driving off every trace of water from any salt, and then enclosing this salt in a bottle without exposure for an instant to the outside air so that it could be weighed without risk of attracting moisture. This device greatly helped his work as did also the nephelometer, an instrument for detecting minute traces of suspended precipitate by means of the light reflected by them. Both of these

instruments were original with him. He has always pointed out very emphatically that the chemical difficulties in work of this kind greatly exceed the physical ones. The operation of weighing is far more easily controlled than the solubility of precipitates and the retention of foreign substances in the material to be weighed. For this reason he has preferred to use rather small quantities of material and to prepare these in a state of undoubted purity. As he has pointed out, there is no object in weighing 100 grams of material even to within 5 milligrams, if it contains as much as 0.01 percent of impurity. A much better result can be obtained by weighing 10 grams to within 0.1 of a milligram, provided that the material itself contains no more than 0.001 percent of impurity.

Richards's contributions to the science of chemical thermodynamics have been varied in nature, and, as in the other cases, they have had in part a practical interest and in part also primarily a theoretical one; his first published paper was a brief study of the constant heat of precipitations of argentic chloride, now so well explained by Arrhenius's theory. Subsequently he has studied a wide variety of thermochemical phenomena with unusual precision, having devised entirely a new method of calorimetry for this purpose. This method, first put in practice by him, consists in causing the environment of the calorimeter to change in temperature at precisely the same rate as the calorimeter itself. Thus at one stroke the various corrections for cooling, and for the lag of the thermometer, are wholly eliminated, and a more satisfactory thermochemical result is obtained than can be reached in any other way. With the help of pupils, he has applied this method to the determination of the specific heats of solids at low temperatures, the specific heats of liquids, the heats of solution of metals in acids, and the heats of combustion of organic substances, having obtained a great variety of data upon these various topics, many already published and

many awaiting publication. He has been able to show in most cases that others have made greater or less important errors in their work, for example, in the case of the determination of specific heats of solids when corrected for the heat loss or gain during transfer by running parallel experiments with a hollow vessel of the same bulk and same material as the solid piece of metal to be measured, thus making possible by mere subtraction the accurate correction for this error. He was also able to prove that Julius Thomsen's methods for correcting the results with concentrated solutions to those with dilute solutions was incorrect in detail.

In his study of the specific heats of the elements at low temperatures he emphasized especially the rapid falling off of the specific heat with the temperature in many cases, a phenomenon recently taken up more in detail and at even lower temperatures by Walther Nernst. His study of heat capacities, however, was not limited to the practical laboratory work. In a paper, which deserves especial mention because it has been frequently overlooked, he pointed out on the basis of such data as were available at that time that the change of heat capacity of a reacting system was in all probability connected with the difference between the total energy change and the free energy change in that reaction. He was the first to point out that in all probability the two latter quantities are equal to one another in case no change of heat capacity occurs during the reaction, and he also pointed out that in all probability an increase in heat capacity during a reaction signifies that the total energy change is less than the free energy change, whereas, on the other hand, a decrease in the heat capacity during the reaction probably causes the total energy change to be greater than the free energy change. These statements clearly made in 1902 are without question the basis of Nernst's subsequent mathematical treatment of the subject. Richards' data were rather inadequate and

his paper tentative, but the essential ideas involved are unquestionably outlined in this paper, although not treated there in full detail.

Electrical problems were first attacked by Richards in his effort to discover if the electrochemical equivalents are precisely equal to the corresponding chemical equivalents, as the atomic theory would lead one to expect. He studied therefore in great detail the copper and the silver voltameter (or coulometer, as he more appropriately named the instrument). He was able to trace the error in the former due to the formation of cuprous sulphate, and a very elaborate study of the silver coulometer led him to discover the chief causes of error in the instrument as used up to that time, and then to propose several methods of obtaining accurate results. The difficulty of the work seems to be indicated by the discussion which has since been raised by the subsequent work of others in the light of the recent investigations conducted at the Bureau of Standards at Washington as well as by G. A. Hulett, but there can be no question that every point made in Richards's papers was correct.

He was able to show in these researches not only that Faraday's law of electrolysis holds with great exactness, but also that this exactness is fully equalled by the behavior of fused salts when subjected to electrolysis. He proved also that electrostenolytic effects are likewise without influence upon Faraday's law. These investigations taken together constitute the most striking evidence as yet obtained of the accuracy of this fundamental generalization. They place it among the very few laws which seem to be as exact as far as our very careful observation can show.

His electrochemical work has also included the determination of single potential differences as well as of the electromotive forces exhibited by dilute and concentrated liquid amalgams. The most interesting contribution to the former class of phe-

nomena is that concerning the electromotive force of iron under varying conditions and the effect of occluded hydrogen. In this research he not only for the first time discovered the true single potential difference exhibited by iron, but explained the reasons for the low results obtained by others and threw new light upon the nature of hydrogen occluded by iron and the mechanism of overvoltage. All his results on this subject have subsequently been confirmed by Förster in a monograph published by the Bunsen Gesellschaft. With regard to his work upon electromotive forces produced by dilute amalgams, it is enough to say that with the help of pupils he has studied amalgams of cadmium, zinc, thallium, indium, lead, tin, copper, and lithium, in many cases using very concentrated solutions of the metal in mercury, and these varied data were made the basis not only for a striking verification of the exactness of the law of concentration-effect at great dilution but also a basis for a thermodynamic analysis of the cases of the deviations exhibited by concentrated solutions.

The work upon the significance of changing atomic volume and atomic compressibility which has occupied much of Professor Richards's time during the last thirteen years has both a practical and a theoretical aspect. His views concerning the nature of the liquid and solid state have led him to make a large number of determinations of compressibility, of surface tension, and heat of evaporation, which have enriched considerably our knowledge upon this subject, and which cannot but be of lasting value, even independent of any hypothesis. Prominent among these data are the determinations of the compressibilities of the elements. In a series of investigations using an entirely new method, devised by himself, for determining compressibility, he determined the relative compressibilities of thirty-five liquid or solid elements, so distributed as to depict for the first time clearly the periodic nature of this property.

The close correspondence between compressibilities of the solid elements and their atomic volumes is shown by the two curves in the accompanying diagram, cut from one of his publications.*

In addition to these data concerning the elements he has, with the help as before of a number of pupils, determined the compressibilities of a variety of simple compounds, such as the halides of lithium, sodium, potassium, and thallium, on the one hand, and hydrocarbons, alcohols, esters, amines, and organic halides, on the other hand. These data, many of them entirely new, afford a basis for a variety of interesting theoretical conclusions concerning the mechanism of the compression of solids and liquids. His work on surface tension and heat of evaporation, which was undertaken in order to test his hypothesis concerning the relation of these properties, has never yet been fully published, and therefore cannot be fully discussed at present, but enough has appeared in print to show the importance of the work.

As has been stated, all these investigations were suggested or inspired by Richards's theory of atomic compressibility which differs radically from the current kinetic conception of the structure of solid and liquid bodies. His hypothesis first arose in his mind from the consideration of the behavior of gases, and the now generally accepted variability of the quantity b in the equation of van der Waals. He reasoned that if b is changeable, the actual size of the molecules to which b is probably nearly related must also be changeable. This implies molecular compressibility, and if molecules are compressible, they must be much compressed by the great forces of cohesion and chemical affinity which exist in solid and liquid substances. Accordingly he immediately sought for evidence of the compressing effect of chemical affinity and cohesion, and promptly found it in the rediscovery of the general but not invariable rule;—greater affinity usually causes greater contraction on combination. This

* This diagram is not reproduced here.

idea has been suggested by Davy one hundred years ago, and several others since have revived it; but the idea nevertheless made no impression upon chemical literature as a whole, and was entirely overlooked by Richards until after the publication of his first papers. It must be said, however, that the oversight was perhaps more fortunate than not, because the entirely new approach to the subject led Richards to penetrate much more fundamentally into it than those who had preceded him. He has been able to show without much room for doubt that the reasons for the occasional deviations from the general rule, deviations which probably destroyed earlier confidence in the whole matter, are almost certainly due to the concomitant action of both chemical affinity and cohesion; in other words he by approximate quantitative evidence was able to show that not only the combination of atoms to make molecules causes compression, as the affinity is greater, but also that the molecules in cohering to one another in order to form a liquid or a solid compress one another in this process also. Hence the total volume of a liquid or solid appears according to his hypothesis to be the result of these varying and very different affinity-pressures.

He has been able to show that in a great many cases this hypothesis which has led him to consider atoms and molecules as closely packed without spaces between them in liquids and solids is consistent with a great variety of widely different phenomena both physical and chemical. For example, it gives entirely a new insight into the tenacity, ductility, hardness, brittleness, and surface tension; it gives a new and easily conceivable interpretation of the critical point; the peculiar relations of material and light, such as magnetic rotation, fluorescence, partial absorption, etc., may be referred to the modified vibrations of compressed atoms. He has pointed out also that the theory gives a very plausible explanation to the reason why as a rule among isomers the denser isomer is less volatile, less

compressible, and possesses a greater surface tension than the less dense isomer.

A clear kinetic picture of the asymmetric carbon and in general the mechanism of the actual chemical affinities of any two atoms may be based upon this hypothesis. As he has said in the Faraday Lecture: "The satisfying of each valence of an atom would cause a depression on the atomic surface, owing to the pressure exerted by the affinity in that spot. The stronger the affinity, the greater should be this distortion. Evidently this conception gives a new picture of the asymmetric carbon atom, which combined with four other different atoms, would have upon its surface depressions of four unequal magnitudes, and be twisted into an unsymmetrical tetrahedron. The combining atoms would be held on the faces of the tetrahedron thus formed, instead of impossibly perching upon the several peaks. According to this hypothesis, the carbon atom need not be imagined as a tetrahedron in the first place; it would assume the tetrahedral shape when combined with the other four atoms. One can easily image that the development of each new valence would change the affinities previously exercised, somewhat as a second depression in the side of a rubber ball will modify a forcibly caused dimple in some other part. Thus a part of the effect which each new atom has on the affinities of the other atoms already present may be explained."

He has published a number of papers upon the subject of atomic compressibility; the whole matter is summed up briefly in his Faraday Lecture of 1911. During the twelve years since his first publication upon the subject, no one seems to have been able to advance a first-rate argument against this theory of compressible atoms, and if it continues to gain ground, as it has during this period, one may safely predict that before long it is bound to cause nothing short of a revolution in the kinetic point of view concerning the nature of equilibrium and change in solid and liquid substances as well as a better understanding of the deviations of gases from the exact gas law.

BIBLIOGRAPHY

Note: As was customary in the last century, Richards usually published the results of his researches in both English and German scientific journals. To list all of Richards's papers would be to expand this bibliography unnecessarily. Therefore only one explicit reference is listed below for the report of an investigation.

KEY TO ABBREVIATIONS

- Am. Chem. J. = American Chemical Journal
 Am. J. Sci. = American Journal of Science
 Ber. = Berichte der Deutschen chemischen Gesellschaft (later, Chemische Berichte)
 Carnegie Inst. Wash. Publ. = Carnegie Institution of Washington Publication
 Carnegie Inst. Wash. Year Book = Carnegie Institution of Washington Year Book
 Chem. News = Chemical News and Journal of Physical Science (later, Chemical Products and the Chemical News)
 Chem. Rev. = Chemical Reviews
 J. Am. Chem. Soc. = Journal of the American Chemical Society
 J. Franklin Inst. = Journal of the Franklin Institute
 J. Phys. Chem. = Journal of Physical Chemistry
 Orig. Com. 8th Internat. Congr. Appl. Chem. = Original Communications of the 8th International Congress of Applied Chemistry
 Proc. Am. Acad. Arts Sci. = Proceedings of the American Academy of Arts and Sciences (later, Daedalus)
 Proc. Nat. Acad. Sci. = Proceedings of the National Academy of Sciences
 Z. anorg. Chem. = Zeitschrift für anorganische Chemie (later, Zeitschrift für anorganische und allgemeine Chemie)
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