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OF
BERTRAM BORDEN BOLTWOOD
1870-1927

BY

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Bertram B. Boltwood

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PROFESSOR BERTRAM BORDEN BOLTWOOD was an important figure in the development of radioactivity as a science. His contributions were significant in that so many of them brought forth facts of fundamental importance so that his name is connected not only with radioactivity, but also with isotopy, both of which branches of science gave us new conceptions of physics and chemistry, and with the geologist's problem of determining the ages of formations. There is not a long array of publications by him but each one is the outcome of much experimentation, being comprehensive in statements of procedure and in the results which are very candidly discussed. His love of the laboratory arts and his immense knowledge of them made him the person much sought by those about him in need of assistance in experimental work. On account of his wide acquaintance with sciences in particular and culture in general he was welcomed in groups in which he moved. As a teacher he was connected with Yale for twenty-nine years, about one-half of this time with the physics department and the other half with the chemistry department. His untimely death brought forth expressions of sorrow and of appreciation of his scientific worth from scientists in all parts of the world.

ANCESTRY

His paternal ancestors were of English stock. The American lineage is headed by Robert Boltwood, who immigrated sometime before 1648 and became a freeman in 1658. For a while he lived in Wethersfield (now Glastonbury), Conn., until certain religious difficulties arose, when under the leadership of John Russell he left Connecticut and settled in Hadley, Mass., where he was a miller. His wife Mary is of unknown parentage. Their oldest child and only son was Samuel, who like his father was a miller and was also a sergeant. He fought at Peskeompskut during Philip's War, and also at Deerfield, where he and one of his sons, Robert, were slain in the combat on the Meadows, Feb. 29, 1704. Both were buried with the other victims in a common grave at Deerfield. His wife was Sarah (Lewis). They had five sons and five daughters. Their youngest son Solomon (1694-1762) removed to Amherst about 1737 and married Mary Norton Pantry, with whom he had three sons and three daughters. The oldest son of Solomon, William (1725-1779), settled in Amherst, was a lieutenant and served on the frontier in the French and Indian wars. His wife was Mary Sheldon and they had five daughters and two sons. The younger son, William (1766-1835), was a farmer and a blacksmith at Amherst. William was married three times, his first wife being Eunice Noble. Their second child was Lucius (1792-1872).

William, being a small farmer, was not able to aid greatly his son Lucius in his ambition to secure an education. Lucius, however, worked his way and ultimately graduated from Williams College in 1814. He settled in Amherst, practiced law, and became one of her most influential citizens. He was active in the founding of Amherst College and "his heart was filled with joy and pride when Amherst College became a reality in 1821." He was secretary of Amherst College from 1828 to 1864. He was one of the founders of the Liberty Party and was its first candidate for governor of Massachusetts in 1841. In 1824 he married Fanny Haskins (1807-1888), daughter of Rev. Mase Shepard (Little Compton, R. I.) and Deborah, daughter of John Haskins (Boston, Mass). Deborah Haskins was a sister of Ruth Haskins Emerson, mother of Ralph Waldo Emerson. In 1835 Lucius Boltwood built a stately mansion (on which spot is located at present the Converse Memorial Library of Amherst College). Hither came the intellectual men and women of New England during the middle of the nineteenth century, to enjoy the hospitality of Lucius and Fanny Haskins Boltwood. A brother of Fanny Haskins (Shepard) Boltwood was the distinguished mineralogist and authority on meteorites, Charles Upham Shepard (1804-1886), a graduate of Yale, connected with Yale from 1825 to 1847—in the latter years as lecturer in Natural History—and later a professor at Amherst.

The eighth of nine children of Lucius and Fanny Haskins Boltwood was Thomas Kast Boltwood (Feb. 15, 1844, to Dec. 25, 1872), father of Bertram Borden Boltwood, the subject of this memoir. Thomas's middle name, Kast, is the name of the Kast family (Boston, Mass.) of which Dr. Thomas Kast married Hannah Haskins, who was a sister of Deborah and Ruth mentioned above. Thomas Kast Boltwood was a graduate of Yale College, 1864; studied law at the Harvard Law School, at Utica, N. Y., and at Albany Law School. From the latter institution he received the LL.B. degree in 1866. He practiced law in Toledo, Ohio, as a member of the firm Potter and Boltwood. His health broke down in 1869 and later he gave up the profession. He died in Hartford, Conn., in 1872.

The Boltwood family in its various ramifications was quite influential in the community life of Amherst for several generations. Various memorials are to be found in the Grace Episcopal Church at Amherst which connect the names of Boltwood, Shepard, Haskins and Kast. This church was the place of worship of the Boltwood family but Bertram Borden never became a member of it, although in his childhood he attended it quite regularly with his grandparents. The old cemetery (within the town of Amherst) is the resting place of most of the Boltwoods, including Bertram Borden.

His maternal ancestors were of Dutch stock. His mother was Margaret Mathilda (Sept. 25, 1842, to Oct. 12, 1909), daughter of Jeremiah Wall and Margaret (Ostrander) Van Hoesen, and their ancestors were among the early settlers in Rensselaer County, N. Y. The first Van Hoesen came to America in 1644. Bertram's mother was born in Castleton, a village of Schodack, Rensselaer County. She married Thomas Kast Boltwood in 1868. Their first son, Charles, died in infancy and Bertram Borden was the second child. She was considered a very beautiful woman throughout her life. She died in Manchester, England, in 1909, where she accompanied Bertram when he went there to carry on researches with Sir Ernest

Rutherford in the Physical Laboratory of the Victoria University of Manchester, of which laboratory Sir Ernest was the director. She was buried at Manchester.

BOYHOOD PERIOD: 1870-1888

Bertram Borden Boltwood was born July 27, 1870, in his paternal grandfather's home in Amherst. His middle name Borden was given to him for a classmate and friend of his father. The place of his birth became a second home to him and all his summer vacations as a boy in school he spent at Amherst with his grandparents. His mother made her home in Castleton, her native village. She did everything in her power to give Bertram the best education possible. In his early childhood he had a governess and also attended a private school until 1879 when he entered the Albany Academy at Albany, N. Y., to prepare for Yale, and graduated from the Academy in 1889.

There was an unusually strong bond between Bertram and his mother. She was not only a mother to him but a chum and a companion as well. His letters to her from school, college and from his European trips breathe tenderness and love. To her he looked for approval or disapproval of his conduct or of his plans for the future not only through the days of childhood but also later when he was already becoming recognized for his scientific work; and during this later period she gave up her home at Castleton to live with him at New Haven.

As a boy he showed all the traits of a busy youngster, being attracted by sports in which boys are generally interested, loving his fishing rod and the bow-gun and later his camera, and in fact liking very much anything requiring the use of his hands, a trait perhaps common to many boys but in his case seeming to suggest an inherent quality which in later years was so evident to his colleagues and which is so necessary to successful work in experimentation, namely, the mastery of the laboratory arts, which fascinated him and to which he also contributed. Reports have it that he was a bit mischievous and liked to carry a joke to a practical conclusion, but that he was absolutely truthful and honest. A letter written to his grandmother Van Hoesen

BIRTHPALCE OF B. B. BOLTWOOD: HOME OF HIS GRANDFATHER, LUCIUS AMHERST. IT IS THE SITE OF CONVERSE MEMORIAL LIBRARY, AMHERST

B. B. BOLTWOOD AS A BOY

from Amherst in 1882 shows his interests as an active boy but also gives a glance at his character and at his interest in and some knowledge of minerals, which later received much attention from him. He begins by saying that he went to church and he must tell her because he thought it would please her. He describes his activities and also writes: "I have been looking in the ashes of the Walker building* twice, the first time I found nothing, but as good luck would have it I found a good piece of Iceland spar, . . . and another mineral of which I do not know the name." He ends: "I am sorry to trouble you but will you please send my bow-gun and fishing rod if possible. I remain your aff. Grandson B. B. Boltwood."

His mother frequently accompanied him to Amherst but his grandmother Boltwood also took much interest in him and had considerable influence on him. She had the opportunity to see him at play and to observe his pranks and his use of vacation time. It would seem that at times she, who had relatives intellectually prominent, thought that young "Bertie" gave books a second place, while camera, minerals, etc., received considerable attention. Doubtless she had her own interpretations of these observations, and while she realized Bertram's youthful years yet she considered it necessary to draw his attention to fundamentals which she felt he must realize as he was approaching the threshold of manhood. The following portion of a letter written to him while he had still two years at the Albany Academy will be of interest in this connection.

"Amherst, Nov. 8, 1887.

"My dear Bertie,

"I was glad to get a letter from your mother and to learn that you were going on in your studies. I was glad you had been so successful with the photographs of cousins. It is rather hard for one who has such a taste as you have to settle down to books, but if you live you will find that *now* at your age the *foundation* of your future character and standing depends. I have been

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*Amherst College Museum, burned 1882.

reading of late the life of cousin Waldo [Emerson] by his friend Cabot. I can see much in Waldo that would fit your dear Uncle Charles, my brother, and I hope some of their noble traits may come down to your generation. . . ."

There is no doubt that Charles Upham Shepard, the noted mineralogist, an authority on meteorites and a chemist, was frequently brought up to Bertram as a splendid example of a scientist, and that Bertram's knowledge of minerals, at the early age of twelve, was not altogether fortuitous. Charles U. Shepard lived his last years in Amherst and his noted collection of minerals came into possession of Amherst College but was destroyed by fire in 1882; it is very likely that young Bertram was impressed by his uncle and his great collection of minerals.

UNIVERSITY PERIOD: 1889-1897

In 1889 he entered the Sheffield Scientific School at Yale, registering for the chemistry course. In his freshman year he received a prize for first rank in physics. Physics as well as chemistry was a favorite with him. During the summer of 1890 he was rewarded with a trip to Europe in company with two friends of his family. He kept a very interesting diary of the whole trip and continually kept his mother informed of the sights, impressions and his doings. Both his diary and his letters to his mother breathe forth unmistakable sincerity of love and affection for his mother. His diary shows a study of the characters of his fellow passengers on the boat and of the people of the various countries. It shows a marvelous comprehension of the people, their customs as well as the scenery of the countries visited. He was independent in his decisions where to go and what to see. When his companions got stalled in Switzerland for mountain climbing in which he showed no special interest, either then or at any time later, he decided instead to spend his time in seeing something of Italy, and having apparently thought of Italy before, he concentrated on Florence and Venice. His summer trip lasted from June 25 to Sept. 25 and included parts of Ireland, Scotland, England, France, Switzerland, Italy and Germany.

PENCIL SKETCH OF B. B. BOLTWOOD WHILE HE WAS IN MUNICH

In his senior year at Yale he took the highest rank in chemistry and read at commencement a dissertation on "Iso-nitroso Cyanacetic Ester." Immediately after graduation, in July, 1892, he left for Germany where he spent two years studying inorganic chemistry at the Ludwig-Maximilian University of Munich, working particularly in special analytical methods and on rare earths under Professor Krüss. Returning to Yale in September, 1894, he was appointed assistant in analytical chemistry (1894-1896) in the Sheffield Scientific School of Yale University. During this period he carried on research work on double salts with Professor H. L. Wells and in organic chemistry with Professor H. L. Wheeler. Late in the winter of 1896 he went to Leipzig, Germany, and spent one semester in the study of physical chemistry in Ostvald's laboratory. On both of the trips to Germany he kept diaries. Reading these one finds expressions of appreciation of German thoroughness in scientific preparation and work; and later also expressions of comparison of Germany with other countries in matters of living and commerce, strongly favoring Germany. This kindly feeling for Germany is expressed even more strongly in his later diaries.

INSTRUCTOR IN THE SHEFFIELD SCIENTIFIC SCHOOL, YALE: 1896-1900

Returning to Yale in the autumn of 1896 he was appointed instructor in analytical chemistry and later in physical chemistry. He received the Ph.D. degree from Yale in 1897, his dissertation involving his research work in "Studies on Chlorides." During this period he devoted his time and energy to teaching and to his own improvement in laboratory technique and to devising new apparatus used in physical chemistry. Physical chemistry at this time was still young and the work of Willard Gibbs was comprehended by rather a limited number of chemists. Facilities for teaching it were not extensive and books, especially in English, were not many. To facilitate his work in teaching his elementary classes Boltwood translated from the German two books, one by Alexander Classen, "Quantitative

Analysis by Electrolysis," and the other by Charles Van Deventer, "Physical Chemistry for Beginners." In the laboratory he was busy improving available apparatus and contributing new types, for example, a simple automatic Sprengel pump and a new form of a water blast. Various pumps needed in his laboratory were improved, and years later when the mercury diffusion pump was just invented he still showed interest in the production of a vacuum by devising a form which in many respects is more serviceable than the original type announced.

He devoted much time to gathering all sorts of information on laboratory arts and technique which served him well in his later work and he seemed to be an inexhaustible storehouse of information in this field to his colleagues and to his students (later) in the Sloane Physics Laboratory and the Kent and the Sterling Chemistry laboratories at Yale. In these laboratories in later years he conducted regular demonstration classes in laboratory arts for research students in physics and in chemistry to better fit these students to solve their difficulties in the technique concerned in their researches. He contributed to the laboratory arts in various ways and always found some means of getting over the difficulties encountered. When a wax of low melting point and fair mechanical properties was required—and none existed at the time—he found a way of producing the "Boltwax," which for a long time was a much desired wax in many laboratories of this country.

While he was engaged in teaching and some research during this period, yet, on the whole, it was still a period of study and preparation and perfection in experimentation. One important piece of work carried on under his supervision in 1899 by one of his students, Mr. Langley, was on the separation of radioactive substances from pitchblende. Boltwood refers to it in his paper on Ionium in giving the history of his work which led to the discovery of ionium. The results showed that Mr. Langley was on the verge of discovering actinium which later was made by Debierne in Paris. These experiments, however, were not immediately continued, mainly because Boltwood severed his connection with the Sheffield Scientific School and was preoccupied with other work in his private laboratory.

PERIOD OF GREATEST SCIENTIFIC ACHIEVEMENT: 1900-1910

The most important part of Boltwood's life, viewed from the point of scientific achievement, falls into the period 1900-1910. During the first part of this period he worked in his private laboratory at 139 Orange Street, New Haven, and during the latter part in the Sloane Physics Laboratory of Yale University.

Regarding the first part of this period, Boltwood wrote in the "Biographical Sketches" (1917) of his class of 1892 S. at Yale as follows: "In the year 1900 I severed connection with the Sheffield Scientific School and conducted until 1906 a private laboratory in New Haven. During this period I devoted considerable time to technical chemical work and was for some years associated with Joseph Hyde Pratt,* '93 S. under the title 'Pratt and Boltwood, consulting mining engineers and chemists.' My interest in the scientific side of chemistry remained, however, and I still continued work in these directions." In 1906 he received an offer of assistant professorship of physics in Yale College which he accepted and held until 1910. He says in the "Biographical Sketches": "Although this appointment was in a subject different from the one to which I had chiefly devoted my attention up to that time, it offered increased opportunities for the continuation of my scientific work."

In 1896 Becquerel discovered radioactivity through his investigations of uranium and shortly after that Pierre and Marie Curie with their collaborators made their sensational discoveries in this new branch of science through their investigations of the uranium-bearing mineral pitchblende. This happened during the period when Boltwood was intensely interested in the chemistry of the rare earths and it was in a field of investigation in which he had been studying. It is, therefore, no wonder that he became scientifically interested in these new discoveries.

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* J. H. Pratt, later professor of Economic Geology, North Carolina University, Chapel Hill, N. C.

During the first part of the period in the private laboratory with J. H. Pratt, a geologist, he had, no doubt, much to do with analyses of minerals and incidentally started to collect for future scientific analyses all sorts of radioactive minerals.

Radioactivity at that time was not a science as yet, but merely represented a collection of new facts which showed only little connection with each other. These facts needed some correlation and explanation with some basic hypothesis before they could give, as a whole, a semblance of a science. The initial placing of radioactivity on a scientific basis came with the announcement by Rutherford and Soddy in 1903 of their theory of disintegration of radioactive elements. Briefly stated, this theory postulates that an atom of a radioactive element, *e.g.*, uranium or radium, spontaneously disintegrates emitting energy in the form of radiations and that from what is left of the initial atom, an atom of a new element is formed which may in turn disintegrate. This was a bold theory in 1903 but today it is no mere theory but an established fact verified in every case. To this verification Boltwood contributed early and materially. He devoted much time to the investigation of problems dealing with the origin of radioactive elements and with the genetic relationships among these elements.

EQUILIBRIUM RATIO OF RADIUM TO URANIUM

In his papers dealing with the "Radioactivity of uranium minerals," "Ratio of radium to uranium in minerals," and "Origin of radium," he demonstrated that radium must be a disintegration product of uranium. He had analyzed primary uranium-bearing minerals from all parts of the world and showed that the ratio of the activities of radium and uranium was remarkably constant for all old unaltered minerals from various geological formations and with widely varying amounts of uranium content. Since his original work was announced some other results have been published by other investigators in which some variation of this ratio had been obtained; in some cases, as *e.g.* in the carnotite and autunite the mineral was young (geologically speaking) and the equilibrium between radium and uranium had not been attained or else the ratio based on "bulk" material and small specimens of the same material gave different values of this ratio, indicating some alteration of the material. Boltwood emphasized the necessity of observance of "old unaltered primary minerals" and gave attention to this same problem again in 1920 (with Johnstone) reaching the same conclusion of constant ratio of radium to uranium. This ratio was accurately expressed by him and Rutherford, when the radium standard was established, as 3.40×10^{-7} gm. radium to 1 gm. uranium, and is an important constant in radioactivity.

VERIFICATION OF THE DISINTEGRATION THEORY. DISCOVERY OF IONIUM

The first deduction from these researches, however, was that radium must be a disintegration product of uranium if the disintegration theory is assumed and because the radium occurred in a fixed and definite proportion to the uranium in old unaltered minerals.

Boltwood was a careful and indefatigable experimenter, repeating his analyses and experiments many times to make certain of his results, but he also had the broad vision to realize that it would be necessary to "grow" radium from its parent substance to give the final proof of his contention.

He reasoned that if uranium, through its first product uranium X (discovered and named by Crookes and now known to be two successive products, UX_1 and UX_2), disintegrates directly into radium, it should be possible to detect in a relatively short time the radium "grown" from pure uranium since the intervening product, UX, is of short life. He tried this experiment by purifying uranium and later at different times examining the solution for radium using the sensitive radium-emanation method by means of which minute quantities of radium emanation, and therefore of radium, could be detected. He found that in 390 days no detectable amount of radium was present. To an average mind such a result would be extremely discouraging or else disproving the contention, otherwise supported, that radium is a disintegration product of uranium.

Boltwood, believing in the disintegration theory, found this negative result an incentive for renewed efforts in experimentation to discover the reason for it. He saw a possible explanation for the disappointing result, namely, the possible existence of an element of a long-life period between uranium X and radium. If this should be true then this long-lived element would retard the production of radium so that growth of radium might not be detectable in the short space of 390 days, the time of his experiment. However, if the hypothesis is correct, this intervening element must be present in an equilibrium amount in the same mineral which yields the uranium and the radium. He promptly started to search for this hypothetical "parent of radium." He gave attention to the actinium element discovered in uranium minerals by Debierne and announced by him in two papers of the Comptes Rendus, Paris. Boltwood makes this statement: "In these papers, which were characterized by the lack of precise experimental details and the absence of explicit statements, the chemical properties were described as very similar to those of thorium, from which it had not been found possible to separate it completely." Boltwood, in his work, followed a method in which a precipitate was made with thorium. The substance separated, thought to be actinium, was used to "grow radium." This substance did produce radium and for a while Boltwood thought that actinium, or at any rate what Debierne separated with thorium and called actinium, was the missing parent of radium. Performing many experiments on the separation of actinium he finally found that actinium could be separated with some rare earths and that the thorium could be separated from the actinium and also purified by repeated precipitation (with sodium thiosulphate) so that ultimately he had the actinium with the rare earths and the thorium free of actinium. The "growth of radium" experiments revealed that actinium did not grow radium whereas the thorium precipitate did. The thorium was added to his solution of the carnotite mineral in the experiments when this mineral was used. Evidently, a substance was separated with thorium which proved to be the parent of radium. Further investigation showed this substance to be unlike any known radioactive element, that the α-particles which it emitted had a definite range of their own and that it produced radium in amounts proportional to the time of growth. He was now certain that he had discovered a new radioactive element, the sought-for parent of radium. He proposed to name it Ionium—"a name derived from the word ion. This name is believed to be appropriate because of its ionizing action which it possesses in common with other elements which emit alpha radiation."

It is almost a certainty that some of the material which Debierne separated with thorium and which he thought was actinium must have contained more ionium than actinium. Had Debierne followed up his thorium precipitates he might have discovered the element now known as ionium. On the other hand, if the work of Langley, Boltwood's student in 1899, had been immediately followed up, actinium might have been announced from New Haven instead of from Paris.

The original experiment of growing radium from purified uranium was still necessary for a complete proof of radium's genetic descent from uranium. The solution originally prepared was examined about four years later and showed a growth of ionium but the activity was too small to yield a quantitative proof. However, Soddy's experiments in 1919 along the same line on material about twenty years of age gave conclusive proof on this point and also a fairly accurate determination of the half-value period of ionium. Boltwood's material prepared at that time and sealed to be examined after a long period of time is extant and will be examined in due time.

HALF-VALUE PERIOD OF RADIUM

The knowledge that ionium is the direct parent of radium and that it is a disintegration product of uranium and that all these elements are in the same given uranium-bearing mineral, suggested to Boltwood a method of finding the "average-life" of radium and from this, of course, the half-value period and the characteristic constant. The method consists in separating the radium and the ionium from an old unaltered uranium-bearing mineral in which the uranium, ionium and radium are in radioactive equilibrium. The rate of disintegration of the ionium found in the mineral is equal to the rate of growth of radium from the same ionium and this rate of growth is equal to the rate of disintegration of the radium found in the mineral because of the equilibrium condition. Consequently, by growing radium from the ionium for a suitable time, the rate of growth can be obtained and knowing the radium in the mineral, the "average life" is deduced. The comparison is made by employing the radium emanation method. The method of obtaining the life of radium in this manner has the advantage over other methods in that no standard of radium is necessary. His was one of the first experimental determinations of this constant. Miss Ellen Gleditsch carried on these determinations some years later under Boltwood's direction at Yale and later at Oslo, growing the radium over longer periods for more accurate comparisons and her value of the half-period is 1690 years, which is undoubtedly our best value of this constant.

CHEMICAL INSEPARABILITY OF IONIUM AND THORIUM. ISOTOPY

The very extensive and careful chemical work done by Boltwood in connection with the discovery of ionium brought out a very important scientific fact which was so startling that many chemists and physicists seized upon it as a clue to other investigations the results of which form the foundation of a new branch of the physical science, namely, Isotopy. Boltwood separated ionium with thorium. In some cases he used large quantities of thorium and then tried to separate these two elements from each other. He did an immense amount of work hoping to find a way of separating ionium from thorium, using every known and conceivable method. He wrote on this point, among other things, under the heading "Chemical Properties of Ionium": "The separation of ionium from thorium presents indeed a difficult problem and I have been unable to discover any indication that even a partial separation can be effected by the use of such characteristic reactions as the precipitation of the thorium by hydrogen peroxide, sodium thiosulphate, metanitro-benzoic acid or fumaric acid. From its position with respect to radium it can be safely assumed that the atomic weight of ionium is probably not far from 230, and the atomic weight of thorium, 232.5, would bring these two elements into close proximity in the periodic table." What he found was the important fact that when ionium and thorium were once mixed, they were then chemically inseparable. Aston, in his book on Isotopes, puts it as follows: "The chemical similarity between these two bodies was therefore of an order entirely different to that exhibited by the rare earth elements, and came as near absolute identity as the most critical mind could require."

In this connection, some of his work on thorium salts and thorium-bearing minerals is also of importance. Hahn had discovered radiothorium and found its half-value period to be two years. Boltwood's study of the activities of thorium oxide prepared from commercial thorium salts and also from various minerals (including the monazite sand from which his commercial salts were produced) showed that the oxides from the commercial salts were only about half as active as the oxides from the minerals. He naturally supposed that the commercial process removed some of the radiothorium which was thought to be directly produced by the thorium disintegration. Data from his experiments showed in that case (*i. e.* if radiothorium is produced directly from thorium) that the half-value period of radiothorium should be nearly six years, and he communicated his results to Hahn. Hahn, attempting to reconcile the two differing values, suggested that an intervening element must exist between thorium and radiothorium and that it was this intervening element which was separated by the commercial process. Hahn searched for it and discovered it and named it mesothorium, deducing for it a half-value period of 5.5 years. Boltwood studied the chemical properties of mesothorium and showed that it can always be separated by exactly the same chemical processes as are used to separate thorium X. This result is in fact identical with the one noted for thorium and ionium.

At that time he was occupied with the experimental proof that ionium is the parent of radium and he did not follow up the work just referred to. However, Marckwald, Keetman, Auer v. Welsbach, Soddy and others did follow the clue suggested in Boltwood's "inseparability" of certain chemical elements, one of which, at least, was always a radioactive element, and they added much information on the similarity if not identity of chemical and physical properties of various radioactive and non-radioactive elements. A. S. Russell and Rossi working in Rutherford's laboratory and using material produced by Boltwood showed by their spectroscopic experiments that the spectra of ionium and of thorium must be the same, since the admixture of ionium to thorium brought out no spectral lines not found in the spectrum of thorium alone. Within a few years it was demonstrated that there are chemical elements possessing the same chemical and physical properties differing only in the atomic weights and radioactive properties (if radioactive), and that such elements would occupy the same place in the periodic table of chemical elements. Soddy, who contributed much to this subject, coined the word "isotopes" designating such elements.

LEAD AS FINAL INACTIVE DISINTEGRATION PRODUCT OF URANIUM

Boltwood was very early impressed with the fact that all his analyses of uranium-bearing minerals showed the presence of lead. On reviewing various published analyses of minerals containing notable proportions of uranium he was further impressed with the almost invariable report of the occurrence of lead. Communicating on this matter with W. F. Hillebrand of the U. S. Geological Survey, whose analyses of uranium minerals have been many and of recognized authority, Boltwood states that he was particularly impressed by the information, supplied in a private communication, "that so far as his [Hillebrand's] experience goes he does not remember to have found uranium in any mineral without its being accompanied by lead, and he adds 'the association has often caused me thought.'" With his usual scientific zeal Boltwood wanted to make a certainty of this apparent fact feeling it to be of great consequence. Under "Lead" in his first paper on the "Ultimate Disintegration Products of Radioactive Elements," he writes: "Out of a considerable number of analyses undertaken with the particular object of discovering whether or not lead was present, I have been unable to find a single specimen of a primary mineral containing over 2 per cent of uranium in which the presence of lead could not be demonstrated by the ordinary analytical methods." Farther on he says: "Through a dawning appreciation of the significance of the persistent appearance of this element in uranium minerals, the writer was led to suggest in an earlier paper * that lead might prove to be one of the final inactive disintegration products of uranium. All the data which have been obtained since that time point to the same conclusion." In his later work he reported much to strengthen this conclusion.

What we know now is that the final product, radium G, of the uranium-radium series is an isotope of common lead, with the same chemical properties. The work of Richards and of others on the isotopes of lead makes this definite; and the application of the displacement law to the elements of the uranium-radium series places the final product, radium G, in the same place as lead in the periodic table. The theoretical atomic weight of this product comes out 206.17 when we assume that of uranium to be 238.17 and of each of the eight α-particles emitted in the disintegration to be 4. Richards and his pupils at Harvard, Hönigschmidt in Prague and in Vienna, and Miss Gleditsch (at one time a research student under Boltwood at Yale) in Oslo have determined the atomic weights of the lead in some particular old primary uranium-bearing minerals and found values of 206.046 to 206.2, while the atomic weight of ordinary lead is 207.20. These values are for all the lead isotopes, including actinium D and perhaps traces of thorium D and common lead, but mainly radium G. These results are a sufficient verification of Boltwood's contention since isotopy had not then (1905) been brought to light.

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* Phil. Mag. (6) 9: 599-613 (1905).

THE AGE OF MINERALS

Desiring to furnish further proof of his contention, he set down the following conditions to be proven: "In unaltered primary minerals of the same species, and of different species from the same locality, that is, in minerals formed at the same time and therefore of equal ages, a constant proportion must exist between the amount of each disintegration product and the amount of the parent substance with which it is associated. And, in unaltered primary minerals from different localities, the proportion of each disintegration product with respect to the parent substance must be greater in those minerals which are the older and should correspond with the order of the respective geological ages of the localities in which the minerals have been found. It also follows that in secondary minerals, namely, in minerals which have been formed by the subsequent alteration of the original, primary minerals, the relative amounts of the disintegration products must be less than in the primary minerals from the same locality, provided, however, that the disintegration products can not be considered as original chemical constituents of the secondary mineral." His second paper on the "Ultimate Disintegration Products of the Radioactive Elements. Part II. The Disintegration Products of Uranium," deals with this problem and the data given for the ratio of lead to uranium, not only from his own analyses but from many of Hillebrand's and others, convince him that the conditions set above have been met and that they constitute evidence that lead is the final disintegration product of uranium.

The "geological ages" as used so far were really only relative and not quantitative values. To express them in years he proceeded according to the following plan: "Knowing the rate of disintegration of uranium, it would be possible to calculate the time required for the production of the proportions of lead found in the different minerals, or in other words the ages of the minerals." From the rate of disintegration of radium and the relative ratio of radium to uranium, he deduced the weight of uranium in one gram of uranium which would be transformed in one year into lead and divided the lead to uranium ratio by this quantity. This first calculation was approximate and was stated to be such.

In this work Boltwood laid the foundation for the best method we have today in calculating the "age of the earth." With our present knowledge of the isotopes of lead we find that we are obliged to modify his simple calculations in order to take care of these isotopes, namely, radium G, thorium D, actinium D and common lead. At the time of this work Boltwood did not believe that thorium disintegrated into lead, basing his reasoning on the small amounts of lead generally found in thorium-bearing minerals, not knowing the very much slower rate of disintegration of thorium compared to uranium; and furthermore, the final product of the actinium disintegration was not known. By the application of similar reasoning to the disintegration of thorium and of actinium that Boltwood used in the case of uranium and by determining an extra (important) quantity, namely, the atomic weight of the lead isotopes found in the primary unaltered mineral, it is possible by a somewhat more complicated formula to deduce the age of the mineral.

He also gave attention to the helium found in minerals and by collecting the available experimental evidence he concluded that "the amounts of helium found in radioactive minerals are of about the order, and are not in excess of the quantities, to be expected from the assumption that helium is produced by the disintegration of uranium and its products only." In his calculations he used the equation that uranium (238.5) = lead (206.9) + helium (31.6) *i. e.* "that for every 207 parts of lead there will be formed 32 parts of helium." It must be noted that it was then not yet definitely proven that helium was the result of the emitted α-particles. Discussing the results he points out that "in general with greater density of the mineral a greater proportion of the total helium formed has been retained within it." The evidence is in support of the idea advanced by Rutherford in St. Louis in 1904 that the helium content of uranium minerals may be used to indicate at least the minimum age of these minerals.

GENETIC RELATION OF ACTINIUM AND URANIUM

Studying the activities of the various radioactive constituents of a uranium mineral, Boltwood found early that actinium was as regularly present as radium but that its activity was very much too small to be in a direct genetic relation: uranium-radium. He writes: "Insofar as these experiments throw any light on the question of a genetic relation between actinium and uranium, I think that the constancy of the activity of the different minerals and the fact that quite appreciable amounts of actinium can be separated from all of them make it necessary to assume that the amounts of actinium in a mineral are proportional to the quantity of uranium present. It is therefore extremely probable that actinium is a disintegration product of uranium, although its position in the uranium-radium series is still to be determined." Rutherford, in his Silliman Lectures at Yale in 1905, tried to explain the anomalous relation by suggesting that actinium was a branch product of the main series. Such branchings have since been observed in several places and indicate to us that the complex structure of the atomic nucleus may break down in at least two ways. Under such a supposition the branching may take place at U I or at U II, and generally was assumed from the U II for various other reasons. Boltwood in 1920 in a paper with Johnstone discussed the various possibilities and in view of our incomplete knowledge of the subject left the question open, although inclining to the above mentioned branching, but explicitly stating that it is not impossible that actinium may be a product of an uranium isotope independent of genetic relation to U I and U II. From the recent results of Aston (1929) on the atomic masses of the constituent isotopes of lead from a bröggerite, who found one of atomic mass 207, the principal one being 206 (radium G), it would seem that the actinium came from an isotope (239) independent genetically of U I and U II but mixed with these two. Nevertheless, even if this be true for minerals of much the same age, constancy of activity of actinium to uranium would still be observed as seems to be fairly well established. Much work is left to be done here and the experimental determination of the atomic weight of actinium, in particular before the exact relation of actinium and uranium is established; but from Boltwood's original work we feel certain that a close relation does exist.

OUTSTANDING CONTRIBUTIONS

These outstanding contributions of Boltwood may be summarized as follows:

(1) Discovering a radioactive element, ionium, the parent substance of radium;

(2) Proving the direct genetic relation of uranium, ionium and radium;

(3) Showing that certain elements have identical chemical properties by the chemical inseparability of these elements—a fact forming the starting point of many observations by chemists and physicists from the results of which isotopy had arisen;

(4) Providing evidence that the "lead" found in unaltered primary minerals must be the final inactive disintegration product of uranium;

(5) Devising a method for the calculation of the age of uranium minerals from their lead and uranium contents;

(6) Showing that actinium is genetically related to uranium but not in the same line as radium.

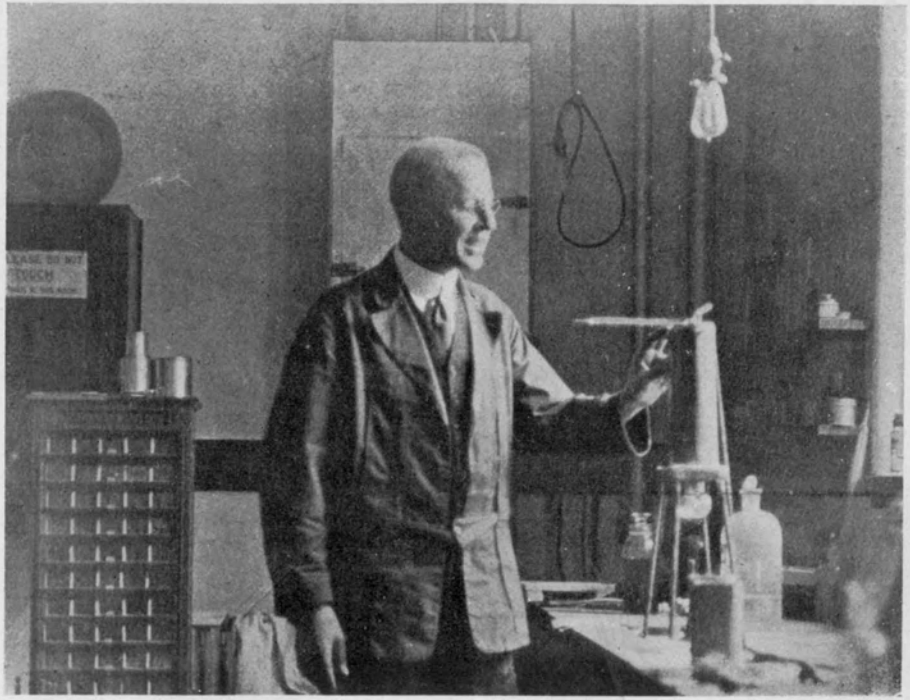
OTHER CONTRIBUTIONS

The above contributions bear the mark of fundamental importance in the physical sciences. Besides these noteworthy investigations, he was first in this country to devise an accurate and quantitative method of investigation of the radioactivity of spring waters. He pointed out that it was necessary to boil the waters (instead of bubbling air through them) to release all the emanation for quantitative measurements. In the absence of radium standards (1904) he was able to give quantitative significance to his measurements in terms of uranium. His standard for comparison was a solution of an old unaltered mineral for which the radium to uranium ratio was known and of which the uranium content had been determined. A known quantity of this solution, therefore, contained a definite amount of radium, the activity of whose radium emanation (radon) was compared with that found in the water studied. In this way the emanation of the water per liter could be expressed in terms of the uranium in grams of his standard. He investigated various natural waters near New Haven and in 1904, at the direction of the Secretary of the Interior, made a survey of the waters of Hot Springs Reservation, Arkansas, not only for the radium emanation but for radium itself held in solution in the various waters.

During his sojourn in Manchester he carried on further research on chemical separations of radioactive substances, in particular of ionium and of actinium. With Sir Ernest Rutherford he studied the production of helium by radium, polonium and ionium to verify the conclusion that all the helium found with these radioactive substances is due to their emitted α-particles.

He thought a great deal on the philosophic and speculative questions that arose in his mind with the discoveries made but the scientist within him kept a severe check on his flights of thought to stay within the realm of scientific knowledge and probability. The following quotation from his "Ultimate Disintegration Products" may be of interest in this connection. Having finished with the discussion of the facts about the various substances found in uranium minerals, he writes next to the final summary under the heading of "Origin of Elements" (1905): "If it can be ultimately demonstrated that lead, bismuth, barium, hydrogen and argon, or any one of them, actually result from the disintegration of uranium, an interesting question which naturally arises will be: Have the quantities of these chemical elements already existing been produced wholly in the same manner? Any discussion of this problem at the present time would certainly be premature, but the time may not be very far remote when the question will deserve serious consideration."

In 1909-10 he was granted a leave of absence from Yale and he spent the year with Rutherford in the Physical Laboratory of the University of Manchester where he held the John Harling Fellowship for that year. It was at this time that I first became



BOLTWOOD'S CHARACTERISTIC SMILE: IN HIS LABORATORY IN SLOANE
PHYSICS LABORATORY, YALE, 1917

acquainted with him, for I had also come to work in Rutherford's laboratory. His joviality and openheartedness made immediately a strong impression on me and we became and remained intimate friends.

In October of 1909 his mother, who accompanied him to Manchester, died there. Those who knew him and his mother and their mutual devotion to each other felt keenly the severe blow that fate had dealt him. Outwardly, he seemed to bear well under it but some of the letters from his New Haven friends to him, at this time, seem to indicate that in his letters to them he showed almost a broken spirit.

He received an invitation to continue his researches in England, but he finally decided not to accept the invitation. He returned to Yale as professor of radio-chemistry and was assigned, as before, to the department of physics where he was associated with Professor H. A. Bumstead. Together with Professor Bumstead he devoted much time and energy to the building of the Sloane Physics Laboratory, which was completed in 1912. During the college year 1913-14, in the absence of Professor Bumstead, he was acting director of the Sloane Physics Laboratory. His connection with the physics department continued until 1918, when, on the retirement of Professor F. A. Gooch, he was appointed acting professor of chemistry in Yale College, 1918-19, and acting director of Kent Chemical Laboratory, 1919-22. During the war he served as an instructor in the Yale R. O. T. C. in 1917, and in 1918 he was in charge of the chemical unit of the S. A. T. C. He was also engaged in experiments on the detection of submarines at the submarine base at New London.

For the first year after the organization of the university department of chemistry in 1918 he was the chairman of the department. During the next four years he was occupied chiefly with undergraduate teaching and with administrative work, including planning of a new laboratory which was to house the reorganized department of chemistry.

The planning of the Sterling Chemistry Laboratory, first projected by the university in 1920, and its construction and equipment involved the application of much time and labor to the consideration of the innumerable technical details. Acting as the representative of the chemistry department in these matters, a considerable proportion of this work fell to his lot and constituted his principal occupation during the years of construction and equipment. Boltwood had thus much to do with two important laboratories of Yale University, the Sloane Physics and the Sterling Chemistry. The work with the latter was so severe that his health broke down under the strain and in 1924 he was forced to ask for a half-year leave of absence to regain his health. He spent this time principally at Chapel Hill, North Carolina, where his former partner in his private laboratory in New Haven, Joseph H. Pratt, is professor of economic geology at the University of North Carolina. The rest from work, change of scenes, and renewal of former friendship with his friend, had a salutary effect on his health and he returned seemingly in good health and cheerful spirits. He applied himself to research with zeal and carried on work on the chemical separation of thorium and other radioactive elements and his notebooks show a large amount of work done. However, his recovery in health was apparently not complete, for he had two more periods of depression and although he again apparently recovered, there was a recurrence of this to some degree again in the summer of 1927, when he ended his own life in Maine where he went to recuperate. He died during the night of August 14-15, 1927, at Hancock Point, Maine.

Boltwood was liked by his friends for his great personal charm and his wide acquaintance with things outside of his science. He found good in everybody with whom he came in contact and was always ready to spend his time and his energy in giving assistance. He had a great personal influence on students and he associated with them a great deal. He took interest in their sports but he himself participated only very moderately and when he did he gave preference to swimming, sailing and walking. His hobbies were photography and in later years "playing" with radio circuits.

In regard to his own work and his contributions to science he was amazingly modest. For biographical works for which he was asked to supply personal data he gave, regarding his work, only: "Contributor to scientific journals." For all that, his contributions speak for themselves and the scientific world knows their worth and gives him its appreciation of it. He remained unmarried.

Boltwood was a member of the National Academy of Sciences (1911); the American Physical Society; the American Chemical Society; the American Philosophical Society of Philadelphia; the American Academy of Arts and Sciences of Boston and the Connecticut Academy of Arts and Sciences. At Yale he belonged to the Sigma Xi, Aurelian Honor Society, Book and Snake and the Cloister Society.

A bronze tablet was placed, in July, 1929, to his memory in the halls of the Converse Memorial Library at Amherst College. It reads:

> IN MEMORY OF BERTRAM BORDEN BOLTWOOD
> July 27, 1870—August 15, 1927
>
> Born in the house of his grandfather on the site of this building and later professor in Yale University.
>
> He was
>
> The Discoverer of ionium and its genetic relation to uranium and radium,
>
> The Demonstrator of the chemical inseparability of certain elements which is the basis of isotopy, and
>
> The Developer of the radioactive method for estimating the age of the earth.
>
> SCHOLAR TEACHER SCIENTIST
>
> BELOVED AND HONORED FRIEND OF ALL WHO
> KNEW HIM

Sources used for this memoir are as follows: The scientific papers of Bertram Borden Boltwood as given in the appended bibliography; scientific notebooks, diaries and personal papers left in his estate to his heir, Lansing V. Hammond; the various genealogical records and papers pertaining to the Boltwood family in possession of Miss Fanny Haskins Boltwood, Goshen, Massachusetts; private information relating to Van Hoesen family from Bertram B. Boltwood's aunt, Miss Albertine Van Hoesen, New York City; "Ralph Waldo Emerson: His Maternal Ancestors" by David Green Haskins, published by Cupples, Upham and Co., Boston, 1887; records of Yale University, Albany Academy and Amherst College; Boltwood's autobiographical sketch in "Biographical Sketches, Class of 1892 S, Yale"; "Who's Who in America," volume 13; "American Men of Science," 3rd ed.; biographical sketches prepared by me for the *Yale Scientific Magazine,* volume 2, 1927, for the American Journal of Science, 5th Series, volume 15, 1928, and for the "Dictionary of American Biography," volume 2, 1929; and besides these, also my personal knowledge of Boltwood beginning with acquaintance in Sir Ernest Rutherford's laboratory at Manchester, England, in 1909, which developed and continued as intimate friendship through the rest of his life.

I desire to extend my thanks to those who assisted me by giving me information and permitting me to use available records in their possession, and in this respect especially I wish to thank Mr. Lansing V. Hammond and his mother Mrs. Fanny Reed Hammond, Miss Fanny Haskins Boltwood and Miss Albertine Van Hoesen.

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