

the methods of exact atomic weight determination of which Richards was the world's master. Hönigschmid was interested in America and Americans. We usually lunched together and in the unusually hot summer months spent much holiday time at the beach on the Danube. The beach had three sections, one for males, one for females, and one for members of both sexes admitted together at the entrance. If girls or men wished to enter the mixed bathing they could wait until some one of the opposite sex arrived with the same desire and form couples or parties, which might dissociate as soon as entrance was gained. Hönigschmid and I sometimes availed ourselves of this opportunity. A large well-supplied restaurant served bathers—in their bathing suits if they wished.

Hönigschmid continued assiduously his work on the purification of radium salts, the atomic weight of radium and the establishment of large standards which were found to agree closely with the Curie official standard. He later married and became Professor in the University of Munich, where he continued his research for many years. After the Second World War when Munich was being occupied, Hönigschmid and his wife both committed suicide rather than give up their apartment to the enemy, which I regret was said to be American. The largest of the old Vienna standards (about 600 mc) was recently opened safely for fear it had developed a dangerous gas pressure.

After World War I, Paneth moved to England where he was well received and enabled to carry on research until his death. He became an authority on the helium content of meteorites and the determination of their ages. Professor Prizbram remained in Vienna and continued research there, particularly in the coloring of salts or minerals and their radio-photoluminescence.

Professor Meyer and his family left Vienna during World War I, and retired to Bad Ischl, where his family had its ancestral seat. Both Meyer and his wife came of wealthy families but both were hard struck by the War. One evening in Minneapolis some years ago I received a telephone call from a young man who said he had just returned from his military service in Austria and brought me greetings and a note from Professor Meyer. The young man kindly accepted my invitation to give me an account of his stay in Bad Ischl. His regiment had been quartered there and he was living with other young officers in the home of Meyer, who with his family had moved into his "Hinterhaus" formerly occupied by the family servants. He had seen Meyer often, but more frequently talked with his daughter, Agatha, who spoke English more fluently. Meyer's note was on a small scrap of paper, showing how he and Austria had been impoverished by the war. But the note was cheerful and uncomplaining. While American troops lived in Meyer's house, their senior officers were living in the

former home of Johann Strauss across the street. Agatha Meyer kept up correspondence with some of the American officers.

Upon my completion of the work on ozone in August it was nearly time for the meeting of the British Association for the Advancement of Science in England, where I was to meet Dr. G. N. Lewis. I regretfully left Vienna and have never had the good fortune to return nor of seeing again any of the friends I met there except Professor Hess, who came to America during World War I and was employed by the U. S. Radium Corporation. He later returned to Austria, only to encounter trouble and deprivations in World War II. He then returned to New York permanently and became Professor and head of Physics at Fordham University, where he remained.

The Institute for Radium Research in Vienna has continued its activities and publications. Its present Director, Dr. Berta Karlik, succeeded Professor Meyer upon his retirement. She has been in the United States several times, and has been the guest of Dr. Elizabeth Rona of the Oak Ridge Institute of Nuclear Studies. The publications emanating now from the Institute show it is recovering its position among the centers of radioactive research.

The Institute of Radium Research was at the time of my visit one of the three great centers of research in radioactivity in Europe, the others being the laboratories of Professor Rutherford in England and of Madame Curie in Paris. Under the able direction of Professor Meyer the Institute attracted a small but brilliant group of research workers, but later (during World War I) lost them all but Prizbram. Fortunately they were all able to continue their researches in their adopted countries to which they managed to escape, Hess in the United States, Paneth in England, Hönigschmid in Germany. One American was trapped in Vienna for the duration but was able to obtain permission to carry on his work in the Institute.

The city of Vienna has always been one of the most attractive in Europe, perhaps next to Paris both in beauty and popularity. Its cathedral and other fine buildings, its layout of avenues and boulevards in the inner and outer city, its old walls remaining from feudal times, all add to its physical attractions. But these external beauties were not exceeded by the contributions from the cultural side, its superb composers, exquisite music both classical and popular, its unexcelled symphony orchestra. That Vienna is today more or less free from the domination of Communism is due to the insistence of its people on retaining their time-tested way of life. Of course the Austro-Hungarian Empire is a thing of the past but Austria and Vienna are themselves better off in being free of the shackles binding them to their former associates.

CHAPTER 8

CARNOTITE IN COLORADO

Early in 1913, while I was still at the University of Michigan, my attention was called to a U. S. Civil Service announcement of an "unassembled" examination for

chemists with some knowledge of radioactivity to work in the newly established U. S. Bureau of Mines laboratory in Denver on the recovery of radium from Colo-

rado carnotite. The opportunity seemed so attractive that I immediately applied and filled out the examination papers, which consisted only of one's record of education and experience. My hope was to gain access to a supply of radium to continue my researches in radiation chemistry using radon as source of alpha rays.

Fortunately my training abroad was given a high rating so that I ranked a few points above the next applicant. I think R. B. Moore, in charge of the work in Denver, would have preferred the second man, who had worked under him at the University of Missouri, and in whom he had well justified confidence. Moore could have passed over me, since the law allowed appointment of any one of the first three ranking applicants. Instead, he consulted his chief in Washington, Dr. Charles A. Parsons, Head of the Division of Chemistry of the Bureau of Mines. Parsons invited me to Washington. I was especially glad of this opportunity to meet him, already the Secretary of the American Chemical Society and possessing an early vision of building it into the great institution he later made it. Parsons then (1913) had but one secretary for the entire Society, and its activities and records were confined to two rooms (rent free) in the Bureau of Mines. Later, on giving up his position in the Bureau of Mines in order to devote full time to the Society, he rented a suite in an office building near the White House, before expanding to an entire floor in the same building. Compare this modest beginning with its present status representing a membership of about one hundred thousand under Parson's trainee and direct successor, Dr. Alden H. Emery. Parsons received me well and after going carefully into my qualifications decided to give me the appointment, to begin at the close of my academic year at the University of Michigan. This gave me some time to familiarize myself with carnotite and to practice uranium and vanadium analysis.

I arrived in Denver on my 34th birthday in 1913. After a cordial welcome from Moore I was introduced to the staff. I remember that Tracy Mulligan, the Chief Clerk, as he was officially designated, raised his eyebrows and twitted me when he noticed I had arrived with a golf bag. Evidently he thought me an inveterate playboy. We became good friends later. He found I confined my golf to Saturday afternoons and Sundays.

My closest associate in our Denver work was a graduate of the University of New Hampshire (under Parsons), Charles Whittemore, an excellent chemist who some years later worked for one of the radium-producing companies where he must have had too heavy exposure. Afterwards he was employed on other work but succumbed to a malignancy believed to have been induced by his earlier work with radium and mesothorium, which latter is even more hazardous. There was, of course, no certainty that his ailment was caused by radioactivity. None of our other scientists or plant workmen was ever affected by it, as far as we knew.

The principal objective of the Denver laboratory was to investigate carnotite (a potassium uranium vanadate deposited in sandstone) as source of radium, vanadium, and uranium, the three valuable constituents. Genetically, radium should occur in any uranium-bearing min-

eral in the proportion: 1 part radium to 3,000,000 parts uranium by weight. To verify this we analyzed about 30 specimens of carnotite from various deposits in Colorado and Utah. In all samples from lots of several tons of ore we verified the constancy of the genetic Ra:U ratio and gave it a slightly different value. This constancy was commercially important because carnotite, previously sold abroad for its radium, had been subjected to a penalty of 10%, on the claim that its radium content was that much below the genetic equilibrium with its parent uranium. All radium ore was bought and sold by the uranium content because it could be determined by direct chemical analysis as radium could not be.

In small hand specimens of ore, however, we found varying ratios of radium to uranium, higher than equilibrium in some, lower in others. This we attributed to weathering—removal of radium from one part of the ore bed, thus lowering the ratio, and depositing it in another part, so as to raise it. But when large portions of the ore bed were removed, thoroughly mixed, and correctly sampled, the ratio was *normal*, as we found it. The 10% penalty was accordingly discontinued, to the immediate advantage of American producers.

Whittemore was an excellent analyst and I had practiced on the analysis of carnotite at the University of Michigan while waiting for the expiration of the academic year in June when I would report to Denver. We therefore had considerable confidence in our analyses and were surprised when a sample representing several tons of ore showed a radium content some 30% below normal. Karl Kithil, the engineer in charge of the mining and purchase of ore, also became suspicious and examined the sample under the microscope. He was able to pick out several crystals of *uranium phosphate*, a yellow substance resembling carnotite in color, which had evidently been added to raise the uranium content and thus give a spurious radium value. We also confirmed this by direct radium analysis. Upon being confronted, the seller confessed the fraud and was permitted to make up the difference in good ore. I do not know why he was not prosecuted for fraud, but imagine the Bureau wished to obtain more uranium ore from him, now that he knew he must be honest.

Carnotite was not acceptable at that time with less than 2% uranium oxide, because of the higher cost of extracting radium and vanadium from lower grade ore. Vanadium had ready sale for alloying in steel, but had no genetic relationship to uranium, hence no constant ratio. Our ore usually carried about twice the percent of vanadium as of uranium. At that time uranium itself had little value and could be sold only in small lots for coloring glass and silk. Nevertheless we thought it too rare to be discarded and recovered all of ours (about 30 tons) after extracting the radium and vanadium and converting it to the black oxide UO₂. I shall refer to it again.

After confirming the value of Colorado carnotite as a source of radium, the Bureau of Mines found two men interested in radium as a therapeutic agent. Dr. Howard Kelly of the Johns Hopkins University Medical School wanted it for his cancer clinic on Eutaw Place,

Baltimore, and Dr. James Douglas, President of the Phelps-Dodge copper mining company wished to make a gift to the Memorial Hospital in New York City, which he had established in honor of a daughter who had died of cancer. These two men organized a corporation known as the Radium Institute and arranged with the Bureau of Mines to produce radium for them under a contract by which they would meet all the expenses of mining and production except the salaries of the regular employees of the Bureau. The initial amount of the contract (\$150,000) would today seem, and be, quite inadequate for such an undertaking. Nevertheless, a small plant for grinding and treating the ore was constructed in south Denver and put under direct supervision of Richard B. Moore reporting to Charles Parsons, in Washington. The Bureau of Mines was then under the direction of Joseph A. Holmes, who upon his death in 1915 was succeeded by Van H. Manning, who remained in charge during the remaining period of the contract.

This put the job of devising and operating a suitable process squarely up to the Denver staff. Sir William Ramsay had suggested a chemical process to Moore, by which carnotite should be treated by an acid that would dissolve radium, rather than by the much cheaper sulfuric acid that would precipitate insoluble radium sulfate, difficult to recover and treat to obtain radium. This meant either hydrochloric or nitric acid as extractant. We soon found that nitric acid was somewhat better. Unfortunate as this was on account of its higher cost, its better extracting power would justify the use, if we could recover the nitrate so as to use it again after regenerating the acid. This we learned to do, so that only 10% of nitric acid was lost in each cycle.

The first operation of extraction was carried out under my supervision using hot 30% nitric acid, in large earthenware pots, in the top of the Denver plant without any hoods or ventilation. Vast clouds of red fumes of nitric oxide poured out around us, but we had to continue without allowing the equipment to cool and thus lower the extraction. It was a miracle we were not all killed. Nitric fumes are very treacherous. They are not unpleasant, even sweetish at the time of inhaling them, but are busy nitrating the tissues of the throat and lungs nevertheless. I remember waking up in the middle of the night with an uneasy shortness of breath and some pain in my lungs. But this persisted only a few hours and next day I was all right. Needless to say we installed hoods, with strong draft over each pot, before beginning again and teaching the workmen to take over the operation.

And so it went on. As soon as we learned in the laboratory downtown how to do the next operation, we went out to the plant to install it and teach the men there to carry it on. But the plant extraction got ahead of us. We had accumulated acid extract and radium-barium sulfates from five carloads of ore before we knew the next step, the enrichment of the radium by separation from barium. Radium is chemically similar to barium to such an extent that their salts act as if they were isotopic—practically inseparable. This is good in the extraction, for the barium originally in the ore (or

added) brings the radium out with it as nitrate. Then the problem is to separate them. It is like sending a dog in for the rabbit and then having to rescue the rabbit.

We wished to avoid fractionation by crystallization of the chlorides. Each step is long and excessively many are required. Also, we always added some barium in the extraction to ensure enough dogs for the rabbits. We sought an initial ratio of 1 million barium to one radium. We thought fractional precipitation as sulfate might be a quicker method of enrichment, though our avoidance of sulfuric acid as extractant should have taught us better. To a large amount of our radium-barium nitrate solution we added enough sulfuric acid to precipitate one-tenth of the barium in hopes of some separation. But our analysis quickly showed that the precipitate had exactly the same ratio of radium to barium as in the parent solution. We wasted no more time in this effort but quickly adopted fractional crystallization, which Madame Curie had devised and used. First at the plant by successive fractionations we brought the ratio down to 1000 barium to 1 radium, then at the laboratory to about 1% radium. Each day's collection was then sealed for a few days for radium measurement by γ -ray comparison against a radium standard. At the end of each month, all the daily collections were opened, thrown together, and in two or three days stepped up by an experienced crystallizer to any desired enrichment, usually about 50% radium. The month's radium was then divided into two equal halves, one for Baltimore, one for New York, but first to the Bureau of Standards for measurement, according to the contract.

Naturally we had stepped up some radium chloride to 100% and prepared our own unofficial standards, which were much higher in radium content and, we thought, superior to the U. S. Bureau of Standards secondary smaller standard. Our standards were necessarily made from ore bought by the Bureau of Mines outside the contract with the National Radium Institute. Also under the contract, our deliveries of vanadium had to be assayed by A. R. Ledoux of New York, who made excellent analyses.

The opening of a tube of the month's collection of high percent radium chloride, to divide between Baltimore and New York was ordinarily a simple operation. (Today the close contact and high exposure to radiation without shielding would not be tolerated). But on one occasion it was attended by unfortunate results. I was opening a glass tube containing 400 mgs of radium element as high grade chloride salt. Ordinarily the salt ($\text{RaCl}_2 \cdot 2\text{H}_2\text{O}$) is thoroughly dehydrated to RaCl_2 by heating for some time at 250°C to remove water which under the α -radiation would be decomposed to hydrogen and oxygen thus producing high gas pressure in the small volume of the tube. But on this occasion the man responsible for the dehydration had made a bad blunder. (I do not name him). Some one had used his electric furnace at a temperature of only 105°C by substituting a heating coil with higher resistance than that of the usual one, and had left it so without changing back to the original coil. Not noticing his low thermometer reading the operator placed his salt in the

furnace and exposed it the usual length of time for dehydration. But the water of crystallization, still there, proceeded to decompose under the α -irradiation, gradually giving a high gas pressure within the small tube containing the radium chloride. The glass tube withstood the pressure until the moment when I scratched it with a file for opening. There was a violent rupture. Most of the radium salt was ejected and scattered across the room sprinkling the highly active salt on an oily motor and radioactive dust over the entire room. Despite all efforts of recovery, only about 90% of the salt was recaptured by washing the walls, floor, ceiling and all other objects in the room for over two weeks. The rest (44 mgs) must have been lost as fine dust. I evidently inhaled some, as I was not masked and protected only by gloves and a glass shield. My urine showed radioactivity for a few days but I suffered no permanent consequences.

Although I was continuously exposed to excessive radiation in all my earlier work, I suffered only one exposure that had evident consequences. In 1919 I carelessly held a drawer containing several hundred milligrams of high grade radium salt, with no protection except the glass wall of the tubes and the thin wooden floor of the drawer. Of course, I received no alpha radiation, but the intense beta and gamma rays reached the palm of my hand and produced a "burn." One feels nothing at the time, but three days later the palm became reddish and began to be sensitive to pressure. The red spots increased in size and number up to ten days when they united into one water blister about the size of a half dollar and half an inch high. There was only slight pain, which could be relieved by draining the liquid with a sterile needle once or twice a day. I went on with my work as usual. After about a month the burn ceased to suppurate and was covered by a hard scab. In time this came off leaving only a whitish scar which is still visible. I have had no after effects although such radiation burns are said to end sometimes in cancer formation. This could still occur, but after forty years I do not fear it.

Professor Robley D. Evans of the Department of Physics of the Massachusetts Institute of Technology was very desirous of knowing how much radium might have been permanently deposited in my system, replacing to some extent the calcium in the bony structures. For some reason, not clear to me now, I had not submitted to a measurement, although I suspected I carried some excess which, owing to its long life of 1620 years, would be quite permanent. Upon one occasion when Mrs. Lind and I, upon a visit to Professor Evans in his laboratory, were engaged in conversation with him, I became aware of a counter clicking away behind my back and it was evident that he was taking advantage of the occasion to get my measurement. I submitted willingly and was glad to learn what I carried about in my system. [He permanently carried about $\frac{1}{4}$ of a microgram of radium in his body.]

The great precautions now recommended by authorities of health physics to assure that no radioactive substances are introduced into the bodies of human beings are in sharp contrast with ideas that prevailed in the

early period of atomic energy. Belief in the virtue of radioactivity was so strongly entertained that its introduction by any means into the system was recommended. I recall that I once charged a liter of water with about 200 millicuries of radon and gave it to my wife to drink for possible benefit to her health. Fortunately the solubility of the inert gas radon is not great, so that it quickly disappears from solution. This together with the short life of the immediate decay products Ra A, B and C probably saved Mrs. Lind from any deleterious consequences which probably would have resulted had it been an equivalent amount of the longer lived and less volatile parent element, radium. Whether she obtained any benefit was not evident since her health was already excellent.

I forgot to say that before we had made any deliveries, the original \$150,000 approached exhaustion. But the Institute was so sure of our ultimate success that it raised the total to \$500,000. This proved to be good judgment. When the work was concluded, we had produced $8\frac{1}{2}$ grams of radium element in the form of RaCl_2 , worth more than \$1,000,000, at the then prevailing price of \$120,000 per gram. And the income from sale of vanadium reduced the cost to \$40,000 per gram. The principal commercial producer of radium objected that this estimate of cost was too low because of the subsidy of Bureau of Mines salaries for the scientists employed in the work. But even after allowing for that, our costs were lower because of his long freight haul of ore from Paradox Valley to Pittsburg, and the less efficient process used there. Unfortunately, the same producer had let all of his uranium, a much greater amount than ours, go down the drain. Today it would have high value.

We had a contract for the sale of our by-products, both vanadium and uranium, to an Eastern steel company, based on the current market price. There was no difficulty selling vanadium. It brought a return which helped to lower the net cost of our radium. But the contracting company would never order any delivery of uranium. Nevertheless we continued to recover and convert it to high grade UO_2 , the black oxide. To keep a uranium price established, we sold small lots of uranium produced from ore not subject to the contract. Finally, when our work was finished, the Radium Institute brought suit in Federal court in Delaware to force the steel company to take our uranium at market price according to the contract. The company resisted on the ground that there was no market for uranium, hence no market price, and no obligation to take any uranium. We produced bills of sale for the small lots we had disposed of, but the case dragged on in court and might have been lost but for a very ludicrous incident. A lawyer for the steel company produced a file of letters which he said were from companies saying they had no use for uranium and would not buy any. But the file he threw on the table was a fatal exhibit. Our lawyer picked it up and after glancing at the top letter asked permission to read it to the court. It was from a larger steel company stating it was greatly interested in uranium as a possible component of alloy steel and would like to purchase quite a quantity for experimental

purposes. The entire courtroom burst into uproarious laughter. Our opponents' lawyers asked the court for an intermission and retired with red faces. After a short intermission and retired with red faces. After a short intermission they returned with two alternatives for compromise, either to buy at a low price, or to pay \$35,000 damages and let us keep the uranium. We accepted the second offer in the belief that uranium would some day become valuable, since it was rare and possessed the highest then known atomic weight. How we would have been set up as prophets could we have looked forward to 1940, to Uranium-235, atomic power, and, alas, the atomic bomb.

As a consequence, our 30 tons of uranium oxide remained in storage in Colorado until the dissolution of the Radium Institute. Then it became the property of Archibald Douglas, the son-in-law and heir of Dr. James Douglas, one of the two founders of the Institute. The entire lot was shipped East to Mr. Douglas and I wonder if it may still be hiding in some old barn, forgotten—awaiting the day when it may be discovered and brought forth to participate in the modern uses for atomic fission and nuclear power. Incidentally, it may be mentioned that the present high price of uranium extends its acceptability from 2% ore down to 0.1%. This widens the ore fields greatly, and the high demand brings a monthly production exceeding our Colorado accumulation extending over four years.

The total produced in Denver for the Institute was 8½ grams of radium element. Under the contract, more than two grams became the property of the Bureau of Mines. This division disappointed the Institute and it applied to the Bureau to remit a greater proportion. The Bureau found it had no authority to make *donation*, but agreed to a *loan*, divided equally between the New York and Baltimore clinics, leaving ½ gram to the Bureau for scientific research. This decision had both happy and unhappy consequences. The two clinics had to keep the Bureau's loan separate from their own radium. This meant that in the collection of radon from the radium solution for therapeutic use, two separate systems must be operated daily for one or two hours each. This kept the operator exposed twice as long to radiation, which may have contributed to the untimely death of two operators in Baltimore before sufficient shielding was provided.

After many years of operation, the Baltimore clinic was closed in 1952 and the building in Eutaw Place was condemned as contaminated by radioactivity. The populace became so alarmed that many would not pass near the building and, according to the papers, the city is considering whether to decontaminate the building or to tear it down. In Cincinnati also, rather extreme measures were taken with a building that became contaminated by an accident with a moderate quantity of radium used in making luminous paints. The New York Memorial Hospital clinic has, so far as I am aware, been free of unfortunate incidents and its radium is still used therapeutically.

All of the early American companies that produced radium have now ceased to operate. The supply from the Belgium Congo ore enabled a price to be set in Belgium just below the American cost of production.

Production later began in Canada and continued for many years giving a large supply. The use of radium has greatly diminished, owing to competition of x-rays of high energy, and of γ -radiation from Cobalt-60, which is artificially prepared and is now available in large quantity at low cost. Consequently both the price and production of radium have sunk to a low level. And the prejudice against its use, promulgated by the authority of Health Physics, has almost put it out of use, both in therapy and scientific research.

But let me revert to the happy consequence of radium production by the Radium Institute already referred to. It gave to the Bureau of Mines a half gram—quite sufficient for scientific uses. While I was still in Golden at the Colorado School of Mines station of the United States Bureau of Mines, the Bureau entrusted me with the entire half gram of radium. This was the goal that had taken me first to Denver four years earlier and had kept me busy during this entire time in the radium work, all the long way from laboratory methods through installation and supervision of plant operations. This same radium has remained with me through the years—in Golden, Colorado; Reno, Nevada; Washington, D. C.; Minneapolis, Minnesota; and finally Oak Ridge, Tennessee. It has been constantly used in studies of radiation chemistry and has provided research material for some two dozen collaborators and graduate students.

Even during the production work we got in a little incidental research. Frank Whittemore and I made an authoritative determination of the radium: uranium ratio in carnotite, which we published in the *Journal of the American Chemical Society* in 1914 (36, 2066). I published three papers on radium analysis, the first describes an improved type of electroscope, the second, the emanation (radon) method, and the third, other methods, all in the *Journal of Industrial and Engineering Chemistry* (7, 406, 1024 (1915); 12, 469 (1920)).

In Golden, as soon as freed from the routine of radium production, I put my ½ gram of radium to research use. About half was devoted to radium standards of different contents, 150, 60, 10, and 1, mgs of radium element (as RaCl_2). These were used in measuring radon by γ -ray comparison. About 250 mgs of radium in the form of RaCl_2 were put into solution in 5% hydrochloric acid for the collection of radon.

The first chemical reaction studied in radiation chemistry, using radon collected from the Bureau of Mines radium just mentioned, was the combination of the gases hydrogen and oxygen to form water vapor. While hydrogen and oxygen combine readily at higher temperature and even explosively if their pressure and temperature are high enough, they do not react at all at ordinary temperature unless activated by some agent. It was therefore thrilling to find them uniting steadily at room temperature when mixed with radon as a source of powerful alpha rays, the doubly positively charged nuclei of helium produced by the spontaneous disintegration of radon and of its decay products RaA and RaC'.

The reaction proceeded as was to be expected, two molecules of H_2 combined with one of oxygen to form two molecules of water. As soon as the concentration

of water vapor reached the vapor pressure of liquid water, droplets began to appear on the wall of the glass vessel. Spherical vessels were used in order to simplify the calculation of the length of paths of the alpha rays within the sphere, which controls the amount of reaction they produce. Since radon is a gas, its alpha rays can originate at any point within the sphere or from its wall and travel in a straight line in any direction until again reaching the wall. Since the number emitted per second is very large, about 111 billion per second per curie, the law of averages applies perfectly. I therefore only needed to know the average length of all straight lines in all directions from all points within a sphere until they reach the circumference. I could not find anyone had ever needed to solve this geometrical problem or to use the relation, though possibly some mathematician, perhaps in ancient times, had worked it out for his own amusement and left it buried in a long forgotten parchment. The mathematics for this solution was solved with the aid of Professor Lunt of the University of Chicago and gave a very simple result. *The average of all straight lines from all points within a sphere to the wall is exactly three-fourths of its radius, and from all points on the inner surface in all directions to the wall is one-half of the radius.*

Estimations for volumes other than spherical indicate that the average of all straight line paths from all points on the interior surface in all directions until again reaching the wall is one-half of the radius of a sphere of equal volume; while that from all points within the volume is three-fourths of the equivalent sphere radius. This similarity to the sphere is restricted to volumes which have no re-entrant angles. A restriction in the calculation of effective path of ionization, common also to the sphere, is that no path shall exceed that of the diameter of the equivalent sphere. The relation seems to apply also to cylinders in which the ratio of length to diameter does not exceed about ten to one.

The hydrogen-oxygen reaction was also used to study the action and ionization by recoil atoms projected in the opposite direction from the emission of alpha rays from radon or from one of its decay products Radium (A) and Radium (C'). This is an example of how a physical problem may be solved by chemical means [*J. Am. Chem. Soc.*, 41, 551 (1919)].

The reaction of hydrogen and oxygen under α -irradiation to form water vapor deserves some detailed consideration as having principles common to all radiochemical gas reactions. Both the hydrogen and oxygen molecules are separately activated by absorption of energy from the highly energetic alpha rays as they pass in straight lines through the electronic structure of the molecules. About half of the absorbed α -energy produces ionization of the molecule struck, i.e., removal of one or more of its electrons, usually one, sometimes two, rarely more. If more than one electron is removed the doubly charged molecular ion will at ordinary pressure soon encounter a neutral molecule of either kind and quickly (probably on first collision) extract an electron from it, thus giving two singly charged ions. Ionization is then one form of activation, but the energy expended by the α -particle in each collision is about twice that necessary to ionize. Evidently then some other

active forms are also produced. They may be neutral radicals or atoms. There is much question about their contribution to the reaction yield. In my early study of this reaction (*J. Am. Chem. Soc.*, 41, 531 (1919)) I found that the effect of excess of either hydrogen or oxygen could be predicted on the basis that the change produced in the ionization of the gas mixture would change the reaction velocity correspondingly. According to Bragg the molecular ionization of oxygen is 1.09 and of hydrogen 0.24, compared with air (1.00). Consequently an initial excess of oxygen increases the relative action velocity, which continues to rise as the mixture is enriched in oxygen by the chemical reaction. Exactly the opposite is the case with excess hydrogen.

The ion yield, the number (about 4) of water molecules formed per ion pair by radon, in an electrolytic mixture of hydrogen and oxygen can be interpreted by the assumption of clustering of neutral-molecules about the positively or negatively charged ions through electrostatic attraction. Since negative ions of hydrogen are not formed, the electrons are free to attach themselves to and activate oxygen which has high affinity for electrons. The cluster theory lacks a good theoretical basis, but experimentally reaches its highest degree of probability through the common value (4) found in the oxidations of H_2 , CO and CH_4 , very different types of molecules, with quite different stopping powers (absorption) and specific molecular ionizations. The products are four molecules of water per ion in hydrogen and oxygen mixtures; four molecules of carbon dioxide in oxygen-carbon monoxide mixtures; two molecules of carbon dioxide and four molecules of water vapor per ion in mixtures of methane and oxygen. In none of these do the ion yields just given depend on the mixtures being stoichiometric. But, of course, the total ionization per length of α -particle path is increased in a mixture with excess of component having the high stopping power (absorption), for example, oxygen in its mixture with hydrogen. This increase becomes greater as the reaction proceeds to remove hydrogen. In a mixture with initial excess of hydrogen the stopping power would be lower and increasingly lowered as the reaction removes oxygen, thus increasing the $\text{H}_2:\text{O}_2$ ratio. In carbon monoxide and oxygen the stopping powers differ by only 15% and in methane and oxygen by still less, but in the latter case two gaseous products are produced, and interchange of activity by ion exchange according to their individual ionization potentials complicates the theory of prediction. Nevertheless the ion yield for the consumption of methane and oxygen is surprisingly constant over 90% of the reaction, which is difficult to interpret.

But I must not leave Colorado and carnotite without mentioning two happy events that had little to do with carnotite except that it brought me to Colorado. In 1915 I courted and married Marie Holladay of Omaha, Nebraska. She has accompanied me in all my wanderings since then as mentioned in the previous and succeeding paragraphs. Also in Colorado our son Thomas was born, who was with us in Reno, Washington, and Minneapolis, until he himself married and moved away to Oklahoma and last to Freeport, Texas, where he is a chemist with the Dow Chemical Company.