MEMOIRS

OF THE

NATIONAL ACADEMY OF SCIENCES

Volume XXI

TENTH MEMOIR

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON
1927

NATIONAL ACADEMY OF SCIENCES

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TENTH MEMOIR

BIOGRAPHICAL MEMOIR EDWARD WILLIAMS MORLEY

1838-1923

BY

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PRESENTED TO THE ACADEMY AT THE ANNUAL MEETING, 1924

Edward W. Morley.

EDWARD WILLIAMS MORLEY

By Frank Wigglesworth Clarke

Edward Williams Morley was born at Newark, N. J., January 29, 1838, and died at Hartford, Conn., February 24, 1923. His father, Sardis Brewster Morley, was a Congregational minister. His mother, whose maiden name was Anna Clarissa Treat, had been a teacher in a girl's school; and Catherine Beecher, the head of the school, said of her, "Clarissa Treat can make girls learn who can't learn." She was evidently a good teacher. Both parents came of early colonial stock, and of purely British origin. The Morley ancestry has been traced back as far as 1681, all in the Connecticut River Valley; but beyond that date the records are obscure. There were men of the same name in eastern Massachusetts as early as about 1630, but no connection between them and Edward's family has been traced.

Soon after Edward's birth the family moved to Hartford, where they remained until 1851. Then his father accepted the pastorate of a Congregational church in Attleboro, Mass. In 1857 they moved to Williamstown, Mass., in order to put Edward and his two brothers through Williams College, their father's alma mater.

In his childhood Morley suffered from ill health, and until he reached the age of 19 his education was carried on at home. His father was his teacher. He learned to read before he was 3 years old, began Latin at 6 and Greek at 11. I gather this information, and much that follows, from some autobiographical memoranda, in Morley's own handwriting, which now lie before me. These memoranda give clear information as to the influences which led him to a scientific career, and how he happened to become a chemist.

When Edward was quite a young lad he found among his father's many books one entitled, "Conversations on Chemistry," which fascinated him even more than the Arabian Nights, that stood near it on the same shelf. When 12 years old he spent all his pocket money on chemical experiments, which he carried on until he entered college. At about the age of 14 he obtained a copy of a textbook on chemistry by Benjamin Silliman, and, says Morley, "this was so much studied that when the subject was taken up in the junior year of my college course there was not much left to be learned." That means, of course, from such books as were within his reach.

At the age of 19 Morley entered Williams College. His preparation for college had been so thorough that he was able to skip the freshman year and to enter with advanced standing as a sophomore. He graduated in 1860 as A. B., and was valedictorian of his class. In 1863 he received his master's degree. A classmate said of him, "Morley recites everything as if it were the most interesting subject he knew," a saying which well describes one of his dominant mental characteristics. He was thorough in everything that he undertook.

Under Prof. Albert Hopkins, astronomy became a fascinating study. It was perhaps not so interesting as chemistry, but it provided an opportunity for the study of methods of precision which was not possible in any other subject at that time and place. Morley, while remaining at Williams for further study, mounted a transit instrument in the prime vertical, constructed a chronograph with Bond's spring governor, and determined the latitude of the college observatory, which so far was known only by sextant observations to within about five seconds of arc. Morley's determination was the subject of his first published paper, which was read before the American Association for the Advancement of Science in 1866. He also read much in the Méchanique Céleste of LaPlace. Furthermore, in a work on astronomy which was read in college, Morley found the statement "that if all the members of the solar system were suddenly brought to rest, they would all fall in straight lines to the center of gravity of the system." Morley called the attention of the editor of the book to the fact that the statement was erroneous, and at his request wrote a paper establishing the configuration of the system that would be required in order to make the statement true. This paper was not

intended for publication. These details I take almost verbatim from Morley's personal memoranda. This early work is a forecast of his later career, and illustrates his intense devotion to accuracy. He might well have become an astronomer, but chemistry was his first love.

It has already been said that Morley's father was a clergyman; and so, too, was his mother's only brother. Quite naturally it was decided that he should follow their example, and so in 1861 he entered Andover Theological Seminary, where he completed the course of study in 1864. It was here, doubtless, that he added to his knowledge of Latin and Greek a good working knowledge of Hebrew.

Morley's health was still poor, and he felt unable to undertake the duties of a minister. The Civil War was nearing its end, and during the year 1864–65 he was in the service of the sanitary commission, and was put in charge of their station at Fortress Monroe, Va. The next year he resumed his studies at Andover, and in the years 1866–1868 he taught in the South Berkshire Academy, at Marlboro, Mass. What subjects he taught is not stated.

His health was now restored and he sought for an opportunity to enter the ministry. Presently he was called to a small church at Twinsburg, Ohio. At about the same time he was offered and accepted the chair of natural history and chemistry in Western Reserve College, at Hudson, Ohio. In this very mild contest between science and theology, science was victorious. This was the turning point of Morley's career. He might have succeeded as a clergyman, for he was conscientious in all his varied kinds of work. He was an admirable lecturer, and doubtless would have been a good preacher; but what a loss to science had he chosen the other path. In scientific research Morley found his true vocation.

When Morley assumed his professorship at Hudson his opportunities for anything like original scientific work were small. The college, like nearly all American colleges at that time, had the old-fashioned fixed curriculum, in which the so-called classical languages were given the first place, and the natural and physical sciences were subordinate to them. The languages were supposed to be the essentials of scholarship; and a man who was deficient in Latin and Greek was not regarded as a scholar. Mathematics was taught as a matter of course, but was not carried very far. The observational and experimental sciences were mainly if not entirely taught by lectures and recitations, which might give some useful information but hardly any mental discipline. Few students were brought to realize that great new branches of knowledge had been developed, which were not only alive but also rapidly growing. Shortly before moving to Hudson, Morley married Miss Isabella Ashley Birdsall, of West Winsted, Conn. They had no children.

It is easy to see that Morley entered upon his duties as a college professor under a heavy handicap. He was called upon to teach, in addition to chemistry, two other sciences, namely, geology and botany, which left him little time for research. For the students the conditions were equally unfortunate. The college curriculum allowed so little time for instruction in any branch of science that even the brightest student could hardly get any real insight into the true significance of his studies.

Morley, however, was not easily discouraged. In spite of difficulties, he fitted up a small room as a chemical laboratory, and his pupils were given their first experience in laboratory practice; that is, they were taught to experiment, to observe facts accurately, and to draw correct conclusions from what they saw. They gained a new kind of mental discipline, of which the classicists had never dreamed. In this mode of teaching Morley originated nothing. He was merely a pioneer in the work of the smaller colleges; work in which the older American universities had already gone far. In the universities of continental Europe the laboratory methods of instruction had long been established, and American students who were able to do so went to France and Germany for advanced training in the sciences, and especially in methods of research. Morley had not had the advantage of foreign study, but he saw the light and followed it. At quite an early date he was even able to offer his students a course in qualitative analysis. Few of the smaller colleges went so far.

Professor Tower, in his biographical notice of Morley, of which I venture to make free use, says that his teaching—

was always inspiring. He insisted not only on a mastery of the principles of chemistry, but he also inculcated the proper use of the English language, good manners, and clear methods of expression. In a word, he made a course in general chemistry a liberal education in itself. This he could do very effectively while the classes were small, but after 1900, as the classes grew larger, he confessed he had not accomplished all he had hoped for. This made teaching less a pleasure to him, and he was not sorry to give it up in 1906. His former students always speak of him with great loyalty and acknowledge the helpful influence of his teaching.

In the college at Hudson, as in all other small colleges, the salaries paid the professors were small. Morley, therefore, found it desirable, and perhaps necessary, to eke out his income by expert work, chiefly analytical, outside of his regular duties. I have no means of knowing whether he was often called upon to testify as an expert in court, but I do know of one amusing case in which he testified to good purpose. I have the story from his own lips, although I had already heard it from others.

The case to which I refer involved certain questions relative to sugar, and the day before the hearing the lawyer on the opposite side notified his friends that if they wanted to see some fun they had better be present and hear him cross-examine the professor. The cross-examination began, and after some preliminary questions the lawyer said: "Now, Professor Morley, what is the chemical formula of sugar?" "What sugar do you mean?" Morley replied. "I asked you, Professor Morley, to tell me the chemical formula of sugar." Morley repeated his former answer. "Professor Morley," said the lawyer, "you need not try to evade my question, but if you don't know the formula of sugar you are not qualified to appear as an expert in this case." "Well," said Morley, "if you don't know that there are at least 20 different sugars, you are not qualified to cross-examine me." The hearers were amused, but not quite as their legal friend had expected. This anecdote illustrates Morley's quickness of mind, and suggests that in his first reply he had laid a trap for the lawyer. He had doubtless heard many foolish questions from students, and knew how to deal with them.

In 1873 Morley added the professorship of chemistry and toxicology in the Cleveland Medical School to his other duties, which forced him to spend much time in traveling between Hudson and Cleveland. This position he resigned in 1888 when his other work made greater demands upon his time. In 1882 the college was moved from Hudson to Cleveland, where, as Adelbert College, it became a part of Western Reserve University. This meant an increase in Morley's opportunities for research, and at Cleveland, where he remained until his retirement, he carried out most of the larger investigations which made him known to the world as an experimentalist of the first rank.

During his residence in Cleveland Morley brought together one of the best private collections of chemical periodicals to be found in America. He even included in it a Russian journal, and learned enough of the Russian language to make use of it. After his retirement from teaching, the university bought his library, and it is now in the new chemical laboratory, for which he drew the plans, and which is now known as the Morley Chemical Laboratory. In 1906 he went to West Hartford, Conn., near the home of his boyhood, where he built a small house, with a garage, and also a laboratory, in which he made, with his usual thoroughness, many analyses of rocks and minerals. Of this work I shall have more to say later. Morley could not be idle. Indeed, for many years he was in the habit of working about 14 hours a day.

Except during Morley's early years his health was fairly good, which made it possible for him to perform his many and varied labors. Professor Tower says of him that—

his laboratory and classroom were on the third floor of the main building of Adelbert College, while his research work was carried on in the basement. He would make the trip up and down stairs scores of times a day, watching a class in quantitative analysis at the same time that he was engaged upon one of his most delicate operations in the basement. Out of curiosity he one day attached to himself a pedometer, and found that he walked about 20 miles when putting in a busy day. However, no constitution could withstand indefinitely this strain of long hours and hard work. In 1895 his strength gave out and he was granted a year's leave of absence, which he spent in Europe, resting and recuperating. This was the only full year's rest that he took during his teaching. . . . After his return in 1896 the college authorities granted him more assistance, and in 1898 the trustees voted to relieve him of as much teaching as he was willing to relinquish, so that he could give more time to research. He chose, however, to retain the course in general chemistry and the one in quantitative analysis.

These courses he continued to teach until he retired as professor emeritus.

In 1878 Morley began the series of investigations that made him famous. His attention had already been drawn to the fact that the proportions of oxygen in air were not absolutely constant, but subject to slight variations. What do these variations mean? That is the question that Morley sought to answer, at least in part, and his task was one of extreme delicacy. The solution of the problem involved the construction of elaborate eudiometric apparatus, with which the probable error of a determination of oxygen in air was not more than one four-hundredth of 1 per cent. The results of his investigation appeared in 10 separate papers, published between the years 1879 and 1882, three years of labor.

On one side Morley's problem was meteorological. Professor Loomis, of Yale College, had put forth the hypothesis that so-called "cold waves," those severe and sudden falls in the temperature of the air, were not due to horizontal currents moving from the north southward but to the descent of air from high elevations at times of high barometric pressure. The upper layers of the atmosphere were poorer in the relatively heavier oxygen than the lower layers near the surface of the earth. Hence, if the Loomis hypothesis is correct, the air collected during a cold wave should show a deficiency of oxygen.

Morley had already made analyses of air from different localities, and in 1880, during 110 consecutive days, he made analyses of the air at Hudson. Each determination of oxygen was made on the day that the sample of air was taken. To quote Morley's own words:

> The theory that the deficiencies of oxygen in the atmosphere are caused by the descent of air from an elevation fairly well agrees with the facts.

This cautious statement shows the scrupulous honesty of the man. A more positive assertion would have been justifiable.

An attempt to trace the workings of another man's mind would of course be rather presumptuous. To do that is the privilege of the novelist, who can create imaginary characters. It seems highly probable, however, that Morley's research upon the composition of air had much in it to suggest his next and most famous investigation on the composition of water; that is, on the relative atomic weights of oxygen and hydrogen. The transition from one research to the other was quite natural. An intermediate step was the determination of the amount of moisture retained by gases after drying by means of sulphuric acid, or over phosphorus pentoxide, for that was an essential preliminary to his work on the composition of water by volume; a study of the proportions by volume in which the two gases, oxygen and hydrogen, combine. The volume relations and the weight relations are not the same. In the determination of gaseous densities the first relation is needed as a small correction to the other.

Morley's work on the atomic weight of oxygen, that of hydrogen being taken as unity, covered a period of 11 years. Much time was spent in the detection of constant errors, and in making "assurance doubly sure" as to the purity of his materials. No precaution was overlooked, for the highest possible accuracy was his aim.

The determinations of atomic weight were made by two distinct methods. First, he effected the direct synthesis of water from weighed quantities of its component elements. The hydrogen was weighed as occluded in palladium, 600 grams of that metal being used. Secondly, he determined the density of the two gases, using the correction mentioned in the preceding paragraph. The results obtained checked each other within the admissible range of experimental uncertainty, and later determinations by other chemists have differed but slightly from Morley's. His final value for the atomic weight of oxygen was 15.879. The outstanding uncertainty is probably not much greater than 1 part in 10,000.

It is evident that this research of Morley's upon atomic weights was quite as much physical as chemical. Even while he was engaged upon it he found time to cooperate with others in some purely physical investigations. He worked with A. A. Michelson in the famous attempt to determine the relative motion of the earth and the luminiferous ether, and also upon the possibility of establishing a light wave as an absolute standard of length. With H. T. Eddy, and afterwards with D. C. Miller, he studied the velocity of light in a magnetic field. With Miller he also investigated the thermal expansion of air, nitrogen, and carbon dioxide. In connection with the latter research Morley constructed a new form of manometer by which differences of pressure as small as one ten-thousandth of a millimeter could be measured. With W. A. Rogers he studied the expansion of metals by the interferential method; and with C. F. Brush the conduction of heat

through water vapor. These researches were published, some of them only in abstract, between the years 1886 and 1905. The references to them can be found in the bibliography at the end of this memoir.

Of all these physical researches the most noteworthy is that of the relative motion of the earth and the ether. Fizeau had already shown that the ether is entirely unaffected by the motion of the matter which it permeates. To repeat Fizeau's experiment was the first task in which Michelson and Morley cooperated, and this was followed by another experiment to detect any difference in the velocity of light owing to the motion of the apparatus toward or away from waves of light in the ether. The details of these investigations can not be considered here, but Morley in his personal memoranda gives a clear statement as to his share in them. I now quote Morley, almost but not quite literally. He speaks in the first person, which I venture to change to the third. Beyond this alteration only a few words have been changed from the wording in the original statements, and then only for the sake of clearness.

When Michelson was ready to repeat Fizeau's experiment, certain conveniences were available in Morley's laboratory, and he was cordially invited to make use of them. Morley had no assistant, and so, naturally, it fell to him to see that Michelson had what was needful, and so became pretty familiar with Michelson's plans. His work was interrupted by illness and absence, and an erroneous diagnosis led him to turn over to Morley an appropriation for the experiment with a request to him to conclude it. Morley had got the apparatus ready for the final observations when Michelson wrote that he should return in a short time. Morley, therefore, ceased work, and wrote, surrendering the conduct of the experiment to Michelson, and the latter accordingly proposed that it should be a joint experiment.

When Michelson was ready to make a decisive experiment on the velocity of light parallel to and across the line of drift through the luminiferous ether, the best available place for the apparatus was again found to be Morley's laboratory, and this experiment also was made a joint affair. The result was negative. No difference was found.

In 1900, as Morley was going to a meeting of the Congress of Physics in Paris, Lord Kelvin saw him and asked him with much earnestness if there was any possibility of escape from the unexpected result of the experiment mentioned above. The conversation showed that Lord Kelvin was anxious to know whether the result would be in any degree altered by change of the sandstone slab of that experiment for other materials. After subsequent interviews with Kelvin, Morley resolved to repeat the experiment, and secured the cooperation of Prof. Dayton C. Miller. With the aid of a grant from the Bache fund, an apparatus of pine was set up at the Case School of Applied Science. After its completion there was not time enough to finish the observations during the summer vacation. When another summer vacation came it was found that the apparatus had been subjected to such heat and dryness during the winter that its instability prevented observations. Accordingly a third apparatus was built of structural steel, in which the optical path could be limited either by the steel of the framework, or by pine distance rods determining the distance of the mirror holders.

With this apparatus it was found that if there were any portion of the results expected in the previous experiment it was not more than one one-hundredth of 1 per cent. Here again the result was practically negative.

In the later years of his life, in his private laboratory at West Hartford, Morley made about 70 analyses of igneous rocks that were collected by J. P. Iddings in the Malay Archipelago. It is hardly necessary to say that these difficult and complicated analyses were made with the greatest thoroughness, and that none better can be found in the whole literature of petrology. Nineteen of these analyses, of rocks from Java and Celebes, were published in a joint paper by Iddings and Morley. This was Morley's last contribution to chemistry. Morley was not a voluminous writer; his published bibliography contains only 55 titles. But a single great research may outweigh many small ones.

Morley was the recipient of many honors, among them three medals, namely, the Davy medal of the Royal Society, the Elliot Cresson medal of the Franklin Institute, and the Willard Gibbs medal of the Chicago section of the American Chemical Society. He had the degree of doctor of laws from Williams College, Western Reserve, Lafayette, and Pittsburgh; of doctor of

philosophy from Wooster, and of doctor of science from Yale. He was an honorary member of the Chemical Society of London, of the Royal Institution of Great Britain, and the only American honorary member of the American Chemical Society. Of the British Association for the Advancement of Science he was a corresponding member.

He was a member of the National Academy of Sciences, and he had served as president of the American Association for the Advancement of Science and also of the American Chemical Society. He also held membership in the American Academy of Arts and Sciences, the American Philosophical Society, the Washington Academy of Sciences, the Astronomical and Astrophysical Society of America, the German Chemical Society, and the French Physical Society. He was honorary president of the Eighth International Congress of Applied Chemistry.

Morley was an extremely versatile man and had many interests apart from his devotion to science. His early training was unusually broad, although as an investigator he was self-trained. In his college days he was much interested in philosophy as taught by the famous president of the college, Mark Hopkins. He was well read in general literature and a good amateur musician. In his manuscript memoranda he says that in boyhood he was so fond of music that he used to practice four hours a day, except on holidays, when eight hours could be used in the same manner. "It was," he says, "a severe trial when professional studies brought devotion to music to an end." For a few years after stopping daily practice, some enjoyment of his own performance on the piano was possible. For a good many more years he could enjoy performing on a cabinet organ. Then he had to await the improvement of the player piano up to the point where the performance was satisfactory. He neglects, however, to add that for a while he played the organ in the college chapel at Hudson. One of his last acts was to give a fund of $5,000 to the Congregational Church in Hartford in memory of his wife, whose death preceded his by only a few months. This money was for the purchase of an organ and in aid of the musical part of the church service. Morley was a religious man, but by no means bigoted or fanatical. In my more than 40 years' personal acquaintance with him I never heard him refer to his theological beliefs.

Morley's life at West Hartford was quiet and uneventful. In a letter to his college classmates, reproduced by Professor Tower, Morley says:

> In 1906, after teaching just forty years, I retired, hoping by timely rest from hard work to retain a fair degree of health and good spirits and power of enjoyment. I built a house and a small laboratory in West Hartford, and we are living there, seeming to find as much enjoyment as at any time in our lives. I grow a good many gladioli and use the camera. Walking and bicycling, which are a great delight, are now somewhat too strenuous; it is six years since I walked from North Adams over Greylock to Adams and took several similar walks in Berkshire County. Now the valleys of Berkshire must content me. My eyesight is still good; I wrote the Lord's prayer within the space covered by a three-cent piece a few months ago, without any magnifying glass. My hearing is not so good.

In this letter Morley fails to mention the pleasure he found in trips in his automobile, which he drove himself. Much lovely scenery was easily within his reach. Only the summer before he died he and Mrs. Morley took a long ride in his machine through northern Massachusetts into southern Vermont.

Professor Morley was a very modest man and by no means given to self-advertising. Consequently he was little known outside of scientific circles, but among chemists and physicists his reputation was world-wide. In his social relations he was rather diffident and made acquaintances slowly. But among his friends he was most companionable. Professor Tower says of him that he had—

> a remarkably retentive mind, so that practically everything that he read was stored in his memory, whence it could be drawn whenever needed. He not only possessed great clarity of expression in writing and speaking, but, what is rarer, he had the ability to present scientific and abstruse matters in a manner which made them interesting to laymen. His public lectures on such subjects as the ether-drift experiments were always well attended, and he held the attention of his audiences to the end.

Morley died, following a surgical operation, in the Hartford Hospital, at the ripe age of 85 years. He and his wife were both buried in the family plot at Pittsfield, the city in which his parents had passed their declining years. If his epitaph could be written in one word, that word might well be "Thorough."

The following bibliography was compiled by Professor Tower, the successor of Morley in the chair of chemistry at Adelbert College.

BIBLIOGRAPHY

On the latitude of Williams College Observatory. Proc. Amer. Assoc. Adv. Sci., 1866, p. 384.

An apparatus for rapid filtration. Amer. Journ. Science, vol. 6, 1873, p. 214.

On the chemical composition of a saline efflorescence occurring at Goat Island. Proc. Amer. Assoc. Adv. Sci., 1876, p. 132.

Measurements of Moller's diatomaceen-probe-platten. Read before American Association for the Advancement of Science. Monthly Microsc. Journ., vol. 15, 1876, p. 223.

Measurements of rulings on glass. Read before American Association for the Advancement of Science, 1876. Monthly Microsc. Journ., vol. 17, 1877, p. 137.

On the limits of accuracy in measurements with the microscope. Amer. Quarterly Microsc. Journ., 1878, p. 93. Read before Amer. Acad. of Arts and Sciences, 1879.

On a possible cause of variation in the proportion of oxygen in the air. Amer. Journ. Science, vol. 18, 1879, p. 168; vol. 22, 1881, p. 417.

Reduction to zero of measured volume of gases. Proc. Amer. Assoc. Adv. Sci., 1880, p. 345. Chem. News, vol. 45, 1882, p. 246.

The most convenient scale for a thermometer used in gas analysis. Proc. Amer. Assoc. Adv. Sci., 1880, p. 346.

Jolly's apparatus for determining the amount of oxygen iu the air. Proc. Amer. Assoc. Adv. Sci., 1880, p. 348.

Some points in the construction of an apparatus for the accurate analysis of gases. Proc. Amer. Assoc. Adv. Sci., 1880, p. 350.

Numerical results for the mean ratio of oxygen to the sum of oxygen and nitrogen in atmospheric air. Proc. Amer. Assoc. Adv. Sci., 1880, p. 351.

Some conclusions as to the cause of the frequent fluctuations in the ratio of oxygen to nitrogen in the air at different times. Proc. Amer. Assoc. Adv. Sci., 1880, p. 353.

On Jolly's hypothesis as to the cause of the variations in the proportion of oxygen in the atmosphere. Amer. Journ. Science, vol. 22, 1881, p. 429.

Method for accurate and rapid analyses of air. Amer. Chem. Journ., vol. 3, 1881, p. 275; Chem. News, 1881 and 1882.

Special instructions relative to collecting specimens of air. Ann. Rept. U. S. Signal Office, 1881, p. 1285.

The amount of moisture which sulphuric acid leaves in a gas. Amer. Journ. Science, vol. 30, 1885, p. 140; Zeitsch. anal. Chem., vol. 24, 1885, p. 533.

Amount of moisture left in a gas after drying by phosphorus pentoxide. Amer. Journ. Science, vol. 34, 1887, p. 199; Proc. Amer. Assoc. Adv. Sci.; Zeitsch. anal. Chem., vol. 27, 1888.

On the determination of the atomic weight of oxygen. Amer. Chem. Journ., vol. 10, 1888, p. 21.

Determination of the tension of the vapor of mercury at ordinary temperatures. Proc. Amer. Assoc. Adv. Sci., 1890, p. 91.

Determination of the volumetric composition of water. Journ. Amer. Chem. Soc., vol. 12, 1890, p. 275; Proc. Amer. Assoc. Adv. Sci., 1890, p. 161; Amer. Journ. Science, vol. 41, 1891, pp. 220 and 279.

Ratio of the densities of oxygen and hydrogen. Proc. Amer. Assoc. Adv. Sci., 1890, p. 163.

Carbon as an impurity in hydrogen affecting determinations of its atomic weight. Amer. Chem. Journ., vol. 12, 1890, p. 460; Journ. Amer. Chem. Soc., vol. 12, 1890, p. 276.

A new method for measuring the expansion of solids. Proc. Amer. Assoc. Adv. Sci., 1891, p. 137.

Synthesis of weighed quantities of water from weighed quantities of oxygen and hydrogen gases. Proc. Amer. Assoc. Adv. Sci., 1891, p. 185.

Jean Servais Stas, Memoir. Journ. Amer. Chem. Soc., vol. 14, 1892, p. 173.

A self-acting mercuric pump. Amer. Journ. Science, vol. 47, 1894, p. 439.

On the volumetric composition of water. Proc. Amer. Assoc. Adv. Sci., 1895, p. 87.

On the atomic weight of oxygen. Syntheses of weighed quantities of water from weighed quantities of hydrogen, and oxygen. Amer. Chem. Journ., vol. 17, 1895, pp. 267 and 396; Zeitsch. physikal. Chem., vol. 17, 1895, p. 87.

On the densities of oxygen and hydrogen and the ratio of their atomic weights. Smithsonian Contributions to Knowledge, No. 980, 1895; Zeitsch. physikal. Chem., vol. 20, 1896.

Value of the atomic weight of oxygen computed from all available data. Western Reserve University Bull., 1895, p. 14.

A completed chapter in the history of the atomic theory. President's address, American Assoc. Adv. Sci., Proc., 1896, p. 1.

William Augustus Rogers, memoir. Biograph. Memoirs, Natl. Acad. Sci., vol. 4, 1902, p. 185.

Are further experiments needed for determining the atomic weight of oxygen? Journ. Amer. Chem. Soc., vol. 22, 1900, p. 51.

Note on the amount of moisture remaining in a gas after drying with phosphorus pentoxide. Journ. Amer. Chem. Soc., vol. 26, 1904, p. 1171; Journ. de Chim. phys., vol. 3, 1905, p. 241.

Alcoholometric tables. Journ. Amer. Chem. Soc., vol. 26, 1904, p. 1185.

Vapor pressure of mercury at ordinary temperatures. Amer. Journ. Science (4), vol. 18, 1904, p. 83; Phil. Mag. (6), vol. 7, p. 662; Zeitsch. physikal. Chem., vol. 49, p. 95.

Oliver Wolcott Gibbs, memoir. Proc. Amer. Phil. Soc., vol. 49, 1910, p. xix.

Fundamental chemical constants. Journ. Franklin Inst., Aug., 1912, p. 203.

PAPERS IN COLLABORATION WITH OTHERS

WITH PROF. ALBERT A. MICHELSON

Influence of the motion of the medium on the velocity of light. Amer. Journ. Science, vol. 31, 1886, p. 377. Also publ. in Nature, Beiblätter, and Repertorium.

On the relative motion of the earth and the luminiferous ether. Amer. Journ. Science, vol. 34, 1887, p. 333. Also publ. in Phil. Mag., Beiblätter, Journ. de Physique, and the Sidereal Messenger.

On the method of making the wave-length of sodium light the actual and practical standard of length. Amer. Journ. Science, vol. 34, 1887, p. 427.

On the feasibility of establishing a light-wave as the ultimate standard of length. Amer. Journ. Science, vol. 38, 1889, p. 181.

WITH PROF. HENRY T. EDDY

On the velocity of light in a magnetic field. Proc. Amer. Assoc. Adv. Sci., 1890, p. 81.

WITH PROF. WILLIAM A. ROGERS

Measurement of the expansion of Jessop's steel by a new method. Proc. Amer. Assoc. Adv. Sci., 1891, p. 138; Science, vol. 2, 1895, p. 35.

On the measurement of the expansion of metals by the interferential method. Physical Rev., vol. 4, 1896, pp. 1 and 106.

WITH PROF. DAYTON C. MILLER

On the coefficient of expansion of certain gases. Proc. Amer. Assoc. Adv. Sci., 1897, p. 123. This paper had to do with air, nitrogen, and carbon dioxide.

Another paper on "the coefficient of thermal expansion of oxygen" was read before another scientific society a year or two later.

Experiments on the velocity of light in a magnetic field. Phys. Rev., vol. 7, 1898, p. 283; Proc. Amer. Assoc. Adv. Sci., 1898, p. 123.

On the speed and accuracy of photographic shutters. Sci. Amer. Sup., vol. 55, 1903, p. 22979.

On the theory of experiments to detect aberrations of the second degree. Phil. Mag. (6), vol. 9, 1905, p. 669.

An experiment to detect the Fitzgerald-Lorentz effect. Phil. Mag. (6), vol. 9, 1905, p. 680; Proc. Amer. Acad. Arts and Sciences, vol. 41, 1905, p. 321.

WITH MR. CHARLES F. BRUSH

The conduction of heat through water vapor. Repts. British Assoc. Adv. Sciences, 1901, p. 525.

A new gauge for the measurement of small pressures. Amer. Journ. Science (4), vol. 13, 1902, p. 455.

WITH PROF. JOSEPH P. IDDINGS

Contributions to the petrography of Java and Celebes. Journ. of Geology, vol. 23, 1915, p. 231.