History of Science

Argon and the Non-Inert Pair: Rayleigh and Ramsay

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In 1904 two London-based scientists became the first British citizens to be awarded the Nobel prize. Lord Rayleigh, at the Davy–Faraday Research Laboratories of the Royal Institution, won the Physics prize "for his investigation of the densities of the most important gases and for the discovery of argon in connection with these studies"; and Sir William Ramsay of University College, London, won the Chemistry prize "for his discovery of the inert gaseous elements in air, and his determination of their place in the periodic system." The significance of their discoveries, in particular their remarkable joint paper ("Argon, a New Constituent of the Atmosphere", *Philos. Trans. R. Soc. London Ser. A* **1895**, *186*, 187–241) is seen to be even more profound now than it was a century ago. But it must not be thought that these two individuals, like some other scientists who have won the Nobel prize subsequently, were focused upon and conquered just one large problem. On the contrary, these two, in diverse ways, were scientific giants, in ways not revealed by the Nobel citation, and the lessons that present-day practitioners in chemical science may draw from the talents, insights, generosity of spirit, humanity, activity, and achievements of Rayleigh and Ramsay are not only instructive to ponder but inspirational to aspiring young scientists (Figure 1).

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Figure 1. Sir William Ramsay and Lord Rayleigh. The picture was taken shortly after the isolation of the first noble gas.

An Outline of Rayleigh's Career

Lord Rayleigh (1842–1919), last of the great British classical physicists, made contributions to every single branch of the physical sciences known in his day. His penetrating insight and prodigious capacity for detailed work enabled him to solve problems previously perceived by his progenitors and contemporaries as intractable as well as to suggest new lines of research that engendered the blossoming of much of 20th (and 21st) century science and technology. No name stands higher in the general esteem of physical scientists, engineers, and applied mathematicians the world over than that of John William Strutt (Third Baron Rayleigh) who was "to the manor born" in rural Essex, some sixty miles from London. No name occurs more frequently in relation to phenomena, principles, and effects with which any student of classical physics must become acquainted than that of Rayleigh. "Rayleigh Scattering" (of electromagnetic waves and the explanation of the blue sky and red sunset), "Rayleigh Waves", "Rayleigh Criterion" (governing resolving power in microscopes and telescopes), "Rayleigh Number" (in convection), "Rayleigh disc" (for measuring the absolute intensity of sound), "Rayleigh Fading and

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Rayleigh Distance (terms used in the propagation of electromagnetic waves), ”Rayleigh Damping“, the ”Rayleigh–Jeans Law“ (for black body radiation)—these are by no means an exhaustive list of the impact of his work. They reflect but a fraction of the fields and phenomena in which his interests ranged with the most fruitful of results. For example, in 1885 Rayleigh published an article on the propagation of surface acoustic waves. This was a seminal paper that, for modern-day seismologists and earth scientists, is the basis for detecting and pin-pointing the location of distant earthquakes, and for electronic engineers forms that basis for practical delay lines in circuits used in radar and television.

Rayleigh was born John William Strutt at Terling Place in the county of Essex on November 12, 1842. As an infant he exhibited no sign of precocity, and he was almost three years old before he could talk. His schooling was rather fragmentary, short spells first at Eton then at Harrow (two of the premier private schools in the UK) being terminated by ill health. In the autumn of 1857 he was put under the care of Rev. George T. Warner, who took pupils at Torquay where he remained for four years. He entered Trinity College, Cambridge in October 1861 and was soon following the rigorous courses in mathematics given by or Edward J. Routh (of Peterhouse) a phenomenally successful tutor who, in 33 years of teaching produced 27 senior wranglers (the name given to the person who came top in the mathematical tripos examinations). J. W. Strutt was senior wrangler in January 1865. Sir James Jeans, the eminent astronomer and cosmologist, writing some 60 years later, said that *“there still lingers in Cambridge a tradition as to the lucidity and literary finish of his answers in the examination”*. The fine sense of literary style which Strutt displayed even under pressure in the examinations never deserted him. Every paper he wrote—and there were some 450 over a fifty year period—even those dealing with the most abstruse subjects—is a model of clarity and simplicity, and conveys the impression of having been written with effortless ease.

After his triumph in the mathematics examination he took a course on chemical analysis (from George D. Liveing, the newly appointed Professor of Chemistry at Cambridge). This choice of course was partly because young Strutt had a passion for experiment, but chiefly because no course was available in Cambridge dealing with experimental physics—an incredible state of affairs for the University where Newton had studied and taught.[1] In 1866 he was elected a fellow of Trinity College but it was not until 1869 that his first scientific paper appeared bearing the title “On Some Electro-Magnetic Phenomena Considered in Connection with the Dynamical Theory”[2] This paper was a brilliant example of the method and style that its author was to pursue throughout his career. The “dynamical theory” in question was James Clerk Maxwell’s monumental work on the electromagnetic field, which Maxwell had cast in terms of complicated mathematical equations that were not readily transparent and fully appreciated by his contemporaries. Strutt elucidated and simplified this recondite theory—almost, as Jeans said later, made it intelligible to the average person. This simplification was done by showing that the intricate processes of the electromagnetic field found practically perfect analogies in such well-understood phenomena as the bursting of a water pipe under sudden pressure. And so, by adding to his towering mathematical skills the capacity for[3] “*understanding everything just a little more deeply than anyone else*, *and the consequent capacity for exhibiting it in its simplest aspect*”, Strutt began on his extraordinary scientific career, one marked by a catholicity of tastes and an exceptional combination of mathematical power and (later) experimental virtuosity.

Soon after his lucid interpretation of Maxwell’s electromagnetic work, there came another major contribution which emerged from his reading the articles of Hermann von Helmholtz on sound. In 1860, Helmholtz had studied the acoustic resonator, now associated with his name. The 28 year old Strutt felt he could improve the mathematical treatment considerably, and this formed his first excursion into acoustics, which led to his classic paper entitled “On the Theory of Resonance”[4] In this major paper he attacked the problem of the oscillations of the air in the mouth of a resonator from the standpoint of energy; and he also introduced the invaluable concept of the acoustic conductivity of an orifice. He significantly extended Helmholtz’s results, including (among other novelties) a discussion of coupled resonators. Ruminating over Helmholtz’s famous treatise on tone,[5] he realized that there existed no up-to-date book on acoustical problems that provided an adequate mathematical treatment of well-established experimental phenomena.[6] No one had taken the trouble to summarize in a single text the classical memoirs of Euler, Lagrange, D’Alembert, Bernoulli, and other theorists of the eighteenth century.

By that time, 1871 to be precise, he had married Evelyn Balfour, sister of Arthur J. Balfour, the future Prime Minister, and later the author of the Balfour declaration that established a national home for the Jews.[8] Shortly thereafter he was struck by a severe attack of rheumatic fever, which led to his devoting a winter to travel in Egypt and Greece. It was while he was holidaying on a houseboat on the Nile that he drafted—without access to a library—Volume One of his monumental two volume *The Theory of Sound*, in which he examined questions of vibrations and the resonance of elastic solids and gases.[9] But before he left for the Middle East he had, in a two year period, published a dozen other outstanding papers. Arguably one of his most celebrated is entitled: “On the Light from the Sky: its polarization and colour”[10] and it marked the beginning of his concern for the scattering of radiation in general. He arrived, in this paper, at both the intensity and polarization of the scattered light by use of dimensional analysis and properly explained why the sky is blue and the sunset is red.[11] The amplitude of the Rayleigh scattered light is inversely proportional to the square of the wavelength.

In 1873, the year that his father died and when, therefore, he inherited the title of Lord (the Third Baron Rayleigh), he was elected Fellow of the Royal Society (FRS). Taking up residence in the family seat, Terling Place, he built a laboratory adjacent to the manor house. Although his primary interest was (and remained throughout

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his life) scientific research, he now found himself compelled to devote a part of his time to the management of his estates. He acquired considerable knowledge of agriculture, which, combined with his general scientific knowledge and acumen led to his practice in estate management being in many regards in advance of its time.

This period saw the commencement of Rayleigh's lifelong interest in psychical research.[13] According to Sir James Jeans,[3] at first Rayleigh expected that investigation would rapidly lead to a definite conclusion, either positive or negative. Apparently he expected the former, in which case he was prepared to throw the greater part of his energies into a study of psychic phenomena. Rayleigh returned to orthodox scientific work when it became clear that no such definite conclusion was being attained.

Professor at Cambridge and at the Royal Institution of Great Britain

In 1879 James Clerk Maxwell, the first occupant of the Cavendish chair of experimental physics at Cambridge, died of intestinal cancer. Rayleigh agreed to serve as the second Cavendish professor for the period 1879–1884. He took his university duties very seriously both with respect to the instruction of students and to the carrying out of a vigorous research program that set about redetermining the values of electrical standards (the ohm, volt, and amp). A classical series of papers resulted from this ambitious project. But after a five-year tenure, he returned to his laboratory at Terling Place. Later he became (from 1887 to 1905) professor of Natural Philosophy at the Royal Institution.[14] In the intervening time, he accepted the secretaryship of the Royal Society, vacated by the resignation of one of his former teachers, Sir George Gabriel Stokes. The duties of such a post were not onerous, and there was no falling off of Rayleigh's output throughout his eleven years of secretaryship.

The tenure of this office gave him the opportunity to discover (in 1891) and rescue from oblivion the valuable memoir in which John J. Waterston[15] in 1846 had anticipated some of the important features of the kinetic theory of gases.

Helping Miss Pockels

An example of Rayleigh's scientific generosity was the support that he gave to some research by Miss Agnes Pockels. In January 1891, after he had published several papers relating to liquid surfaces and surface tension, Rayleigh received a long letter (in German) from Agnes Pockels (1862–1935) of Braunschweig (Figure 2). She had read Rayleigh's paper in her brother Friedrich's[16] journals and wanted to tell him of some experiments on surface forces that she had carried out in her kitchen sink. At that time no mechanism for the formal university training of women existed in Germany. So after she completed her education at the Municipal High School for Girls, she came under the tutelage of her scientifically adroit brother. In 1880, while still a teenager, she had begun a series of researches on the effect of oil films on the surface tension of water. To measure surface forces quantitatively, she had suspended a horizontal disk from one arm of a balance scale until the disk just touched the surface of the pure (or contaminated) water. Based on her "surface-balance" work, she sent letters outlining her results to various German scientists, but they displayed little interest in her work. It was her brother who urged her to write to Rayleigh, who immediately saw that she had achieved several fundamental advances in the surface physics of liquids. Rayleigh then published her paper in *Nature* in 1891, with an introduction by himself commenting on the importance of her work.

Figure 2. Agnes Pockels.

This public recognition by a distinguished British scientist brought her instant fame: her later papers, it was alleged,[12] were treated by journals with deferential respect. Professor Voight of the Physical Institute, Braunschweig, offered her laboratory facilities. She later visited illuminati such as Quincke, Ostwald, and Weber, all eminent surface scientists. Irving Langmuir, a later Nobel laureate (1932), adopted essentially her method for measuring surface forces.

The Discovery of Argon[17]

It was at the Royal Institution that Rayleigh largely conducted the work that earned him the Nobel Prize in Physics and brought him his greatest fame. Rayleigh had long been intrigued by Prout's hypothesis that the atomic weights should be integral numbers. If we assign hydrogen to be 1, oxygen should be 16, but it was not quite so. Was the discrepancy real? Rayleigh therefore determined the densities of hydrogen and oxygen; and then he moved on to nitrogen (in 1892). In a letter to *Nature* (submitted September 24 of that year, published September 29) he wrote:[18]

I am much puzzled by some results on the density of nitrogen, and I shall be obliged if any of your chemical readers can offer suggestions as to the cause. According to the methods of preparation, I obtain two quite distinct values. The relative difference, amounting to about one part in 1000, is small in itself, but it lies entirely outside the errors of experiment, and can only be attributed to a variation of the character of the gas.

His two sources of nitrogen had been ordinary air with the oxygen removed by heated metallic copper, and a "lighter" nitrogen obtained by decomposition of ammonia. No illuminating response came at that time from the chemical public, but his colleague at the Royal Institution, Sir James Dewar, said that some of the atmospheric N_2 was in

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an allotropic state, such as N_3, just as some oxygen exists as ozone O_3. Rayleigh was skeptical about this; and he continued (for two years) to prepare nitrogen by several methods. Such chemically produced nitrogen was always lighter in density than atmospheric nitrogen. One of Rayleigh's lecture-demonstrations at the Royal Institution was a repeat of some of Henry Cavendish's studies, carried out a century earlier, in which a globe of ordinary air was subjected to electrical sparking so as to consume the oxygen as an oxide of nitrogen (that could be absorbed by potash). In this manner, all of the nitrogen was removed, excect, as Cavendish had noted, a very small residue. In other words, Rayleigh verified the reclusive Cavendish's results that had lain unnoticed in the literature for over 100 years.

Rayleigh expatiated on these puzzling facts in a lecture given to the Royal Society on April 19, 1894. This prompted a member of the audience, William Ramsay, to converse with Rayleigh. By the end of May of that year, Ramsay had shown that nitrogen gas, when repeatedly exposed to heated magnesium (to form the solid nitride) could be made progressively denser. Continuing his experiments through the summer, Ramsay produced in early August a gas, apparently unaffected by further treatment with magnesium (Figure 3). This result led to an exchange of letters. Sir William Crookes examined the gas and reported that it was new and quite distinct from nitrogen. Rayleigh told Ramsay that the residue was neither oxygen nor nitrogen. The two immediately joined forces, and on January 31, 1895 announced to the Royal Society the discovery of a new gaseous element, apparently inert chemically, which they called argon (for inert, without work).

4th August, 1894

Dear Lord Rayleigh,
I have isolated the gas. Its density is 19.075, and it is not absorbed by magnesium.....

6th August , 1894

Dear Prof Ramsay,–
I believe that I too have isolated the gas, though in miserably small quantities...

Figure 3. The opening sentence of the letters in which Rayleigh and Ramsey report their simultaneous isolation of argon.

Rayleigh and Ramsay's 54-page joint paper gave the density, refractive index, solubility in water, ratio of specific heats (C_p/C_v), and atomic spectrum of the new gas, and they postulated a new zeroth column, for noble gases, in Mendeleeff's Periodic Table. Some scientists argued that so heavy an element could not possibly be a gas. Rayleigh, with aristocratic humor, replied:

...the result is, no doubt, very awkward. Indeed, I have seen some indications that the anomalous properties of argon are brought as a kind of accusation against us. But we had the very best intentions in the matter. The facts were too much for us, and all that we can do now is apologize for ourselves and for the gas.

In the process of isolating argon, Rayleigh designed the refractometer that bears his name, and the Rayleigh modification of the Huygens manometer. Lord Kelvin hailed argon as undoubtedly the greatest scientific event of the year. Specifically, he said:

If anything could add to the interest which we must all feel in this startling discovery, it is the consideration of the way by which it was found—arduous work—commenced in 1882, has been continued for 12 years by Rayleigh, with unremitting perseverance.

When Rayleigh received his Nobel Prize in 1904 the monetary value amounted to some £7700, a huge sum in those days. He donated his money to the University of Cambridge, and it was used to construct a new extension to the Cavendish Laboratory, the so-called Rayleigh Wing. This institution was built using wooden pegs and stone and cement instead of metal nails, to provide a facility better suited for sensitive electrical measurements. (Wilson's cloud-chamber measurements were carried out in this extension. All my present efforts in electron microscopy are also done in the Rayleigh wing). In his later years, honors and responsibilities fell much upon Rayleigh. He was one of the original recipients (1902) of the Order of Merit, and he accepted that Presidency of the Royal Society in 1905 (having earlier declined it).

According to Sir James Jeans:

...his massive, precise and perfectly balanced mind was utterly removed from that of the erratic genius who typifies the great scientist in the popular imagination...The outstanding qualities of his writings were thoroughness and clearness; he made everything seem obvious. Rayleigh died is Essex on 30 June 1919, having been at work on a scientific paper only five days previously...The inscription on his memorial in Westminster Abbey, 'An unerring leader in the advancement of natural knowledge', does not overstate the case.

Sir William Ramsay (1852–1916)

Rayleigh's co-discoverer of argon was born in Glasgow on October 2, 1852. He inherited scientific ability from both his parents; for, whilst his father was a civil engineer of no mean achievement and his paternal grandfather a well-known manufacturer of chemicals used by dyers, his mother was descended from a Scottish family which had produced many medical doctors of note.

As a child he showed remarkable skills with language and, like the polymath, Thomas Young (1773–1829), is said to have read the Bible when he was about four years of age. Brought up in a Calvinistic (Methodist) background he was exposed as a young child to long (and for him rather boring) sermons, during the course of which he acquired aptitude for German and French by reading the Bible in those languages. In his early teens while pursuing a conventional classical education (he was intended for the church) he broke his leg and spent a long convalescent period in bed. To while away the time, his father gave him chemicals with which he experimented. Ramsay later wrote:[19,20]

I had the misfortune to break my leg at football. During my convalescence I read Graham's chemistry, chiefly, I must admit because I wanted to know how to make fireworks. I remember that my father gave me small quantities of potassium chlorate, phosphorus, sulphuric acid, and some small flasks and beakers and a spirit lamp, and with these I amused myself during several weary months.

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The thought that a young child had access to the potentially explosive mixtures of potassium chlorate and phosphorus in his bedroom fills one with alarm even now!

Young Ramsay attended an elementary (state) school and then proceeded to Glasgow Academy where he quickly revealed his flair for languages. Apart from knowing much of the Bible by heart, he acquired fluency in German and French (later he learned to speak Italian, Norwegian, Swedish, and Dutch and could read several other ancient and modern languages).

At Glasgow University, which he entered in 1866, Ramsay studied classics general literature, logic and mathematics; but after a year he decided to become a chemist. In 1869 he worked for a short while in the laboratory of the chemical supplier Robert Tatlock. At the close of the Franco–Prussian War he went to Heidelberg with the intention of studying under Robert W. Bunsen, but early in 1871 he changed to Rudolf Fittig's laboratory at Tübingen where he obtained the degree of Ph.D. for research on toluic acid (methylbenzoic acid) and nitro-toluic acids. In 1874 he became the assistant to the Professor of chemistry at the University of Glasgow, but in barely six years he became (1880) first, Professor of Chemistry at University College, Bristol, and then, a year later (shortly after his marriage to Margaret Buchanan) its principal. In 1887 he succeeded the renowned organic chemist A. William Williamson as head of general chemistry at University College, London. By the time he left Bristol, Ramsay had established himself as a formidable physical chemist, knowledgeable about critical phenomena, under which liquids and gases are in equilibrium, and dexterous in the design and imaginative use of his own apparatus for handling minute volumes of gases.

The meeting between him and Lord Rayleigh in 1894 after the latter's lecture (on the anomalous density of nitrogen) at the Royal Society marked a major turning point in Ramsay's career. Their joint discovery of argon was soon followed by another of equal importance. It came about after Sir Henry Miers (1858–1947) of the British Museum had suggested that argon might be identical with an inert gas, supposedly nitrogen, that William Hillebrand (1853–1925), of the United States Geological Survey, had obtained by heating certain uranium containing minerals, such as cleveite (impure UO_3). Ramsay prepared this gas and found that it was not argon, but yet another, new inert gas, identical in its spectrum with the element helium, the presence of which in the sun had been spectroscopically detected during the eclipse of 1868 by Sir Norman Lockyer and Sir Edward Frankland.

Recognizing the remarkable inertness of both argon and helium, Ramsay divined that there must exist a whole related family of such inert elements. He set about, with almost frenetic speed (along with his galvanized collaborators, especially his pupil Morris W. Travers) to search for others (Figure 4); and after many months of hard work using the process of fractional distillation three new inert elementary gases, neon (the new one), krypton (the hidden one), and xenon (the strange one) were all isolated and identified in mid-summer, 1898. These gases were isolated by Ramsay and Travers from one hundred and twenty tons of air which had been liquefied!

Figure 4. Picture by the London cartoonist-Leslie Ward ("Spy" 1851–1922); Ramsey points to the eighth group of the Periodic Table which only contains elements that he discovered and isolated.

At the turn of the nineteenth and twentieth centuries, Ernest Rutherford and Fredrick Soddy[21] discovered, at McGill University, Montreal, that thorium had associated with it, in minute quantities, a radioactive gas, which they designated thorium emanation. It, too, was chemically inert. In 1903 Soddy joined Ramsay's department at London and began to apply the refined techniques of analysis perfected earlier. The "emanation" gas showed no discharge spectrum, but after a time, the spectrum of helium developed. This was incontrovertible proof of the transmutation of elements, an idea that, in 1903, had been proposed by Rutherford and Soddy. In late 1910, the "emanation", later called radon, was weighed by one of Ramsay's colleagues (Whytlaw-Gray) with a balance of (then) unsurpassed sensitivity. They found that 6.58×10^{-5} cm^3 of radon weighed 6.55×10^{-7} g, and thus they arrived at the atomic weight (222), thereby completing the entire Nobel gas group of the Periodic Table.

Ramsay's Character, Style, and Humanity

Apart from being one of the greatest chemical discoverers—he and Humphry Davy between them discovered 14 of the elements of the Periodic Table—he was gifted with rare scientific insight and imagination, and was the possessor of a most wonderful skill and dexterity in the devising, constructing, and use of apparatus for the delicate and exact investigation of gases. According to one of his greatest protégés, Frederick George Donnan (1870–1956)—of membrane equilibria fame—who succeeded Ramsay as Professor in 1913, he was:

…a man of sanguine and courageous temperament, of tireless energy, and power of instant action, he fearlessly attacked problems the experimental difficulties of which would have dismayed and deterred most men…. Nothing was ever postponed. What an ordinary very active man would do on Monday morning, Ramsay did on Saturday afternoon. He was endowed with extraordinary personal charm, and a most kindly, generous and gentle disposition… An

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excellent linguist and musician, a witty and humorous speaker both in public and in private. The quickness and receptivity of his mind were remarkable, so that he was ever the enthusiastic friend and exponent of new advances in science. Thus he was one of the first chemists in England to teach and expound the work of Ostwald, Van't Hoff and Arrhenius with each of whom he could converse in their mother tongue.

Ramsay, like Rayleigh extended his activities in many directions: he found time to write a number of excellent texts on chemistry, was an ardent apostle of reform in converting the University of London into a great teaching University, and served as a member of the Royal Commission on sewage disposal and several other public bodies. Like many other truly great scientists, he could spot winners, two outstanding examples being Fredrick Soddy, Nobel Laureate 1921, and Sir Stafford Cripps, FRS (1889–1952) Statesman, Lawyer, Leader of the House of Commons in Winston Churchill's war-time cabinet, and chancellor of the exchequer in Clement R. Atlee's post-war government.[22] The papers which won Cripps from Winchester a Natural Science Scholarship to New College, Oxford in 1907 were so remarkable that Ramsay, who had been asked to scrutinize, persuaded Cripps to prefer the better equipped laboratories of University College London. This change meant that Cripps was doing advanced research even as an undergraduate. It resulted in Cripps being a part author of a paper on the properties of xenon read before the Royal Society when he was twenty-two.[23]

A Harmonious Partnership

It is fitting that this essay should end with reference to Helmholtz a natural philosopher greatly admired by both Rayleigh and Ramsay. Rayleigh heard Helmholtz give the Faraday Lecture at the Royal Institution in 1881, and it was Helmholtz's pioneering work that stimulated Rayleigh to write his *The Theory of Sound.* During the course of a memorable Friday evening Discourse at the Royal Institution on "*Argon*" in 1895, Rayleigh said:

In what I have to say from this point onwards, I must be understood as speaking on behalf of Professor Ramsay as for myself. At the first, the work which we did was to a certain extent independent. Afterwards we worked in concert, and all that we have published in our joint name, must be regarded as being equally the work of both of us. But, of course, Professor Ramsay must not be held responsible for any chemical blunder into which I may stumble tonight.

These are the very words uttered and written by Rayleigh in the enthralling account that he gave at the Royal Institution.[24] Rayleigh ended his lecture with the following words:

It will be known to many that during the last few months of his life Helmholtz lay prostrate in a semi paralyzed condition, forgetful of many things, but still retaining a keen interest is science. Some little while after his death we had a letter from his widow, in which she described how interested he had been in our preliminary announcement (upon the subject of Argon), and how he desired the account to be read to him again. He added the remark, 'I always thought that there must be something more in the atmosphere'.

I acknowledge with gratitude the advice and guidance given to me by many: Professors Alwyn Davies, E. A. Davis, Arthur Humphrey, R. J. H. Clark, and C. R. Calladine and Dr. Andrea Sella and Dr. Aimee Morgan. I am also grateful for the kind assistance provided by Ms Joanna Corden (Royal Society), Ms Erica McDonald (Peterhouse), Ms Shazia Riaz (Davy Faraday Research Laboratory), and Dr. Robert Raja.

[1] Sir George Gabriel Stokes (another senior wrangler), the Lucasian Professor of Mathematics, whom Strutt greatly admired, did carry out some lecture-demonstrations, and he also ran his own laboratory, where, he discovered the phenomenon of fluorescence. The only experimental courses available in Cambridge in the mid-1860s were those in chemistry, mineralogy, and certain biological sciences, a narrowness of choice which Strutt greatly resented.
[2] J. W. Strutt, *Philos. Mag.* **1869**, *38*, 1–15.
[3] Sir James H. Jeans, *Dictionary of National Biography*, **1912–1921**, p. 515.
[4] J. W. Strutt, *Philos. Trans. R. Soc. London* **1870**, *161*, 77–118.
[5] H. von Helmholtz, *Lehre von den Tonempfindungen*, Berlin, **1863** (translated by A. J. Ellis under the title *Sensations of Tone* (**1875**).
[6] Helmholtz's monograph specialized primarily[7] in physiological and psychological accoustics and music.
[7] R. B. Lindsay, *Lord Rayleigh*: *The Man and His Worth*, Pergamon, **1970**.
[8] Evelyn Balfour was also the niece of another British Prime Minister, Lord Salisbury.
[9] The first volume appeared in 1877, the second in 1878. This treatise soon became, and remains, the standard and authoritative text dealing with all aspects of the production and propagation of sound and acoustic attenuation in all kinds of elastic media.
[10] J. W. Strutt, *Philos. Mag.* **1872**, *41*, 107–120; J. W. Strutt, *Philos. Mag.* **1872**, *41*, 274–279.
[11] Dimensional analysis, pioneered as a mathematico-physical tool by Strutt, was later extended by others, notably the Nobel Laureate Percy W. Bridgman[12].
[12] "The Scientific Research of John William Strutt, Third Baron Rayleigh": J. N. Howard, *Proc. R. Inst. GB* **1988**, *60*, 73–86.
[13] One should not be surprised by the fact, for there were other contemporary, great scientists (like William Crookes, inventor of the radiometer and discoverer of the element thallium, and later, like Rayleigh, President of the Royal Society) who were deeply interested in psychical phenomena. That was a widely held view. In fact when the journal *Scientific American* published an editorial in 1920, under the heading "The Future Based on an Analysis of the last 70 Years", it was predicted that whereas the eighteenth century was characterized scientifically by advances in electricity the twentieth century would be equally remembered for advances in psychic research.
[14] The basic duties at the Royal Institution were light: the incumbent was to give each year a course of six Saturday afternoon lectures before Easter, as well as one Friday evening Discourse per annum, the lectures to be illustrated by experiments. In return he would have the year-round use of a laboratory of three rooms in the Royal Institution. The real attraction, it seemed, was that the Royal Institution was wired for electricity (thanks to the effort of the then Director, Sir James Dewar), which his laboratory at Terling was not.
[15] J. J. Waterston (1811–1883) developed the early Kinetic Theory of Gasses and

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largely anticipated the theory put forward by R. J. E. Clausius in (1857).
[16] Who is now remembered for his studies of the Pockels effect, used in electro-optical modulators.
[17] Part of this account is based on the excellent Friday Evening Discourse given, at my invitation at the Royal Institution by J. N. Howard during my tenure of the Directorship. See ref. [12] for fuller details.
[18] "Density of Nitrogen": Lord Rayleigh, *Nature* **1892**, *46*, 512–513.
[19] W. M. Travers, *A Life of Sir William Ramsay*, Arnold, London, 1956; see also obituary notice in *Proc. R. Soc. London Ser. A* **1956**, *93*, 1916–1917.
[20] I am greatly indebted to Professor Alwyn G. Davies FRS for making available to me his notes for a lunchtime lecture (on Ramsay) given at University College London, March 19, **2004**.
[21] Ramsay had spotted Soddy in 1898 as a bright young student at the University of Oxford where he was external examiner and Soddy had headed the honours list in chemistry.
[22] Other members of Ramsay's team in London, included M. W. Travers, E. C. C. Baly, N. Collie, F. Soddy, R. Whytlaw-Gray, and E. Egerton, all of whom, like Donnan, became Fellow of the Royal Society.
[23] H. S. Patterson, R. S. Cripps, R. Whytlaw-Gray, *Proc. R. Soc. London Ser. A* **1912**, *86*, 579–590.
[24] Lord Rayleigh, *Proc. R. Inst. GB* **1895**, *14*, 524–538.

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