Rediscovery of the Elements

Moseley and Atomic Numbers

James L. Marshall, *Beta Eta 1971*, and Virginia R. Marshall, *Beta Eta 2003*, Department of Chemistry, University of North Texas, Denton, TX 76203-5070, *jimm@unt.edu*

Introduction. Manchester in northwest England was founded as a Roman fort in 79 A.D. After the Roman departure it evolved into a typical Medieval village and after a millennium matured into a manufacturing giant. An influx of Flemish wool and linen weavers in the 14th century, followed by a developing supply of cotton from India and the American South in the 1700s, launched a large textile industry during the Industrial Revolution which brought wealth and prosperity to the community. By the mid-1800s, Manchester was the second largest city in England and gained a reputation as a center of invention and technological progress. In 1781 a prestigious scientific institution was founded—the Literary and Philosophical Society (commonly known as the "Lit. and Phil.").[1] In this society John Dalton (1766–1844),[2a] who arrived in Manchester in 1793, formulated his atomic theory at the turn of the century.[3] At the very same platform[4] where Dalton proposed his idea of atoms and atomic masses (Figures 1, 2), Ernest Rutherford one century later first proposed the nuclear atom, a dense positive core surrounded by electrons.[5]

Ernest Rutherford had arrived in 1907 from McGill University, Montreal, Canada.[2d] At the University of Manchester (then named the Victoria University of Manchester) he assembled a powerful team of gifted individuals including an Oxford graduate named Henry Gwyn-Jeffreys Moseley (1887–1915), who joined the group in 1910. During 1913–14 Moseley published two papers which established the physical basis of the atomic number and resolved several long-standing problems

(continued on page 44)

Figure 1. This was the Literary and Philosophical building at 36 George Street in Manchester built in 1799 which served the scientific community for 140 years before being destroyed in a German bombing raid in December 1940. Here the main meetings of the Lit. and Phil. were conducted, including the century-apart presentations of Dalton's atomic theory and Rutherford's nuclear atom.[4]

Figure 2. Today the site at 36 George Street in Manchester is occupied by Devonshire House, used for University functions. A blue plaque (left, on wall and shown below) reads: "John Dalton (1766–1844), Founder of the scientific Atomic Theory, President of the Manchester Literary and Philosophical Society, had his laboratory here."

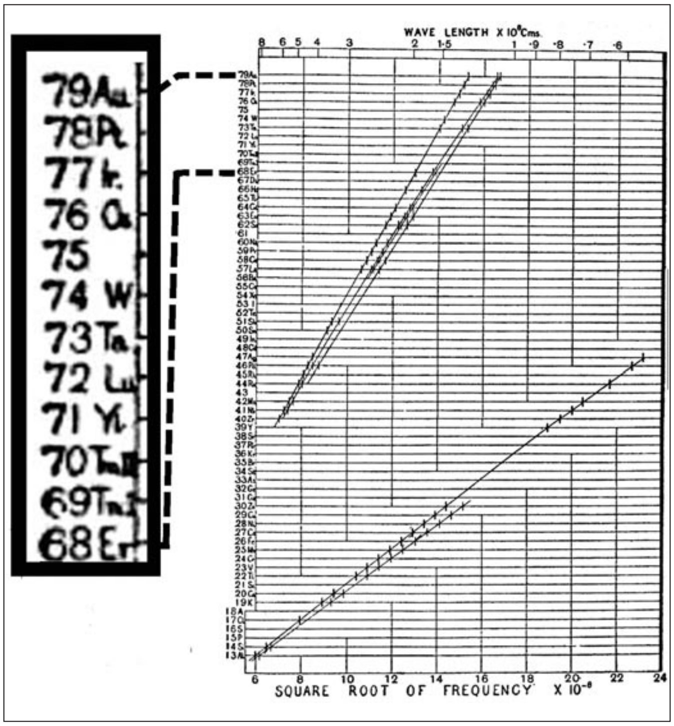


Figure 3. Right: Moseley's X-ray plots ("Moseley's law") establishing the validity of atomic number, N, as published in "High Frequency Spectra of the Elements, Part II".[15] This plot is displayed in the Moseley Room of Lindemann Hall (physics building) of Oxford University. The ordinate is atomic number N, with elements identified, ranging from aluminum to gold; the abscissa is the square root of the X-ray frequency. The upper series of the plots are L-lines; the lower are K-lines. The elements included are Al, Si, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Y, Nb, Mo, Ru, Rh, Pd, Ag, Sn, Sb, La, Ce, Pr, Nd, Sm, Eu, Gd, Ho, Er, Ta, W, Os, Ir, Pt, Au. Expansion at left: Notice the confusion of elements 70, 71, 72, misidentified by Moseley as "thulium II," "ytterbium," and "lutetium"; these were not corrected until he analyzed Urbain's samples (in May 1914; see text) and until hafnium (72) was discovered in Copenhagen (in 1923).

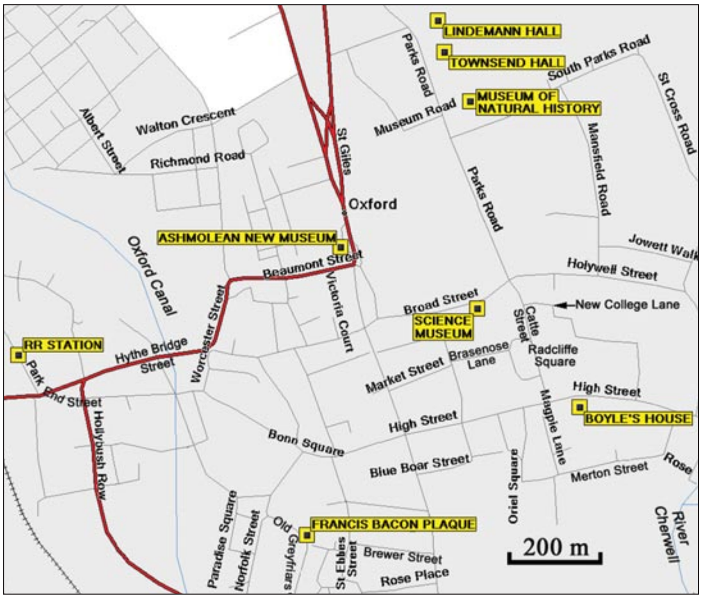


Figure 5. Oxford, England.

ASHMOLEAN MUSEUM OF ART AND ARCHEOLOGY, Beaumont Street– N51° 45.31 W01° 15.00.

MUSEUM OF THE HISTORY OF SCIENCE, displays of Moseley and others, Broad Street– N51° 45.26 W01° 15.33.

ROBERT BOYLE, site of original house, High Street, plaque– N51° 45.16 W01° 15.15.

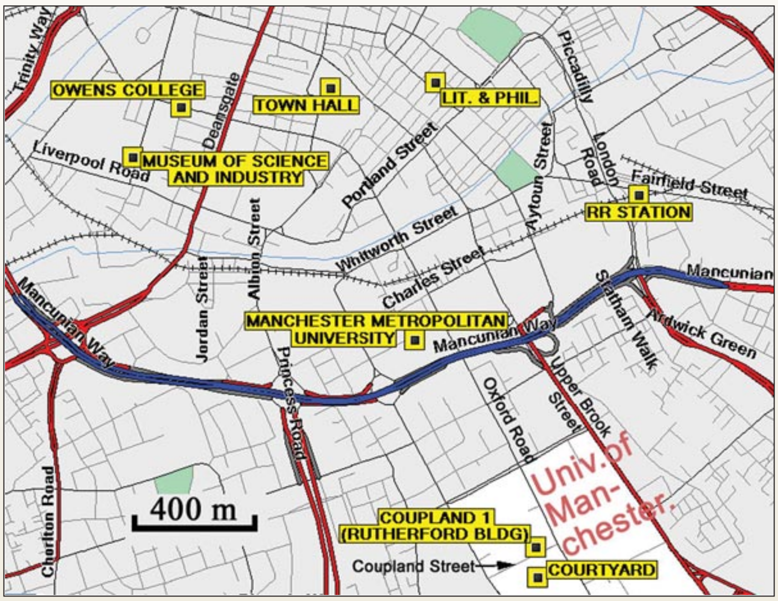
FRANCIS BACON, site of original home, Old Greyfriars Street, plaque– N51° 45.01 W01° 15.64.

MUSEUM OF NATURAL HISTORY, several statues and Lewis Carroll exhibit, Parks Road– N51° 45.51 W01° 15.36.

TOWNSEND HALL (Electrical Building), Physics Department, laboratory of Moseley, Parks Road– N51° 45.56 W01° 15.39.

LINDEMANN HALL, Physics Department, Moseley Room with original apparatus and memorabilia, Parks Road– N51° 45.59 W01° 15.41.

Figure 4. Manchester, England landmarks, including those not only for Rutherford and Moseley, but also Dalton and Roscoe (discussed in previous HEXAGON articles[2a,c]):



OWENS COLLEGE (now a barrister's office building), where Roscoe first prepared metallic vanadium, N53° 28.72 W02° 15.12.

TOWN HALL, marble statues of Dalton and Joule, Ford Maddox Brown's famous mural paintings portraying the history of Manchester, including one of Dalton collecting marsh gas; Albert Square–N53° 28.77 W02° 14.66.

LIT. & PHIL. (Literary and Philosophical Society), destroyed in WWII raid (December 1940); now Devonshire House, 36 George Street, blue plaque– N53° 28.76 W02° 14.38.

MANCHESTER METROPOLITAN UNIVERSITY, site of Dalton bronze statue, Chester Street– N53° 28.32 W02° 14.44.

UNIVERSITY OF MANCHESTER: [OLD] COUPLAND 1 BUILDING (now called Rutherford Building), site of Rutherford's and Moseley's pioneering studies, Coupland Street– N53° 27.96 W02° 14.08.

UNIVERSITY OF MANCHESTER: COURTYARD, University of Manchester, WWI tribute to Moseley– N53° 27.93 W02° 14.05.

concerning the Periodic Table. With Moseley's discoveries one could now establish the correct ordering of elements and predict specifically which ones were yet to be discovered.[6a]

Henry Moseley came from a distinguished scientific family. His paternal grandfather had been a famous mathematician and physicist at King's College, and his maternal grandfather trained as a barrister but later pursued his love of conchology (mollusks). His father (who died in 1891) was a professor of biology at Oxford University; he was part of the scientific staff of the H. M. S. Challenger oceanographic expedition of 1872–1876. The young Henry (who was known as "Harry" by his friends) attended the famous Eton College and then Trinity College at Oxford where in 1910 he received his M.A. degree.[7]

A natural experimenter, Harry wanted to do original research. Impressed with the superior physics program at Manchester, he joined Rutherford's group after graduating from Oxford. Moseley was assigned a problem in radioactivity, but he was intrigued by the new phenomenon of X-rays (discovered by Wilhelm Röntgen in 1895).[6a] In July of 1912 it was discovered by William Lawrence Bragg (1890–1971) that X-rays generated a diffraction pattern when passed through a crystal.[8] Moseley traveled to Leeds to the laboratory of William Henry Bragg (1862–1942) to learn the art of X-ray analysis (father William Henry and son William Lawrence received the Nobel Prize in 1915 for X-ray spectroscopy). Back in Manchester, Henry Moseley and Charles Galton Darwin (1887–1962; a grandson of *the* famous Charles Robert Darwin 1809–1882) initiated an X-ray investigation of metals, where they investigated the behavior of reflected X-rays from crystal surfaces.[6a]

Meanwhile, Moseley had independently formulated a new research idea. In 1906 Charles Glover Barkla (1877–1944) had discovered that a metal target when bombarded by electrons would emit homogenous X-rays characteristic of the metal; he had observed two series and named them K-lines ("hard" radiation) and L-lines ("soft" radiation)[9] (these are now known to arise from electrons falling to vacancies in the lowest two atomic electronic levels, logically named the K and L shells). Moseley decided he would explore the possibility of relating the frequency of these emitted X-rays to a physical property of the element. These physical parameters—which we know were discussed during a conversation of Moseley, Darwin, Bohr, and Hevesy in June 1913 at Manchester[6a]—might include some function of A (atomic mass) or of Z (nuclear charge). These parameters of A and Z had been developed on the basis of the famous alpha particle scattering experiments at Manchester of Rutherford and Ernest Marsden (1889–1979), the original basis for Rutherford's nuclear atom.[6b] The scattering experiments suggested[10] that, at least for the lowest elements of the Periodic Table, $Z = A/2$.

An amateur Dutch scientist, Anton van den Broek (1870–1926), had proposed that an element's position in the Periodic Table might reflect this "intra-atomic charge" of Z.[11] Broek proposed definite values for Z (he preferred the notation M, for "Mendeleev's number") for selected elements through uranium,[11] calculated by the use of formulas he contrived while employing assumed (but incorrect) pre-Bohr electronic configurations. Broek actually put

Figure 6. The Rutherford Building in Manchester. This was the original physics building opened in 1900, known at first as the Schuster Building and then as the Coupland I Building. Here Rutherford assembled his distinguished team of nuclear pioneers. A plaque on the building reads: "Ernest Rutherford . . . led this laboratory 1907–1919—Herein discovered the nuclear atom, split the atom, and initiated the field of nuclear physics."

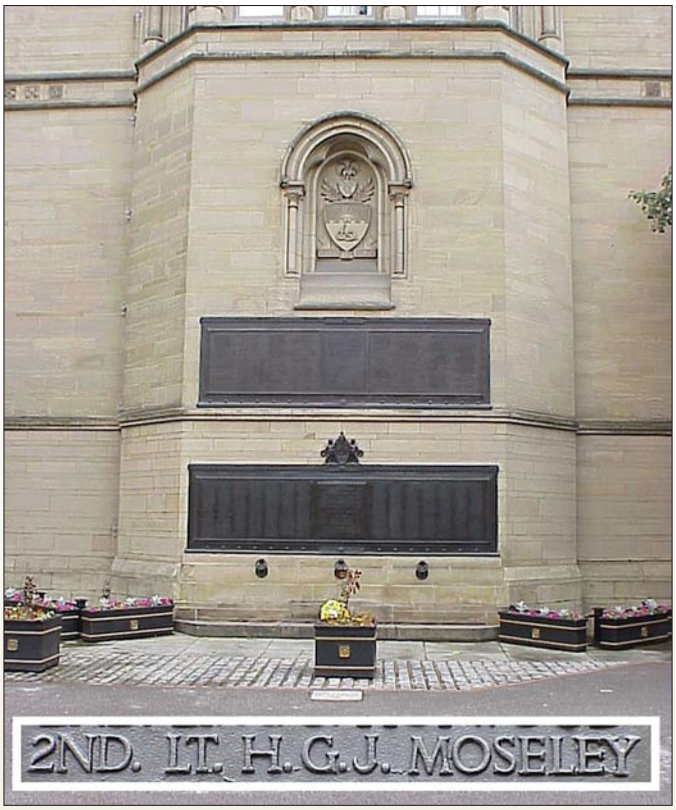


Figure 7. The Roll of Honor and the World War I Memorial in the courtyard of Whitworth Hall. In the center is inscribed: "To the members of the University of Manchester and of the Officers Training Corps who laid down their lives in the Great War of 1914–1919. In grateful and enduring remembrance. He has brought his eternity with a little hour and is not dead." Moseley was a member of the Royal Engineers. Inset at bottom: Moseley's entry.

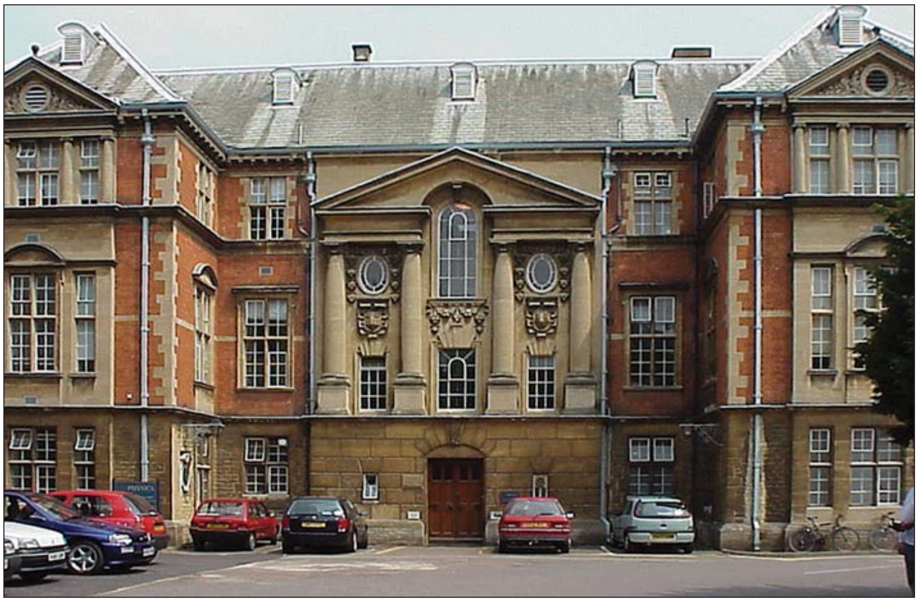


Figure 8. Townsend Hall, where Moseley performed his research in Oxford. This building presently lies 100 m north of the Museum of Natural History which includes specimens of a dodo, a flamingo, and other creatures which inspired the creatures in Lewis Carroll's (Charles Lutwidge Dodgson 1832–1898) Alice in Wonderland. *Townsend Hall was originally known as the Electrical Science Building, built in 1910, just in time for Moseley to continue his X-ray studies in 1913. It is, unfortunately, not known which laboratory inside the building he used. Next door (north) is Lindemann Hall (not shown) with the Moseley Lecture Hall with a small display on Moseley (see Figure 3). This photograph was taken in 2001; in 2007 a plaque was mounted by the door (see next figure).*

Figure 9. Royal Society of Chemistry (RSC) plaque mounted at entrance of Townsend Hall. The Clarendon Laboratory of physics encompasses Townsend and Lindemann Halls. Courtesy, Jim Williamson, Emeritus, Atmospheric, Oceanic and Planetary Physics, University of Oxford.

forward correct values through 50, but then fell into error for the heavier elements, e.g., W = 78, Au = 83, U = 96 (instead of correct 74, 79, 92, respectively). But before Moseley's work, no one knew how to get at an independent measure of this intra-atomic charge.

Moseley's goal was specific: "My work was undertaken for the express purpose of testing Broek's hypothesis . . ."[12] Moseley had gained a reputation of perhaps being the only one to equal Rutherford's hard work, drive, and results;[7] and by the fall of 1913 he had obtained the K-line spectra of the series calcium (20) through zinc (30) (excepting the scarce element scandium, 21). Accurate measurements were possible because of the preparatory collaborative work with Darwin. The calcium-zinc series included the perplexing pair nickel and cobalt: nickel had a lower atomic mass, but its chemical behavior more closely resembled the higher family including palladium and platinum. Moseley's results were dramatic and simple, which he described in an article entitled "The High Frequency Spectra of the Elements."[13] He found that the frequency ν of K-alpha (the strongest line) was accurately described by the equation $\nu/\nu_0 = 3/4\ (N-1)^2$, where ν_0 was the Rydberg frequency (previously developed in spectroscopic studies) and N was a number termed "the atomic number" by Moseley (and perhaps jointly with Rutherford).[14] The 3/4 coefficient was recognized by Moseley as the $1/1^2 - 1/2^2$ term already observed in Rydberg expressions, and the "1" in the (N - 1) term was rapidly identified as the shielding effect of inner electrons.[12] Moseley pointed out that his work clearly established that indeed nickel had a higher atomic number than cobalt. The confident Moseley unequivocally stated: "We have here a proof that there is in the atom a fundamental quantity, which increases by regular steps as we pass from one element to the next. The quantity can only be the charge on the central positive nucleus, of the existence of which we already have definite proof."[13] Moseley went on to predict: "It [the correlation of X-ray spectra with N] may even lead to the discovery of missing elements, as it will be possible to predict the position of their characteristic lines. . . ."[13]

The next step in Moseley's research was to produce the X-ray spectra of the higher elements. But Moseley performed no more work at Manchester. In November of 1913, after writing his seminal paper,[13] Moseley returned to Oxford. It is apparent that he was homesick for "The City of Dreaming Spires" with its more scholarly atmosphere, and he wished to be closer to his widowed mother[6a] and the opportunities of the countryside where he had spent many pleasant years pursuing bird-nest collecting and other hobbies.[7] A letter to his mother from Manchester gives an insight to his feelings: "Today the fog is so thick, that I shall probably get lost on my way to the College; it tastes acrid and tickles the throat . . . . Monday the fog was thinner but more yellow. Sunday it poured all day. . . ."[7] Also, he was apparently uneasy in the less formal industrial culture and mixed student body of Manchester, perhaps "feeling himself above students, even equal with Rutherford, whose tea-time conversation of slang, banter, and wisecracks he judged more suitable to a caricature of a colonial rather than a professor of physics."[10] Whatever the reasons, the motivation to return to Oxford was strong, because he departed Manchester immediately upon finishing his work, even though no appointment awaited him in Oxford.

Once settled in Oxford, Moseley was given access to a laboratory in the Electrical Science Building (physics building), and by private means he assembled equipment to continue his research (his X-ray tube had been broken and a new one needed to be constructed). By April of 1914, he had gathered data from additional lower elements using K-lines as well as higher elements using L-lines. The equation for the L-alpha lines was $\nu/\nu_0 = 5/36\ (N-7.4)^2$, where 5/36 was recognized as the Rydberg expression $1/2^2 - 1/3^2$ and 7.4 was an electron shielding factor. In all he was able to establish unambiguously Z values for 38 elements in a range from aluminum (13) to gold (79) (Figure 3) which he presented in his second paper, "High Frequency Spectra of the Elements, Part II."[15] Again, his plot clarified the situation of "odd pairs"—lighter potassium had a higher atomic number than argon, and lighter iodine had a higher atomic number than tellurium (the iodine-tellurium problem had existed since 1871, when Mendeleev reversed tellurium and iodine in accordance with their chemical properties; he resolved the difficulty by assuming the atomic mass determined for tellurium was incorrect![2b]). Furthermore, Moseley's plot removed confusion with the lighter rare earths 57–68 (but not 69–71; see caption to Figure 3). And lastly, his atomic numbers unequivocally identified the location of the true gaps where elements were yet to be discovered. Moseley did not analyze elements beyond gold (79) but two years later the Swedish physicist Karl Manne Georg Siegbahn (1886–1978; Nobel Laureate 1924) determined[16] that uranium lay at the high end of the natural elements with atomic number 92, establishing the prediction that future elements would be discovered with N = 43, 61, 75, 85, and 87 (Tc, Pm, Re, At, and Fr, respectively).

Georges Urbain (1872–1938), a rare-earth chemist in Paris and one of the co-discoverers of lutetium, heard of Moseley's remarkable technique and visited him in May of 1914. One of Urbain's goals was to verify his tentative discovery of a new rare earth "celtium." He was "flabbergasted"[10] that his samples were analyzed in one session— the samples which had totally occupied his attention with his laborious crystallization schemes for many years. Moseley's X-ray analysis removed confusion regarding the heavier rare earths (see Figure 3)— but no trace of celtium was found, and gaps remained at 61 (promethium) and 72 (hafnium). Urbain returned to France disappointed but amazed at the power of Moseley's technique.

Urbain's analyses were the last laboratory work Moseley performed. During the summer of 1914 he traveled to Canada, the U.S., and to Australia, where he attended the annual meeting of the British Association. When World War I broke out in August, Moseley returned to England and was determined to enlist, despite the fact that he could have served as a noncombatant.[7] He was commissioned in the Royal Engineers and was shipped to the Dardanelles in June 1915. At the tragic Battle of Gallipoli in Turkey, he was killed August 10, 1915.

Figure 10. X-tube used by Moseley in Oxford, constructed there since the one he used at Manchester had been broken (on exhibit in the Lindemann Hall Moseley Room).

Figure 11. This is the classic photograph of Moseley in 1910, in the Balliol-Trinity laboratories during his earlier stay at Oxford, before he went to Manchester. Moseley was a brilliant experimenter and customarily designed and prepared his own equipment. He once wrote to his mother while at Manchester: "Remaking the apparatus took a long time, as the laboratory assistant spent his time mending Rutherford's motorcar, and I had to make everything myself."[7]

Rediscovering Moseley. The two cities which can (and do!) claim credit for Moseley's discoveries, Manchester and Oxford, have their maps presented in Figures 4 and 5. In the map for Manchester are also included locations relating to John Dalton and Henry Enfield Roscoe (1813–1915) (respectively discussed in previous *HEXAGON* articles[2a,c]). The site of Rutherford's laboratory (Figure 6) was originally the physics building Coupland I, now called the Rutherford Building, located at the present University of Manchester. The Rutherford Building is now used by the Department of Psychology, but present plans include developing an exhibit on Rutherford there. At the main Courtyard at the University of Manchester is the World War I memorial which includes the name of Moseley (Figure 7). At Oxford Moseley performed his research at the Townsend Hall (physics building) (Figure 8). A tribute was erected to him and posted on this building in 2007 (Figure 9). An exhibit at the adjoining Lindemann Hall (physics building) Moseley Room, as well as collections at the Ashmolean Science Museum in Oxford, include a large portion of Moseley's equipment and apparatus he used in his studies (Figures 3, 10).

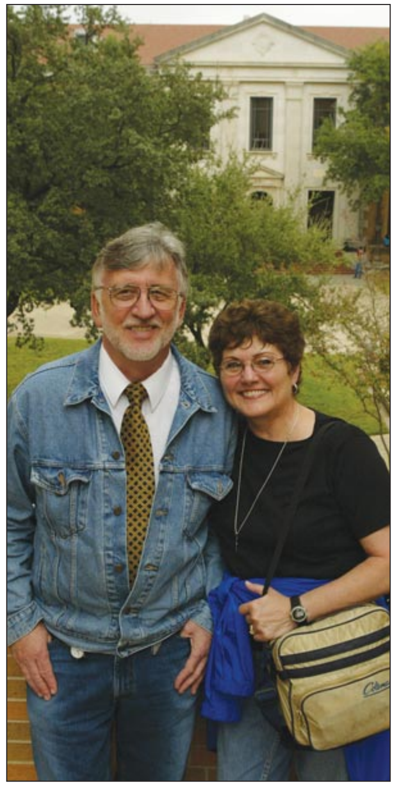
Moseley's Legacy. It is difficult to overestimate the importance of Moseley's work (Figure 11). In two papers he interlaced physics and chemistry, and put Rutherford's atom on a firm footing acceptable to all scientists. In a personal interview in 1962, Niels Bohr explained: "You see actually the Rutherford work [the nuclear atom] was not taken seriously…. There was no mention of it in any place. The great change came from Moseley."[7] When Urbain had visited Moseley in May of 1914, Moseley was astonished to find that Urbain did not care to understand the origin of the X-ray K- and L-lines.[7] Urbain had not the slightest curiosity of *why* Moseley's law worked.[7] Moseley marveled, "Where we try to find models or analogies, they [Continental scientists] are quite content with laws." But soon it became apparent that the well-known British need for "the robust form and vivid colouring of a physical illustration"[7] was perfect for the times—and it was Moseley's discoveries that persuaded the Continental scientists that the "childish British" atomic models[10] were in fact *real*.

Moseley performed his famous work on his law of atomic numbers during a period of about eight months. There is little doubt that if he had lived, he would have become a Nobel laureate *before* the other members of Rutherford's team—Soddy, Hahn, Bohr, Hevesy.[10] With Moseley's passing, both sides of the Great War mourned.[7] Asimov remarked, "In view of what he might have accomplished (he was only 27 when he died), his death might well have been the most costly single death of the war to mankind generally."[17] Moseley's death prompted Rutherford and others to convince the public and the British Ministry of Defence that scientists should be preserved in wartime since they are an asset not only to the public at large but to the military.[7]

But beyond this, Moseley's death represents so much more. Mustafa Kemal Atatürk (1881–1938), Turkish leader at the Battle of Gallipoli and founder and first president (1923) of the Republic of Turkey,[18] lamented the futility of war—his words are inscribed on the Anzac Cove Memorial (N40° 14.32 E26° 16.62), overlooking the main staging area in the Gallipoli Campaign:[19] "Those heroes that shed their blood and lost their lives…. You are now lying in the soil of a friendly country. Therefore rest in peace. There is no difference between the Johnnies and the Mehmets to us where they lie side by side here in this country of ours…. You, the mothers, who sent their sons from far away countries wipe away your tears. Your sons are now lying in our bosom and are in peace. After having lost their lives on this land they have become our sons as well." Atatürk's evocative words truly apply to Henry Moseley. Of the ca. 130,000 Allied and Turkish personnel who perished in this campaign April 25, 1915—January 9, 1916—an attempt of the Allies to control the Dardanelles straits leading to Istanbul (Constantinople)[20]—virtually all are buried on the Gallipoli peninsula, and a major portion of these lie in unidentified graves, including, as far as anyone knows, Moseley. Henry Moseley's name is memorialized by the inscription on the Helles Memorial (N40° 02.81 E26° 10.68) at the southernmost tip of the Gallipoli Peninsula, 23 km south of the Anzac Cove Memorial.[21]

References.

1. R. H. Kargon, *Science in Victorian Manchester*, **1977**, Johns Hopkins University Press, Baltimore, Maryland, 2–10.
2. J. L. Marshall and V. R. Marshall, *The HEXAGON of Alpha Chi Sigma*, (a) **2006**, *97(4)*, 50–55; (b) **2007**, *98(2)*, 23–29; (c) **2008**, *99(3)*, 42–46; (d) **2010**, *101(2)*, 22–26.
3. John Dalton, *A New System of Chemical Philosophy*, **1808**, Manchester.
4. Personal communication, Allan Jefferies, Administrator, Lit. & Phil. Soc., Manchester.
5. E. Rutherford, *Proc. Man. Lit. Phil. Soc.*, **1911**, *55*, xviii-xx.
6. J. L. Heilbron, *Historical Studies in the Theory of Atomic Structure*, **1981**, Arno Press, (a) "The Work of H. G. J. Moseley," 229–364; (b) "The Scattering of α and β Particles and Rutherford's Atom," 84–145.
7. J. L. Heilbron, *H. G. J. Moseley. The Life and Letters of an English Physicist, 1887–1915*, **1974**, University of California Press.
8. W. L. Bragg, *Proc. Cambridge. Phil. Soc.*, **1913**, *17*, 43–57; *Nature*, **1912**, *90*, 410.
9. C. G. Barkla, *Phil. Mag.*, **1906**, *11*, 812–828.
10. J. L. Heilbron, *Ernest Rutherford and the Explosion of Atoms*, **2003**, Oxford University Press.
11. A. van den Broek, *Nature*, **1911**, *87*, 78; **1913**, *92*, 372–373; **1913**, *92*, 476–478.
12. H. Moseley, *Nature*, **1913**, 92, 554 [*received Jan. 5, 1914*].
13. H. G. J. Moseley, *Phil. Mag.*, **1913**, *26*, 1025–1034.
14. E. Rutherford, *Nature*, **1913**, *92*, 423.
15. H. G. J. Moseley, *Phil. Mag.*, **1914**, *27*, 703–713.
16. M. Siegbahn and E. Friman, *Phil. Mag.*, **1916**, *31*, 403–406.
17. I. Asimov, *Asimov's Biographical Encyclopedia of Science and Technology*, **1964**, Doubleday & Company, 512–513.
18. A. Mango, *Atatürk*, **2000**, Overlook Press, Woodstock, N.Y.
19. B. Scates, *Return to Gallipoli*, **2006**, Cambridge Univ. Press, Cambridge UK.
20. E. W. Bush, *Gallipoli*, **1975**, St. Martin's Press, N.Y.
21. Records of the Commonwealth War Graves Commission, *http://www.cwgc.org/*.



Jenny and Jim Marshall

Rediscovering The Periodic Table, One Element at a Time

Shortly after getting married 12 years ago, Jim Marshall, a chemistry professor at the University of North Texas, took his new bride Jenny, a now-retired middle school computer teacher, on the honeymoon of a lifetime. Together, they set out in search of the birthplace of each of the 114 elements on the periodic table. They've finally completed their journey and compiled a comprehensive interactive DVD called "Rediscovery of the Elements."

"Rediscovery of the Elements" featured on PRI's "Here and Now"

There is a wonderful segment of PRI's "Here and Now" that ran on September 8, 2010, featuring an interview with Jim and Jenny Marshall, creators and authors of the popular "Rediscovery of the Elements" series. *http://www.hereandnow.org/2010/09/rundown-98-2/*