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Henry Moseley, X-ray Spectroscopy, the Nobel Prize and the Matteucci Medal

Abstract – The year 2019 was designated as the International Year of the Periodic Table by UNESCO, marking the 150th anniversary of the publication in 1869 by Dmitri Mendeleev of his first version of a periodic table of the chemical elements arranged in order of their atomic weights (these days given the symbol A). The year also marked the centenary of the posthumous award of the *Medaglia Matteucci* of the *Societa Italiana delle Scienze* to Henry Moseley in 1919. Before his untimely death in the pivotal battle of the Gallipoli campaign of World War I in August 1915, Moseley had shown that the frequencies of the characteristic X-rays emitted from different elements under bombardment by cathode rays could be linked to an ordinal number (now known as the atomic number Z) which defined both the charge on the atomic nucleus and the position of the element in the periodic table. The technique of X-ray spectroscopy that he had pioneered also revealed that there were four missing elements before gold. This short paper gives an account of the life and legacy of Henry Moseley; and in particular analyses the impact of X-ray spectroscopy in shaping the modern form of the periodic table. The paper also explores the story behind Moseley's nomination for Nobel Prizes in both chemistry and physics shortly before his death in 1915. Finally it discusses why he was awarded the *Medaglia Matteucci* four years later: Moseley remains the only posthumous recipient of this prestigious Italian award in its 150 year history.

Keywords: Henry Moseley; X-ray spectroscopy; atomic number; periodic table; Matteucci Medal; Nobel Prize.

Riassunto – L'UNESCO ha proclamato il 2019 come Anno internazionale della tavola periodica, in occasione del 150° anniversario dalla pubblicazione, nel 1869, da parte di Dmi-

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tri Mendeleev della prima versione di una tavola periodica degli elementi chimici disposti in ordine del loro peso atomico (oggigiorno indicato con il simbolo A). Inoltre il 2019 è anche l'anno in cui si celebra il centenario dell'assegnazione postuma a Henry Moseley della Medaglia Matteucci da parte della Società Italiana delle Scienze. Prima della sua prematura scomparsa nell'agosto 1915 nella battaglia cruciale della campagna di Gallipoli durante la prima guerra mondiale, Moseley aveva dimostrato che le frequenze caratteristiche dei raggi X emessi dai diversi elementi bombardati da raggi catodici potevano essere messe in relazione a un numero d'ordine (oggi noto come numero atomico e indicato con la lettera Z) che definiva sia la carica sul nucleo atomico sia la posizione dell'elemento nella tavola periodica. La tecnica della spettroscopia a raggi X, di cui Moseley ad oggi è considerato uno dei pionieri, gli permise anche di scoprire che dovevano esistere altri quattro elementi con un numero d'ordine inferiore a quello dell'oro, che risultavano mancanti nell'allora conosciuta tavola periodica. Questo breve articolo fornisce un resoconto della vita e dell'eredità di Henry Moseley e in particolare analizza l'impatto della spettroscopia a raggi X nel dare forma alla struttura attuale della tavola periodica. Vengono inoltre ricostruite le vicende che hanno portato alla nomination di Henry Moseley ai premi Nobel per la chimica e per la fisica nel 1915 senza che poi nessuno dei due premi venisse in effetti a lui assegnato. Infine si discutono le motivazioni per cui invece fu premiato quattro anni dopo con la prestigiosa Medaglia Matteucci, di cui Moseley rimane l'unico destinatario postumo nei 150 anni di storia del premio.

Parole chiave: Henry Moseley; spettroscopia a raggi X; numero atomico; tavola periodica; Medaglia Matteucci; Premio Nobel.

Henry Moseley: a brief biography

Henry Gwyn Jeffreys Moseley (known as Harry to his friends and family) was born into a distinguished academic family. His father, Henry Nottidge Moseley, was a Fellow of the Royal Society of London (FRS) and Professor of Anatomy in the University of Oxford: he was a close friend of Charles Darwin and had played an important part in the Challenger expeditions. His mother Amabel was a well-known amateur zoologist and expert chess player. However, at around the time Harry was born, his father began suffering from what proved to be a terminal neurological condition. This meant that although the family home remained back in Oxford, the Moseleys had moved to Dorset in the hope that sea air might prove therapeutic and Harry's birth was registered in Weymouth. His father died in 1891 when Harry was four (Hopkins 2018).

Formal education began at Summerfields School in Oxford, followed by Eton, the famous English school for the elite. Here his first passion was chemistry and his award of a scholarship at Trinity College Oxford starting in 1906 was probably made on the basis that he would study this subject for his degree. But after achieving top marks in first year mathematics, he switched to physics. Based on his Finals Examinations, Harry was disappointed in 1910 to be awarded a second class degree (a photograph taken around this time is shown in figure 1). However, he secured a position as University Demonstrator in Physics at the University of Manchester, working under the patronage of Ernest Rutherford, Nobel Laureate in

Fig. 1. Henry Moseley in a laboratory run by Balliol and Trinity Colleges in Oxford in the early 1900s. This photograph was probably taken in 1910 just after his Finals examinations and is the only known photograph of Moseley in a laboratory (Image by courtsey of Trinity College, Oxford).

Chemistry in 1908 (Hopkins 2018). During his first two years at Manchester, Moseley had a heavy teaching load. As with the rest of Rutherford's group, his research was on radioactivity. Moseley did not find this research to be very exciting or intellectually stimulating. In the autumn of 1912 he began his research on X-rays, leading to a joint experimental paper with Charles Glanton Darwin in May 1913 (Moseley and Darwin 1913): this Charles Darwin was grandson of the better-known evolutionary biologist of the same name, and a family friend from an early age (Todd 2018).

In September 1913 Moseley was elevated to receive a half-share of a departmental fellowship in physics. This gave him more time to do research and in a remarkable few weeks between August and November 1913, he designed and completed the first tranche of his pioneering experiments on «High Frequency Spectra of the Elements» (Moseley 1913), to be discussed below. With this work in full flow, he resigned from Manchester and moved back to Oxford in November 1913, without any formal position on offer. However, he secured research space in the 'Electrical Laboratory' and acquired sufficient equipment to get going with a second phase of experiments. By April 1914 he had succeeded in measuring X-ray spectra of almost forty elements (Moseley 1914a; Frederick-Frost 2018). He continued to work on X-ray spectra of the lanthanide elements after the publication of his second «High Frequency» paper, before setting off with his mother to attend a meeting of the British Association for Advancement of Science in Australia. After a long journey, they arrived in Australia on 8 August 1914. Four days earlier Britain had entered what became the Great War. Moseley's work figured strongly in a discussion on «the Structure of Atoms and Molecules» held in Melbourne on 18 August, while on 25 August he presented a formal paper on his work in Sydney (Bruton 2018).

Keen to do his bit in the war effort, Harry travelled back from Australia, sailing from Sydney on 29 August 1914 and arriving back in England via San Francisco and New York. He abandoned research and threw all his energies into trying to gain a commission in the Royal Engineers – who were not convinced that a physicist could make a good army engineer. Harry finally enlisted as a Second Lieutenant in October 1914. After several months of training in signalling, he became a Signals Officer in the 38th Brigade of the 13th Division of Kitchener's «New Army». Harry expected to join forces on the Western Front, but was instead sent to the Gallipoli peninsula as part of the British Mediterranean Expeditionary Force. On arrival in Gallipoli early in July 1915, Harry quickly found himself in the front line trenches of Cape Helles at the southern end of the Gallipoli peninsula. After a brief withdrawal to the island of Lemnos, on 5 August Harry landed in Anzac Cove in support of the «Anzac Breakout» operation. Five days later on 10 August he was killed in the pivotal engagement of the whole Gallipoli campaign. Although it has been stated many times that he was shot by a Turkish sniper, there is no evidence that he was specially targeted. In fact Harry died in the face of an overwhelming infantry assault by the Ottoman forces, supported by a «hailstorm» of indiscriminate machine gun fire. His body was never recovered (Bruton 2018).

Moseley's X-Ray Experiments: Background and Execution

At the end of the nineteenth century Wilhelm Röntgen stumbled across a new form of penetrating radiation emitted from discharge tubes when high energy cathode rays (electrons) impinged on a metal target (Authier 2015). He made extensive investigations of the properties of these mysterious «X-rays» or *Röntgenstrahlen,* leading to the award of the *Medaglia Matteucci* in 1896 and the first Nobel Prize in Physics in 1901 (Egdell, Offi and Panaccione 2018). Important steps toward understanding the nature of X-rays lay in the work of Charles Barkla, who showed that when primary hard X-rays fell onto an elemental target, secondary X-rays were emitted and that this radiation contained a component «characteristic» of the element in the sense that rays from different elements had different attenuation lengths in thin metal foils. He further showed that some elements emitted two different sorts of characteristic radiation: more penetrating (harder) K-type X-rays and less penetrating (softer) X-rays (Barkla 1911). The next major step was the observation by Friedrich and Knipping that a spot pattern developed when X-rays from a discharge tube passed through a crystal onto a photographic plate. Max von Laue gave an explanation of these patterns in terms of interference effects of short wavelength electromagnetic waves, leading to award of both the Nobel Prize in Physics and the *Medaglia Matteucci* for 1914 (Egdell, Offi and Panaccione 2018). Moseley was excited by these results, but looking closely at von Laue's papers he realised that the explanations were wrong in detail (Datta 2015). Working with Darwin, Moseley came up with a «proper» explanation of the spot patterns and gave an account of his work at a meeting in Manchester on 1 November 1912. This talk was probably the first public airing of what is now known as the Bragg equation, but there is no formal record of the content of the presentation. William Henry Bragg (Professor of Physics at Leeds) was in the audience: he told Moseley that his son William Lawrence Bragg (then a student in Cambridge) had derived a similar explanation a few days earlier.

> I gave a lecture [on X-rays] on Friday. Bragg the chief authority on the subject (Physics Professor at Leeds) was present. The men [Laue *et al.*] who did the work entirely failed to understand what it meant, and gave an explanation that was obviously wrong. After much hard work Darwin and I found out the real meaning of the experiments, and of this I gave the first public explanation on Friday. I knew privately however that Bragg and his son had worked out [the] explanation a few days before… We are therefore leaving the subject to them (Moseley 1912).

The younger Bragg's results were presented to the Cambridge Philosophical Society by J.J. Thomson ten days later on 11 November 1912 and appeared in print shortly afterwards (Bragg 1913).

Both the Manchester team and the Braggs realised that interference effects could be observed more easily in a reflection geometry and both built X-ray spectrometers that used specular reflection from a crystal to sort the radiation from a platinum X-ray tube into its different wavelength components based on the equation:

$$n\lambda = 2dsin\theta$$

Here θ is the specular angle of diffraction by a series of atomic planes with inter-planar spacing d in a reflection geometry and λ is the wavelength of the X-rays. The integer n specifies the «order» of the reflection.

The two competing groups both published papers showing a series of characteristic L emission lines in different orders, superimposed on a broad background of what is now called *Bremstrahlung* radiation: the Manchester paper appeared in print about a month after the paper from Leeds (Bragg and Bragg 1913; Moseley and Darwin 1913). At this point there was a parting of the ways and the Braggs concentrated on using a fixed radiation source to probe d spacings in different crystals, thus founding the field of X-ray crystallography. Moseley by contrast was more interested in using one fixed crystal as a monochromator to explore the wavelengths of X-rays emitted from different elemental targets, thus establishing the new field of X-ray spectroscopy.

Around August 1913 Moseley began to plan a systematic series of experiments on X-ray spectra of the elements. He was obsessive and unrelenting in finishing an experiment once it had started, even if this involved staying in the laboratory throughout the night.

> Moseley was without exception or exaggeration the most brilliant man – and the hardest worker I have ever met. There were of course no regular meals, and work often went on for most of the night. Indeed one of Moseley's expertises was the knowledge of where one could get a meal in Manchester at 3 o'clock in the morning (Darwin 1962).

Darwin found it impossible to match Moseley's uncompromising approach to experimental work and in the next tranche of experiments Moseley was alone. This work was motivated in part by discussions with Neils Bohr. Experiments conducted in Manchester by Hans Geiger and Ernest Marsden shortly before Moseley's arrival had led to Rutherford's nuclear model of the atom, with the positive charge concentrated in a small volume at the centre (Rutherford 1911). This model explained the surprising scattering of α-particles through large angle by thin metal foils observed by Geiger and Marsden. Bohr was a regular visitor to Manchester and was in the throes of refining Rutherford's model to explain the atomic spectra of hydrogen and other atoms in terms of «stationary states» with well-defined angular momentum. Within his model the energy of the stationary states depended on the square of the charge on the atomic nucleus (Bohr 1913).

In his first paper on «High Frequency Spectra of the Elements» Moseley presented X-ray spectra of the elements from Ca through to Zn, the latter being present in a sample of brass (Cu/Zn), thus avoiding the danger of melting the zinc in the electron beam (Moseley 1913). Sc was missing for the simple reason that elemental Sc was not available in 1913. His experimental set up involved an important innovation in sample handling: several samples were mounted on a «railway track» and could be pulled into the cathode ray (electron) beam using threads attached to bobbins. This avoided the need to evacuate the X-ray tube every time the sample was changed. He also opted to detect the diffracted X-rays on photographic plates, rather than using an ionisation detector, as in his paper with Darwin. The results of these experiments are summarised in a diagram now known as Moseley's staircase, which showed X-ray photographs aligned on a common angular scale, thus demonstrating a progressive decrease in diffraction angle (and hence decrease in wavelength and increase in frequency) in moving from one element to the next across the transition series (figure 2). Moseley found that the frequencies $\nu_{K\alpha}$ of the strongest lines in his spectra conformed to a simple mathematical formula

$$\nu_{K\alpha} = \nu_0 \frac{3}{4} (N - 1)^2$$

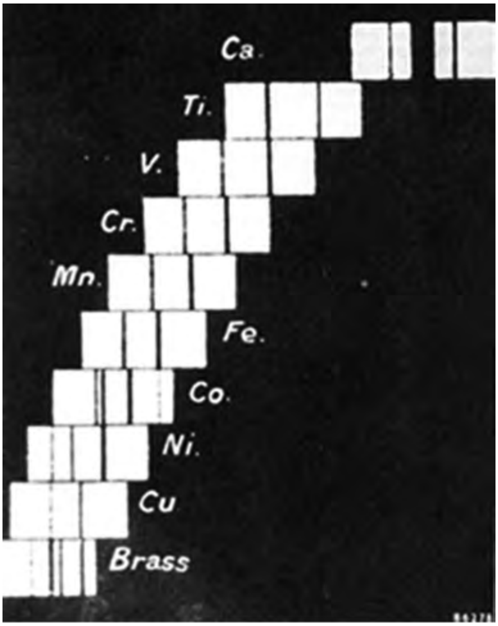

Fig. 2. Moseley's staircase. The angle of diffraction increases from left to right. (Original Source: *Philosophical Magazine Series 6*. 26, 1024-1034, 1913, now in the public domain).

where v_0 is the frequency of radiation required to ionise a hydrogen atom and N is the order number of the element in the periodic table. Moseley concluded that:

> 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. This quantity can only be the charge on the central positive nucleus, of the existence of which we already have definite proof.

And:

> Its [X-ray spectroscopy's] advantage over ordinary spectroscopic methods lies in the simplicity of the spectra and the impossibility of one substance masking the radiation from another. It may even lead to the discovery of new elements, as it will be possible to predict the position of their characteristic lines (Moseley 1913).

The occurrence of v_0 in Moseley's expression and the prefactor $3/4 = 1/1^2 - 1/2^2$ provided an immediate link to the energy of $n = 1$ and $n = 2$ stationary states in the Bohr Model. Moseley's experiments also settled the issue of ordering of Co and Ni in the periodic table. It was a longstanding problem that the atomic weight of Co was slightly higher than that of Ni, but chemical properties suggested that Co should precede Ni.

The second of Moseley's key papers was published in the spring of 1914, based mainly on work completed in Oxford (Moseley 1914a). He measured X-ray spectra of almost forty elements and presented his results as a plot of atomic number against the square root of the X-ray frequency (figure 3). He measured K-shell spectra for elements between Al and Ag; and L-shell spectra for elements between Zr and Au. Aside from Cl, where he obtained a spectrum from KCl rubbed onto a

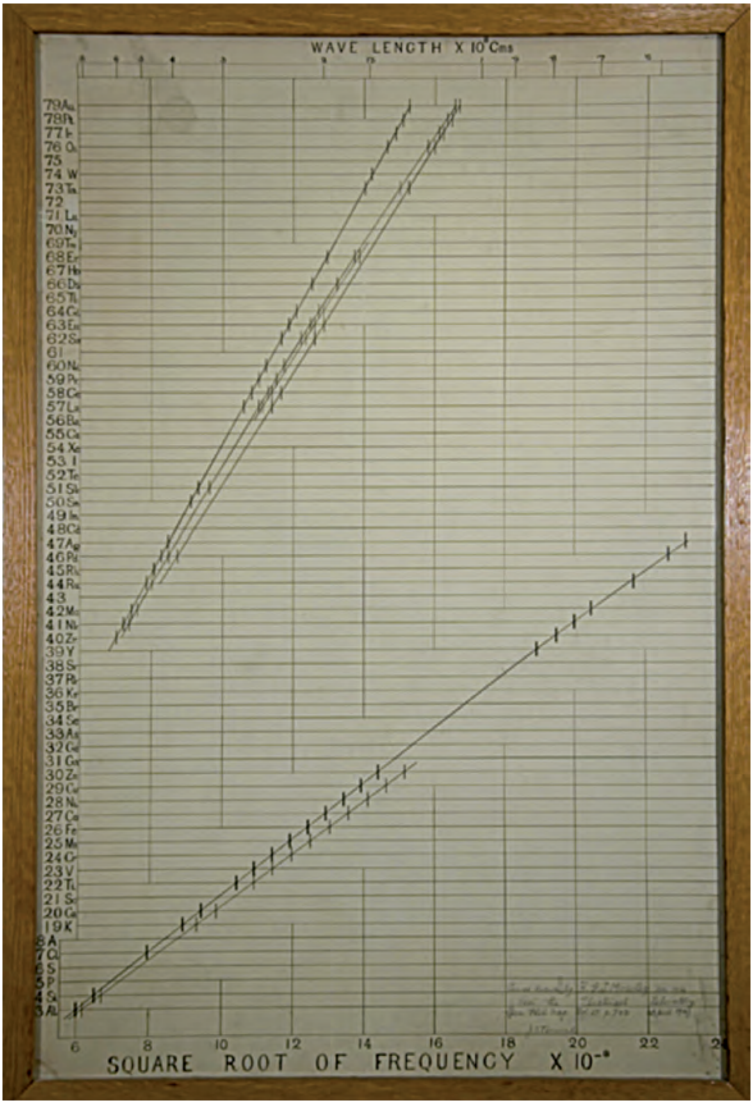

Fig. 3. A photograph of a framed hard copy of Moseley's original plot of atomic numbers for the elements against the square root of X-ray frequencies for K and L lines. The plot hangs in the Clarendon Laboratory in Oxford (Source: photograph by courtesy of Department of Physics, University of Oxford).

Ni plate, no data for non-metallic elements were included and it was also impossible to deal with low melting point metals unless present in an alloy or compound. As well blank spaces for these known elements, the published plot contains gaps for three «missing» elements, those with Z values of 43, 61 and 75.

The second paper included some data for rare earth elements, but most samples available to Moseley were «terrible mixtures». His published plot contained two striking errors. The order of Dy (Ds) and Ho was wrong; and he allowed for two form of thulium, TmI and TmII, thus displacing Yb and Lu into the wrong places as elements 71 and 72. After publication of his paper he obtained samples of several more rare earth samples from French chemist George Urbain and was able to insert hand drawn corrections onto his master plot: Dy (Ds) and Ho were put in the correct order and just one version of Tm was included, thus leaving room for a fourth missing element with Z = 72 (figure 4). Urbain arrived in Oxford in the spring of 1914 with a sample of what he claimed to be the missing element 72, prepared by repeated recrystallisations of extracts from monazite sand rich in rare earths. The name celtium had been proposed for this element. Much to the disappointment of both Urbain and Moseley, celtium proved to be a mixture of elements 69 and 70, Yb (Ny) and Lu (Frederick-Frost 2018).

Moseley's formula for the strongest L-rays turned out to be:

$$v_{L\alpha} = v_0 \frac{5}{36} (N - 7.4)^2$$

In this case the prefactor suggested involvement of stationary states with n = 2 and n = 3 since $5/36 = 1/2^2 - 1/3^2$. Although the framework for fully understanding the results did not exist at the time, sketches in Moseley's correspondence suggest he was quite close to developing a picture similar to that which would now be used to explain X-ray spectra to an undergraduate (figure 5). He also realised M-rays with a prefactor $1/3^2 - 1/4^2$ should be observable for heavier elements.

Fig. 4. A comparison between the published version of Moseley's plot and the corrected version shown in figure 3 for the later lanthanides. Several corrections are apparent. (Photograph and figure prepared by the authors).

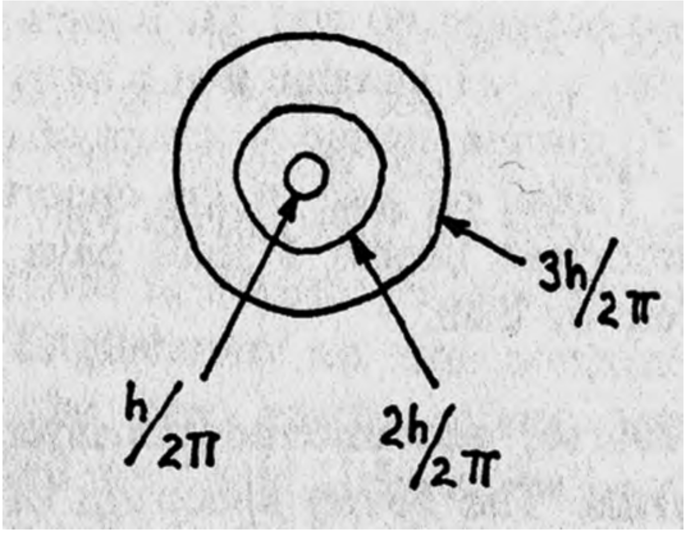

Fig. 5. Sketch in Moseley's letter to Darwin discussing the nature of K and L X-ray lines (Moseley 1914b).

> My formula $\nu = (1/2^2 - 1/3^2)\ \nu_0\ (N\text{-}s_n)^2$ for the L rays turns out to be triumphant, a great piece of luck as I published it [in the first «High Frequency» paper] on the slenderest evidence – I take it that the formula means that the second ring is a 2h/2π ring. What the formula means physically I cannot imagine – I am going to look for an M series $(1/3^2 - 1/4^2)$ – It might interest you if you have any spare time to work out the properties of an atom with 3 rings (Moseley 1914b).

Moseley's Legacy

There are main three strands to Moseley's legacy. Perhaps the most important but the least tangible is that the measurements of X-ray spectra and derivation of simple laws for X-ray frequencies were of critical importance in promoting acceptance of the Bohr Model, leading in turn to the quantum and wave mechanical descriptions of atomic structure that now underpin almost all areas of physics and chemistry. In Bohr's own words:

> – you see actually the Rutherford work [the nuclear atom] was not taken seriously. We cannot understand today, but it was not taken seriously at all. There was no mention of it any place. The great change came from Moseley (Bohr 1962).

Secondly, and more concretely, as Moseley had anticipated, the two 'High Frequency' papers laid the foundations for the new field of X-ray spectroscopy. X-ray emission spectroscopy is now one of the most important techniques for elemental analysis, with applications in fields as diverse as scrap metal dealing, geological surveying and forensic science. X-ray emission spectrometers have even found their way into space. Moreover a huge range of other techniques including X-ray absorption and X-ray photoelectron spectroscopy exploit the characteristic energies of core levels: a literature search using Web of Science software throws up in excess of 500,000 papers involving X-ray spectroscopy broadly defined published since 1945 (Egdell 2018a).

Thirdly, X-ray spectroscopy has played an important part in shaping the modern form of the periodic table. As we have seen, Moseley's experiments left gaps for four elements before gold ($Z = 79$), those with Z values of 43, 61, 72 and 75. With further measurements up to and including uranium ($Z = 92$) published in 1916, Manne Siegbahn established that there were two further gaps at $Z = 85$ and $Z = 87$ (Siegbahn and Friman 1916). The expectation in the early post-war years was that each element would be discovered in a straightforward way by measurement of X-ray spectra in material derived from naturally occurring minerals, possibly preceded by chemical enrichment procedures.

Things did not turn out to be so straightforward: only two of the six missing elements, those with $Z = 72$ and 75, ultimately proved to occur naturally at sufficiently high concentration to enable characterisation by X-ray spectroscopy, and even for these two discovery was mired in controversy as discussed below. Elements 43 (now technetium Tc), 61 (now promethium Pm), 85 (now astatine At) and 87 (now francium Fr) all transpired to have short half-lives and initial characterisation relied radiological techniques, involving chemical separation procedures and examination of the characteristics of the radioactive decay. This was the traditional way in which trace naturally occurring radioactive elements (Po, Rn, Ra, Ac, Pa with Z values 84, 86, 88, 89 and 91) had been discovered. Moreover Tc, Pm and At required nucleosynthesis in a cyclotron or atomic pile (Fr appeared as a short lived element in the decay chain of Ac). Nonetheless claims for discovery of each of the elements 43, 61, 85 and 87 based on X-ray spectra appeared in the published literature between the 1920s and the 1940s. All too often these false claims relied on reports of X-ray frequencies in tables without supporting raw data; or plates where weak X-ray lines were too weak to pass contemporary scrutiny (Egdell 2018b).

Returning to $Z = 72$, we recall that Moseley had searched for this element in his experiments on Urbain's samples in 1914. Despite the finding that celtium was a mixture of $Z = 70$ and 71 (ytterbium and lutetium), Urbain never gave up on the idea that his recrystallisations of extracts from rare earth minerals had not isolated traces of a new rare earth. At Urbain's request, in 1922 Alexandre Dauvillier re-examined the same sample that Moseley had studied, using an X-ray spectrometer designed by Maurice de Broglie. Dauvillier claimed he had found very weak X-rays lines characteristic of element 72 (Dauvillier 1922), but this claim was never substantiated. However it was becoming obvious from developments in the understanding of the periodic table based on recent advances in quantum mechanics that element 72 should in fact be a transition metal in the same group as zirconium. Accordingly in 1923 Dirk Coster and Georg von Hevesy subjected zircon minerals to X-ray analysis and immediately found strong and convincing L emission lines characteristic of element 72 in virtually all samples they could lay their hands on. They proposed the now-accepted name hafnium for element 72, based on the Latin form for the city of Copenhagen where they had conducted their research in Bohr's institute (Coster and von Hevesy 1922; Coster 1972). Controversy over the naming of element 72 rumbled on over many years and was only settled in favour of hafnium after Urbain's death in 1938 (Egdell 2018b).

Element 75 was the second to be discovered by X-ray spectroscopy by the German team of Walter Noddack, Ida Tacke (who later married Noddack) and spectroscopist Otto Berg. In 1925 they published a paper showing a L-shell X-ray spectrum of element 75, for which the name rhenium was proposed (Noddack, Tacke and Berg 1925). Isolation of a 1 gm sample of rhenium followed in 1929 (Noddack and Noddack 1929). However the 1925 paper was sullied by also containing a table of K-shell X-ray frequencies for element 43, for which the name masurium was proposed. This work was never substantiated and element 43 was first found in 1937 as the product of deuteron bombardment of molybdenum ($Z = 42$) in a cylcolotron. It was eventually named technetium after the Greek for artificial (Perrier and Segrè 1947).

The Nobel Prize and the Matteucci Medal

On 30 January 1915 (shortly before the 1 February cut-off date) Svante Arrhenius nominated Moseley for Nobel Prizes in both chemistry and physics. This was Moseley's only nomination, but Arrhenius was winner of the Nobel Prize in Chemistry for 1903, and was one of the most influential figures in the Royal Swedish Academy of Sciences at the time. The Physics Committee of the Academy passed over detailed consideration of the nomination to the Chemistry Committee, who decided that it was probably too early to assess the full significance of Moseley's work and recommended award of their Prize for 1915 to Richard Willstätter. In any case Moseley was killed before the full Academy (who took final decisions that could be at variance with those of specialist subject committees) could vote on nominations for the 1915 awards. The statutes of the Nobel Foundation did not allow for consideration of a posthumous Prize for Moseley in subsequent years (Friedman 2018).

Shortly after the end of the Great War two Nobel Prizes in Physics were however awarded for work on X-rays and these are often regarded as proxy prizes for Moseley. The first of these was to Charles Barkla in 1918 (this was in fact the deferred Prize for 1917) for his work on characteristic X-rays discussed earlier. Barkla's award was based on a single nomination – made by Ernest Rutherford after the formal deadline of 1 February 1918! Rutherford's nomination made no specific reference to Moseley, and neither was Moseley mentioned in the presentation speech delivered by the Chairman of the Physics Committee, Gustaf

Granqvist. Barkla's Nobel Lecture made only passing reference to Moseley – the presentation revealed that Barkla had little understanding of recent developments in physics, and about half the lecture was spent discussing «evidence» for J-type X-rays, which had no place in the Bohr Model (Friedman 2018).

The second Prize was awarded to Manne Siegbahn in 1925 (again a Prize deferred from the previous year, in this case 1924). This was a controversial award as the Physics Committee found it difficult to identify a concrete discovery or invention on which they could pin the Prize, as required by the statutes on the Nobel Foundation. They eventually settled on the discovery of M-type X-rays, which Moseley had anticipated back in 1914. The Committee had five members, including Siegbahn himself, who obviously could not vote. The remaining four members were divided on institutional line, with Svante Arrhenius and Vilhelm Carlheim-Gyllensköld from Stockholm Högskola opposed to the nomination; and Carl Wilhelm Oseen and Alvar Gullstrand, colleagues of Siegbahn at Uppsala University, in favour. As chairman of the Committee Gullstrand, was able to give the casting vote. Gullstrand's presentation speech was effusive in acknowledging the importance of Moseley's work. It gave the clearest indications possible that Moseley would certainly have been awarded a Nobel Prize in Physics had he survived the Great War, and that Barkla's award was indeed a tribute to Moseley.

> As the atomic number has proved to distinguish the elements better than the atomic weight, it has now attained the very greatest importance for atomic physics of the present day. Moseley fell at the Dardanelles before he could be awarded the prize, but his researches had directed attention to the merits of Barkla, who consequently in 1917 was proposed for the Nobel Prize, which was awarded to him without delay (Gullstrand 1925).

Somewhat ungraciously, Siegbahn made no mention of Moseley in his Nobel Lecture (Friedman 2018).

Although it must always remain a matter of speculation as to whether Moseley would indeed have won a Nobel Prize had he survived the War, he certainly did win another major international award in Physics, the *Medaglia Matteucci* of the *Societa Italiana delle Scienze* (Egdell, Offi and Panaccione 2018). The *Societa* (now known as *L'Accademia Nazionale delle Scienze detta dei XL*) was originally founded as the *Societa Italiana* by Antonio Maria Lorgna in 1766. The *Medaglia Matteucci* was established a century later by the distinguished physicist and physiologist Carlo Matteucci in 1867, marking his election as *Presidente* of the *Societa* the year before. The first prize went to Charles Wheatstone in 1868. The award was formally ratified by *Regio Decreto* in 1870, two years after Matteucci's death in 1868 (the bequest which established the award in perpetuity was part of his will). The *Medaglia Matteucci* therefore predates the Nobel Prize in Physics by over thirty years, although it must be admitted that it has never aroused the level of public interest surrounding Nobel Prizes. It is obvious from Moseley's case that posthumous award of the *Medaglia* is not precluded, although Moseley is the only individual to have received the award posthumously in its 150 year history. Documents held in the archive of the *XL* in Rome tell us that Moseley got an honourable mention in the *Relazione per il conferimento della Medaglia Matteucci* for the Braggs, who won the medal in 1916. Moseley's *Relazione* for the 1919 medal was prepared by a *Commissione* of three fellows of the *XL*: Antonio Roiti (*Presidente* of the *Commissione*), Augusto Righi and Orso Mario Corbino (who as *Relatore* conveyed the outcome of the deliberations of the *Commissione* to the *Presidente* of the *Societa*). Material in the Rome archive conveys no sense of the political machinations and influences which surrounded Nobel nominations and awards at this time. Neither could we find any record of who first suggested a posthumous award to Moseley in 1919, although it is perhaps significant that in that year both Ernest Rutherford and Edwin Ray Lankester (an Oxford based anatomist and a close family friend of the Moseleys) were elected as Foreign Members of the *XL*.

Matteucci's bequest specified that the *Medaglia* should be made of gold to the value of 200 Lira. A series of documents in the Rome archive suggest that there were problems in acquiring the gold needed to mint the medals in the post-war years and by 1922 a backlog stretching back to 1915 (when Johannes Stark was the winner) had developed. Moseley's mother finally received her son's medal in July 1922. The medal has remained with the offspring of Moseley's sister Margery ever since. We thought it fitting to analyse the medal by energy dispersive X-ray emission spectroscopy in a scanning electron microscope. The X-ray spectrum is dominated by the gold M emission line, and shows the medal to have been cast from 99% pure gold with small traces (less than in typical costume jewellery) of copper and silver (figure 6).

As an addendum to this discussion we note that the next recipients of the *Medaglia* after Moseley were Albert Einstein in 1921 and Niels Bohr 1923. Aside from highlighting the place of Moseley in the international pecking order at the time, the award to Einstein in 1921 is of particular interest to historians of physics. Award of the *Medaglia* in 1921 came a year before his (deferred) award of the 1921 Nobel Prize in Physics in 1922. Moreover the *Matteucci* award was specifically for Einstein's work on the theory of relativity. Relativity was politically and culturally unpalatable to the Nobel Committee: they were determined to block recognition of relativity and dealt with the overwhelming groundswell of support for Einstein by giving him a prize for lesser (but still important) work on the photoelectric effect. Finally we note that the Nobel laureates Charles Barkla and Manne Siegbahn never won the Italian *Medaglia* (Friedman 2018; Egdell Offi and Panaccione 2018)

Postscript

The two papers on high frequency X-ray spectra of the elements published just before outbreak of the Great War had a huge impact on the development of chemistry and physics throughout the twentieth century, while X-ray spectroscopy

Fig. 6. Colour photographs of the front and Back of Moseley's *Medaglia Matteucci* along with an image of the medal taken in a scanning electron microscope and an electron beam excited X-ray spectrum, dominated by the gold M emission line (Photographs and images by courtesy of Trinity College Oxford and the Department of Materials, University of Oxford).

remains a vibrant area of research to this day. The statutes of the Nobel Foundation meant that a Nobel Prize for Moseley was not to be, but he received just recognition in Italy as the father of X-ray spectroscopy. Moseley introduced the definitive ordering principle for the periodic table, but no element has ever been named after him, despite campaigns for «Moseleyum» or «Moseleyium» stretching back to the 1925 and a recent letter of support endorsed by Nobel Laureate Roald Hoffman published in the Times newspaper on 27 February 2016 when names for the superheavy elements 113, 115, 117 and 118 were under discussion (Egdell 2018c). If elements beyond Z = 118 are ever made perhaps Moseley's will finally be recognised: in the meanwhile before a name is assigned by the International Union of Pure and Applied Chemistry, each new element is identified by Moseley's atomic number in a Latinised form.

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