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Rise of the Quantum Atom

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Abstract:
Affirmation of the atom and the ever-deeper quests into the structure of the subatomic has been a central occupation of physics in the last hundred years. Penetration of the atom concept into our society's consciousness is so complete that most kids would recognize by sight miniature solar systems figures as atoms. Atomicity has a long history. However the physical structure of atoms could be meaningfully probed only after the discovery of X-rays by Roentgen. This highly energetic and penetrating radiation provided the first direct probe into the subatomic. Concurrently, quantum ideas were developed to explain the workings of matter. In this article we analyze a scenario of this epochal era of modern physics, in particular a chain of events from the summer of 1912. These were outgrowths of Rontgen's discovery, namely, radioactivity, electrons and X-ray interference by crystals. Another was Rutherford's nuclear model of the atom and the theory of it. We explore the characters, technologies and related sequence of activities. Additionally in this article we attempt to answer the question - what "secret" inspired Bohr to withdraw from extant projects to get busy with the now famous atomic theory? Bohr's quantum theory of the atom was described in his trilogy of articles "On the constitution of atoms and molecules" which appeared in the Philosophical Magazine one hundred years ago in a rapid succession in 1913. It was truly revolutionary for Bohr to be so bold in 1913 to demand that the same quantum principles should apply to physics exactly the same way as to chemistry. Many of the pioneers including Bohr, were to be honored by numerous awards especially from the then new Nobel Prize. Culturally, the vision of electrons as tiny planets orbiting around a nucleus has become the signature icon of the nuclear age, which may be seen in most logos of atomic organizations including that of IAEA.

1. Introduction

The idea of atomicity has a long history. Here, we refer to J. C. Maxwell's classic article (Maxwell, 1873a) in Nature, "Molecules" for an extremely readable accounting of the state of affairs until 1873. Briefly, Democritus and his teacher Leucippus the 5-4th century BCE in Greece are credited with the idea of atoms (Berryman, 2010), as the indivisible building block of matter. A nontrivial concept, many classical philosophers including famously the mentor of Socrates, Anaxagoras were proponents of absolute homogeneity; who reasoned practicality aside, on a matter of principle it is natural that matter should be divisible ad-infinitum down to any scale and argued against atoms as the ultimate building block of mater. They argued the granularity idea unnatural because it sets an artificial finite (lowest) limit to the divisibility of and results in some object that is indivisible or to which the concept of partitioning does not apply.

Modern ideas about the atom began with the grammarian and meteorologist John Dalton's opus magnum (Dalton, 1808), *A new system of chemical philosophy* (1808) is an acclaimed milestone and so is Amedeo Avogadro's (Avogadro, 1811), " Essay on … relative masses ..." as well as Samuel Earnshaw's paper (Earnshaw, 1842), "On the nature of the molecular forces which regulate the constitution of the luminferous ether". Other works that will have direct bearing to the current story is Dimitri Ivanovich Mendeleyev's invention of the periodic table of the elements (1869); Johann Jakob Balmer's (1885) and Johannes Robert Rydberg's (1888) discoveries of regularities in the spectral lines of hydrogen. From the theoretical perspective, the most influential works are Samuel Earnshaw's "On the nature of the molecular forces which regulate the constitution of the luminferous ether" (Earnshaw, 1842) and James Maxwell's *A dynamical theory of the electromagnetic field* (Maxwell, 1865) and *A Treatise on Electricity and Magnetism* (Maxwell, 1873b).

However it was not clear as to what is the smallest part of matter; there remained confusion between molecule and atom- defining what an atom, Maxwell cleared some of the ambiguity by stating that "An atom is a body which cannot be cut in two. A molecule is the smallest possible portion of a particular substance" (Maxwell, 1873a). As we will describe shortly the atom-molecule rivalry continued well into the last century. Other questions arose: can the indivisible itself be composite? Fabricated from similar parts held by gravity like a planet and its moons two or more constituents of opposite polarities north and south or positive and negative? Are the parts alike in all respects except polarity? If composite how are they to be put together because by the third quarter of the nineteenth century the works of Earnshaw, Maxwell and others have identified a stability problem with electric or magnetic binding mechanisms. For example, Earnshaw's theorem pertaining to the impossibility of stable equilibrium of static charges influenced atomic models that were to follow, including the plum pudding model by J J Thompson (Thompson, 1904). In Thomson's model a single atom comprised of many (thousands) electrons (negatively charged plums) that were immersed in a nano-meter size blob (pudding) of positive charges. It is worthwhile to remember that even in the twentieth century skepticism persisted as to the physical reality of atoms.

As with the radio wave's a decade earlier the discovery of X-rays created a rage, even the lay public was inspired to take a look at this novelty. Many practicing scientists were also attracted by its possibilities, in essence X-rays morphed into an "A research tool, " a la Ian Hacking (Hacking, 1983). It is often overlooked that this high-energy radiation was the first contact with the world of the subatomic. However, in 1900, at the British Association for the Advancement of Science Sir William Thomson, AKA Lord Kelvin the dominant "electrician" in J C Maxwell's fabled treaties famously proclaimed, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement". Incredibly in his assessment William Thomson, has so conveniently ignored extant knowledge that he should or must have known are information that since has proven to be momentous; notably X-ray (1895), discovery of radioactivity (1896) and that of electrons (1897).

Some of these events are well described by the Physics Nobelist Emilio Segre (NP 1959) in his book entitled *From X-rays to Quarks* (Segre, 1980). Segre was laser sharp in pointing out the importance of X-rays. Really, modern science and especially physics emerged directly from what. Also we argue these novelties, which disrupted the ever-sanguine Lord's Fin de siècle assessment of a barren future for science, were not in mere accidental temporal succession (which is self-evident) but more importantly, were casually related.

It is no random historical numeric that the discoveries of electron (1897) radioactivity (1896) followed that of X-rays. It is well documented that in his attempts to generate X-rays from phosphorescent potassium uranyl sulfate, Henri Becquerel discovered radioactivity. Likewise J. J. Thompson was able to isolate for the first time ever the elementary particle electrons, in an investigation on ionization of gasses by X-ray in a modified version of Perrin's negative charge experiment from1885. It is unthinkable what the evolution the physical sciences be like without these three.

In his book Image & Logic, the noted historian Peter Galison (Galison, 1997) treats physics as a collection of activities in three "quasi-autonomous subcultures" of instrumentation, experimentation and theory. X-ray is a clear example, theory and experimentation had to be preceded by instrumentation. At a minimum X-ray enabling instrumentation comprise of three critical and ingredients namely (i) the source of high potency (several thousand volts) electricity - induction coil as;(ii) electrically insulated evacuated chamber with inside air pressure about a millionth of atmosphere and (iii) dry photo plates to document or record.

It is well known that until the advent of electronic photo detectors, much of observational astronomy has been dependent on the photography. Interestingly many historians have noted the importance of both high voltage and high vacuum to modern physics but silent about the role of photography especially the dry plate. The development of dry plates around 1878 separated the act of image capturing from the chemistry of plate fabrication and image development also permitted relatively long self-life to the unexposed plates. Roentgen's experimentations and the unexpected discovery of X-rays took place in less than twenty years since the introduction of these plates. Photo recording remained central in a number of basic sciences well into the middle of the nineteenth century for instance - cloud chamber, bubble chamber, auto radiography and photo emulsion techniques.

2. Start of the 20th Century

During the 1900-1910 time frames, X-rays, remained a complex conundrum - was it waves or particles, no clear answers. Understanding the newer discoveries was no better. To make sense of the state of science a collective effort was called for the first Solvey conference (Mehra & Rechenberg, 2001; Marage & Wallenborn, 1999) held in Brussels (November, 1911) , Belgium. To borrow a phrase from Max v Laue (Laue, 1914), let us say that this invitation only event was attended by "acknowledged masters" including Curie, Einstein, Jeans, Onnes, Perrin, Planck, Rutherford, Sommerfeld, Wien and others (see full list). The conference was on the general topic of the ultimate constituents of matter, specifically – Radiation theory and the quanta; Sommerfeld's 'h-hypothesis was discussed; works of Hass, Nicholson were included. Arthur Erich Hass also realized that Planck's ideas were essential in fixing atomic dimension and was the first to derive as (1910) the size of the atom incorporating the Planck's constant. The value ~ $2.8x10^{-10}$ m, estimated for the then current Thomson's model by Hass, was reported (Mehra, 2001; Hass, 1910). Sommerfeld also provided restraint with his comment that more experimental evidences were needed.

This conference is a landmark in the history of the quantum. Arguments for and against the usual forms of the laws of dynamics were discussed; also the frisson of the novel and the associated risks were noted. Reports on then recent successes of quantum ideas in explaining radiation, specific heat and other experimental facts were added with James Jeans' questions as to if this new [quantum] method was capable of "providing an image of reality". Jeans' prescience is particularly remarkable because this was well before the entry of a whole slew of complicated topics such as the principle of uncertainty, duality, wave function, spin and others that were to follow; in this instance he was at least one and a half decade ahead of his peers. In many of the future Solvey meetings the meaning of quantum reality would be dominant especially with the various thought experiment proposals of Einstein. Even to this day, this line of investigation has remained exciting and active thanks to the efforts of our erstwhile colleague Yakir Aharonov and other researchers in the area of foundations of quantum mechanics.

In the UK during first decades of the twentieth century, J.J. Thomson, at Cambridge and Earnest Rutherford at Manchester were the two dominant and influential experimental physicists. However William Henry Bragg (WHB), Henry Gwyn Jeffreys Mosley and Charles G Barkla were notable (X-ray) radiation researchers. WHB was also the first s to perform X-ray experiments in Australia and after 22 years at Adelaide University had returned to UK in 1909 and joined the University of Leeds. Coincidentally

Rutherford had visited the Braggs at Adelaide in 1895 and they have been in contact since that visit. C.G. Barkla discovered the transverse nature of the radiation in Cambridge based on observation (1906) of their polarization. Moseley was at Manchester and developed the eponymous law of X-ray spectra and expected to have a great career but unfortunately ended up being killed in battle (August, 1915) at Gallipoli during WW-I.
The British consensus on the nature of X-rays,if one may call it so was more divided, for example WHB professed a particulate model of X-rays comprising of neutral pairs of oppositely charged constituents. Supporting the corpuscular perspective was the fact that both electrons and X-rays seem to arise from the same source namely high voltage discharges in rarefied gasses. One may argue it will be natural and fair to conclude that they are common or similar in other aspects as well. The difference being electrons are the fraction of particles that cannot get out of the glass enclosure whereas X-rays are far more energetic and penetrating. And once out continues to pass thru other barriers as well. Thomson regarded X-rays as localized "bundles of energy" Barkla followed up with scattering experiments showing an anticipated angular dependency. Apparently even in 1910, Planck-Einstein's energy quantization idea has not quite fully appreciated at least not in this context. However, J P V Marsden's gamma ray results indicated a bias towards more scattering in the forward direction putting caution to energy bundles. The lack of conclusive evidence eventually led W H Bragg to suggest a dual character of X-rays. But prior to Louis de Broglie's idea of wave-particle duality in 1927, waves were supposed to be waves and particles just particles so Bragg's duality idea did not get much traction.
Coming right at the heels of the discovery of Hertzian waves the Germanic sentiment about the nature of X-rays was predictably, in favor of waves. After his discovery Roentgen moved to the Maxmillian University of Munich to be the professor of experimental physics. Based on their method of generation (1896), Emil Wiechert and George Gabriel Stokes have concluded that X-rays must be short waves of electromagnetic pulses. When Luwig Boltzmann left the theory chair in 1893 Arnold Sommerfeld was recruited in that position in Munich, to help in solving the "nature of X-rays" problem. From photoelectric effect measurements in 1907, Wilhelm Wien estimated their wavelength to be $7x10^{-11}$ m.

3. Munich & Max Von Laue

At Munich the theory team had the benefit of its own experimental assistants, mostly people who have had experimental PhD under Roentgen. Sommerfeld's group had the best (extant) estimate of the wavelength of X-rays as $4x10^{-11}$ m from the measurements of diffraction fringe patterns produced by steel edges. Starting in 1909 Max (not yet a von!) Laue became lecturer in optics under Arnold Sommerfeld. Laue had completed his PhD with max Planck on the topic of thermodynamics of coherent radiation and was already well known for his encyclopedia article on optics. In the summer of 1910 Paul Ewald, was amongst the students centering Sommerfeld's group and selected the problem: 'To find the optical properties of an anisotropic arrangement of isotropic resonators'. During the Christmas break of 1911 and January 1912, Ewald had finished calculations and was writing the thesis and told Laue about his calculations. Laue appeared curious about possible behavior of very short wave length radiations. Ewald evidently had aroused Laue's interest to test the wave nature of X-rays by crystal diffraction. As Laue would explain in his Nobel lecture (Laue, 1914) that he was motivated to learn " … which diffraction effects with X-rays might be found, and the question of their true nature answered …".
Fortunately in the spring of 1912 Laue was not aware that in his earliest investigations, Roentgen himself had already studied the scattering of X-rays by crystals. "I continued the experiments to which I referred already in my first communication about the transparency of plates of equal thickness that have been cut from a crystal along different directions, Again, no influence of direction on the transparency could be recognized" – without the slightest indication of a diffraction effect.
However, unlike the simple discharge tube that was at Roentgen's disposal, by 1912 dedicated tubes and targets technology has advanced enough so that higher intensity and arguably better-collimated beams were available to the folks at Munich to make the Laue diffraction experiment practical. Also some authors question-how could Laue, a theoretician, be so bold to suggest once more such an experiment? There is no direct archival record – in the form of letters, diary or manuscript – from which Laue's motivation would become clear (Eckert, 2012; Datta, 2012).
On a skiing expedition during the Easter break (1912) Laue proposed the idea of X-ray diffraction experiments with crystals. Sommerfeld, Wien and others promptly raised doubts especially the possibility of zero point motion (or random vibrations of atoms that persists even at absolute zero temperature) scrambling up the diffraction pattern. Peter Debye and Ivar Waller would eventually develop the theory of zero point contributions which showed that spots will survive but with reduced intensities. This now famous Debye-Waller treatment has become the standard description of many scattering processes including the Noble winning Mossbauer processes.
Back in Munich and not to take no for an answer, Laue discussed the situation with the regulars at the famous "physics table in the Café Lutz", and got a consensus that theory aside the experiment was worth a try, especially because no elaborate set-up was required. Shortly, after some initial setbacks (Datta, 2012) but before the end of April by directly passing the x-rays thru a large copper sulfate crystal Friedrich and Knipping succeeded in producing interference patterns, and recording the "Laue spots". In the photographs of Freidrich et al the X-ray diffraction spots appeared to follow Laue's equations except not all the predicted spots were seen. However, herein lays the genius! Because Laue's gut feel had uncovered a deep down question, a real question as we see shortly, that is the type of question who's answers even when as in this case turn out to be as expected (i.e, yes diffraction spots) leads to a far expanded vista with many more unexpected and new questions to explore. For example, Peter Debye is reported to have remarked, "one should generally not trade merit against luck with such things" (Debye, 1912).
The importance of the discovery and the tremendous significance of the Laue spots were clear right away promptly before the publication of the results pertaining to the discovery, Walter Friedrich, Paul Knipping and Max Laue signed a one-page document stating " The undersigned are engaged since 21 April 1912 with experiments … of x-rays passing through crystals …".

Sommerfeld deposited it on 14 May 1912 (Eckert 2012). The first official publications were by Max Laue, W. Friedrich and P Knipping (Friedrich, Knipping, and Laue, 1912; Laue, Friedrich and Knipping, 1912). Notice although in this document of 1912 all three Friedrich, Knipping and Laue are mentioned but two year later in 1914 the Nobel Prize in physics was awarded only to Max von Laue alone "for his discovery of the diffraction of X-rays by crystals". Laue felt that his two co-workers should have shared the Nobel Prize with him, and he distributed the money equally between the three.

4. Cambridge & Leeds

By word of mouth, lecture presentations and offset-preprint mailings the news of the discovery spread rapidly arousing great curiosity and sensation everywhere. While vacationing on the Yorkshire coast with family, W H Bragg received a long letter (Thomas, 2012) about Laue's results from Lars Vegard, a friend of WHB's and a former visitor to his Leeds laboratory. Vergard was a Norwegian aurora physicist and at that time a co-worker of W. Wien at Wurzburg (Northern Bavaria). Lars had attended a lecture given by Laue at Wurzburg. The letter sent on 26 June 1912, which included a copy of one of the experimental photographs and described Laue's findings in detail. It likely that the senior Bragg an established authority in the field would proceed to explain this new findings (that are somewhat at variance with his own ideas) about the nature of X-rays to his prodigal son W Lawrence Bragg. Lawrence then was a physics student at Cambridge and WHB succeeded to get WLB interested in the Von Laue effect. Interestingly both of WHB's sons Bob (another WW-I casualty; killed in the battle of Gallipoli, 1915) and Lawrence were students at St Peter's College. A school in Adelaide is second only to the Bronx High School for Science in the number of Nobel Laureates among its old boys.

As will be evident shortly, father's telling of this remarkable discovery must have been extraordinarily inspiring to this 22 year youth, to the extent that it electrified Lawrence Bragg into a creative burst. Briefly, after returning to Cambridge at the start of the school year but before Christmas he not only confirms, but improves on the Laue technique, within these short few months he succeeded in proving that the actual mechanism for spots did not arise from Laue's idea of unrestricted three dimensional diffraction but is due to interference of primary X-ray waves that are reflected from atomic planes. By December WL Bragg would also have a paper in Nature describing the correct physical mechanism along with the derivation of his namesake Bragg formula.

To start with Lawrence Bragg was intrigued by a number of details (Datta, 2012; Jeong, Yin, and Datta, 2013a); first- not all the diffraction maxima predicted by Laue's fundamental equations actually appeared in the photographs. Incidentally, the Munich group had tried to explain away the absent spots by invoking ad hoc spectral distribution of the incident X-ray. Secondly- the shape of the spots changed from circular to oval as the pattern moved off incidence and lastly- when crystal was rotated by an angle results in the whole spot pattern bodily turning by twice that angle. Typically, angular displacements of non-specular interference spots are determined by trigonometric functions and produce highly nonlinear response (Data *et al*, 2008). As indicated above, based on these simple observations this mathematically gifted youth figured out that the Laue pattern could not be due to three-dimensional lattices but a sub-set associated with interference of x-ray wavelets reflecting off successive atomic planes. Incidentally now it is understood that 3-dimensional periodicity suppresses 3-dimensional diffraction; simply put, Laue did not realize that scattering off 3-d gratings are not simple extension of cross-gratings.

In his 1915 Nobel lecture (delivered after WW I in 1922) W L Bragg stated " … I tried to attack the [Von Laue] problem from a slightly different point of view, and to see what would happen if a series of irregular pulses fell on diffracting points arranged on a regular space lattice. This led naturally to the consideration of the diffraction effects as a reflexion of the pulses by the planes of the crystal structure…"

In WLB's specular reflection model there are (only) two relevant lengths, the x-ray wavelength and the inter-plane distance (d) also the angle between the incoming and outgoing waves. Lawrence Bragg derived the appropriate conditions for constructive interference and obtained a simple eponymous Bragg formula or equation that relates the order of the interference (n) and the ratio of the lengths with sin(□).

Furthermore based on his equation and the missing spots in the photograph by the Munich group Lawrence deduce that the atoms in ZnS are not in a simple cubic (SC) structure [as presumed by Laue et al] but in fact are ordered in a face centered cubic (FCC) arrangement. Not coincidentally, Sir William J Pope, professor of chemistry at Cambridge University (formerly at Manchester) got interested in WLB's activities. Pope and William Barlow had a "valence-volume theory" of crystal structures. William Barlow a noted armature was the first to introduce SC and FCC and the concept of close packing into crystallography (1883) and had correctly guessed the atomic arrangement of the alkali halide crystals. In WLB's photographs Pope saw confirmation of their (Pope and Bralow) ideas and procured several specimens of sodium and potassium chloride crystals from Germany for WLB to do X-ray analyses.

W.L. Bragg did his own experimental work at the Cavendish Laboratory, Cambridge and in his early papers gave Trinity College Cambridge for address, later worked with his father at Leeds. Shortly thereafter Lawrence left Cambridge to join his father at Leeds. Many of the advances made at Leeds were of practical nature such as apparatus making, invention of x-ray spectroscopy and others. Arguably at Leeds the situation can be best described by a phrase from P.W. Anderson (Anderson, 2011) "theory on tap not on top". People who have known the Braggs in person have remarked at the public perception about their respective individual contributions. Here let us directly quote WLB's own comments on this as follows;

It was the help which I got from Professor Pope, the Professor of Chemistry, and the inspiring influence of C. T. R. Wilson, which led to my analysis of sodium chloride and potassium chloride by the method of the Laue photograph. Pope and Barlow had developed a valence-volume theory of crystal structure, and when my first studies of Laue's diffraction patterns led me to *postulate that zinc sulphide was based on a face-centered cubic lattice, Pope saw in it a justification of his theory and urged me to experiment with sodium chloride and potassium chloride crystals which he got for me from Steeg and Reuter in Germany. These experiments were made in the later part of 1912 and early in 1913. Simultaneously, my father seized on the conception of the reflection of X-rays by crystal planes to design his X-ray spectrometer, and discovered the X-ray spectra.*

In the *grosso modo*, X-rays provided the first proof of the validity of the Planck-Einstein energy frequency (wavelength) relation in the high energy regime of X-rays, extension of spectroscopic frequency laws in to the K, L & M radiations, the recognizable as well as distinguishable stable geometric lattice arrangement of atomic also most importantly the absolute visual documentation of the existence of atoms. The duo William Henry and William Lawrence (WHB & WLB) remain unique in a couple of respects, they are the only father and son to share the same Nobel Prize (1915 in physics) also WLB is the youngest (25 years) Nobelist yet! Amazingly, solid matter as a lattice of atoms (not molecules) did not sit well with the chemical establishment for instance a H. E. Armstrong former President of the (Royal) Chemical Society, in an article in Nature, opined (Armstrong, 1927) that "chess-board pattern of atoms" in NaCl as "repugnant to common sense... It is absurd to the *n*th degree... Chemistry is neither chess nor geometry". Yes, odd isn't it to find out that crystals of sodium chloride, the common salt are not a crystal arrangement of (NaCl) molecules but that of separate sodium and chlorine atoms?

5. Manchester & Cambridge

Let us pick up the other summer happenings in 1912, this time at Manchester and our protagonist is the young Danish physicist Niels Bohr, who in the spring of 1912 has moved to the Victoria University to conduct post-doctoral studies under Rutherford. The previous year, May 1911 Bohr had completed his PhD in Copenhagen and had eagerly traveled to Cambridge to be mentored by J. J. Thomson but after several unsuccessful encounters with Thomson decided to end this unrewarding sojourn at the Cavendish.

Although Rutherford was not yet as accomplished as Thomson, but he was receptive to the ideas of Bohr. At Manchester Bohr were to perform radioactivity experiments in the laboratory as well as do some theory work. The later was related to earlier work of the resident mathematician C.G. Darwin's regarding the absorption of "alpha-rays" and calculation of the transit time of alpha particles. Bohr had some criticisms of the Darwin treatment and was hoping for a rapid progress resulting in a quick short note for publication in the Phil Mag.

On June 12 (1912) Bohr wrote candidly to his precautious younger brother Harald (mathematician, already with a PhD ahead of Niels!) about this work, and promised to send Harald some calculations to look over and thoughts of "treating the electron theory", mentioning that Thomson effect is wrong order of magnitude and Specific heat of metals is lower at low temperatures and the high electric conductivity etc. This is overall a rather long open and candid letter with a lot of detailed mathematical equations. The results of this work appeared the following year in the Phil Mag (Bohr, 1913a; Nielsen, 1972; Hoyer, 1981).

Curiously by the third week of June Bohr has stopped going to the lab. In the now famous "June/July 1912 Manchester memorandum" for talks with Rutherford, he gives particulars regarding a year old atomic model that was proposed by Rutherford[27] as follows; "Consider an atom which contains a charge ± Ne at its centre surrounded by a sphere of electrification containing a charge ∓ Ne supposed uniformly distributed throughout a sphere of radius…Taking R of the order 10^{-8} cm … The question of the stability of the atom proposed need not be considered at this stage, for this will obviously the atom is supposed to depend upon the minute structure of the atom, and on the motion of the constituent charged parts" (Rutherford, 1911) NB: shortly model was refined the ambiguities with charges were gone, in the new scenario negatively charged electrons orbit around tiny and massive positive nucleus. But even the refined model had detractors due to acute problems of stability associated with segregated charges and energy loss by Maxwellian electromagnetic radiation puts severe limits to atomic longevity.

It seems that within in this short time (June/July) Bohr has become preoccupied with Rutherford's atom. It was a dramatic new start for Bohr, a big departure from what he might have gathered at Thomson's lab at the Cavendish. Bohr was also careful to be on familiar grounds when and as possible. So, the memorandum is replete with sketches of various possible rings of electrons circulating around, corpuscles and estimates of energy to be released in molecular dissociations. He mentions Planck & Einstein's quantization of radiation, the relationship between energy E and frequency f, characteristic Roentgen rays, (Henry) Bragg's law of X-ray absorption and uses the Planck constant (h) to make a gross overestimate of dissociation temperature of a diatomic molecule. Curiously Bohr stated his special Hypothesis regarding stability as "…will be a definite ratio between the kinetic energy …and the time of rotation", later he writes the relation E = Kf, K being (at least for the present purposes) just some constant of proportionality; it was implied that the (Final) stability is some type of statistical equilibrium.

Most of the calculations and sketches did not appear in the actual publications, famously called the Bohr-trilogy published in three parts in Phil Mag between July and November 1913. Except for the last equation essentially restating the Virial theorem result that is for any stable bound system the potential energy for an inverse square law force, is twice (with negative sign) the kinetic energy, Bohr applied this to obtain the first equation of the part -1 of the trilogy (Bohr, 1913b), "On the Constitution of Atoms and Molecules". Also in this publication the energy E and frequency f relationship is applied to the radiation using Planck's constant; Bohr also references Einstein's contributions emphasizing the importance of Planck theory in the operations of atomic systems. He was very meticulous in referencing the contributions of his peers, viz., Eric Arthur Hass's computations (Hass, 1910) of the size of the Thomson atom and its connection with Planck's constant was duly credited. Bohr completed his three part opus magnum in rapid succession with part two subtitled "Systems containing only a single nucleus" and the last part "Systems containing several nuclei". The trilogy reflects the resources that Bohr had drawn upon; Rutherford clearly was a big influence both scientifically and in providing with a smooth publication process. In the questions of spectroscopy (X-ray) Barkla, Henry Bragg and Moseley were noted. Also in the pesky question of atomic number and weight the very recent work by van den Broek was included so was his own conclusion from the January 1913 article (Bohr, 1913a) about neutral hydrogen atom having only one negative and one positive charges. In the entire trilogy the oldest article cited is one from 1896 (Part-1) the number of distinct citations are thirty-three total. Bohr was focused and referenced only the recent literature, twenty-two were only a year old (from 1912), and fifteen were from the same year (1913).

Not coincidentally, earlier within about four months of Rutherford's publication of his first paper about the nuclear atom, one John William Nicholson then at Trinity College, Cambridge had incorporated Rutherford's model in an article about "nebulium". This is the same Nicholson whose work was noted in the Solvey conference (Kragh, 2011; Nicholson, 1911; Nicholson, 1912). He too regarded that Planck's ideas are essential in atomic mechanics. He was a maverick in his own right. In another paper (submission date April 28, 1912) published in June, Nicholson extended the interpretation of quantization. He reasoned that the principle of quantization of radiation (action associated with the field) should be more general and include even mechanical action; consequently, the permissible changes in its angular momentum (of an atomic system) must be discrete (quantized). Remarkably this point has escaped other experts of that era including, Planck himself and Einstein. Incidentally Nicholson's results were also the inspiration for Wilson-Sommerfeld's quantization condition.

Demonstrating that "the ratio of energy to frequency" of a quantum system is action, he deduced the quantization in angular momentum. Thus he was the first to introduce the condition of discrete jumps for the changes of angular momentum in a quantum system; achieved mathematically and logically without invoking any "special hypothesis". Incidentally, Nicholson chose not to assign a new name for this unit change of this action (angular momentum), if he did perhaps we would call it Nicholson's constant not "h-bar" (h/2□). Such nomenclature is not uncommon a case in point will be Avogadro's constant (number) and its cousin Loschmidt constant, these two are closely related but not exactly the same hence different names. We observe that arguably the identification of "h" with angular momentum may be Nicholson's single greatest contribution to quantum physics.

Much of Nicholson's mathematical results were already in print by the time of the Manchester memorandum and more details followed during the time of Bohr's writing of the trilogy. Bohr has met Nicholson in Cambridge. It is conceivable that Bohr perceived some insight from Nicholson's results also simply because of availability it is possible that Bohr might have checked his own work against Nicholson's. In many critical issues he (Bohr) had no quarrels instead points out where his own results agree with Nicholson's. In the Part-I of trilogy Nicholson is cited profusely seven times (for a total of nine overall), making him the most amongst all references (see table).

Recently, Heilbron has pointed out that Bohr's strength was in his ability to be critically constructive (Heilbron, 2013). As is well known, criticism did not win Bohr any friendship with Thomson however in the trilogy work Bohr appears to be fully well versed and "sold on the Nicholson program" he clearly absorbed and *ceteris paribus* improved on it. His special hypothesis about energy in the stable state and frequency was ad hoc and equivalent to Nicholson's angular momentum condition but it was not exactly the same either. He saw the truth in the quantum theory of spectroscopic lines and integrated this knowledge to create his quantum theory of atoms. Specifically Bohr was the first to- introduce Planck's radiation quantization condition to transitions between energy states and express the results in terms of frequencies not wave lengths (or inverse wave lengths) like his predecessors Balmer, Rydberg, Nicholson and others. Bohr also was the first to consider quantum absorption. Bohr's work on multi-electron and certainly multi nuclear systems did not stand the test of times but even today his model is an excellent introduction to the subject. Remarkably, it was Nicholson himself who by becoming the most vocal opponent at least in Britain, of (Bohr's) atomic theory disavowed and sold out his ownership of the quantum idea. Also as John Ziman (Ziman, 2000) has observed scientific pursuit, the seeking of truth, is also as much "a game of competition" and mentions recognition process as "…notable scientific achievement by awards of medals and prizes". By this measure clearly Bohr's work has gained its place in modern physics amongst learned societies and academics.

6. Answering the Timing of Atomic Theory

Let us now present a line of reasoning that may answer Heilbron & Kuhn's question posed in their celebrated 1969 article, "Genesis of the Bohr Atom" (Heilbron and Kuhn, 1969). These authors asked "what suddenly turned his [Bohr's] attention … to atom models during June 1912?". First, they were absolutely right; during that short period in question Bohr made a unexpected change in his research and soon produced a spectacular theory. Second "what suddenly (?)", one may insist that there really nothing sudden, but there was a "secret" and Bohr himself writes about it to Harald (June 19, 1912). Bohr writes "…Don't talk about it to anybody, for otherwise I couldn't write to you about it so soon… I have taken off a couple of days from the laboratory (this is also a secret)." So there is indeed a secret! But what is there to conceal, working on an improved theory of alpha and beta absorption and scattering, devoting all energy and time in doing these big calculations not justifiable and authorized work? May be it was an inspirational news about someone making a great and unexpected discovery.

The biggest physics news in May-June of 1912 came from Munich with Laue's discovery. As we have described earlier, news of Laue's discovery arrived to Henry Bragg by second hand via letter from Lars Vagard in late June of 1912. The Laue pictures were the first visual proof of atoms. As Lawrence Bragg stated Laue spots revealed with thousand times better resolution than light, the perfect geometric arrangement of tiny objects sitting in equilibrium. The Braggs were electrified they jumped in to immediate action, quickly published remarkable papers one after another, created new fields in physics and within two years become Nobel Prize winners!

Rutherford in Manchester would have also received news perhaps directly from Munich. Cliché's abound- seeing is believing or a picture is worth a thousand words etc., really after Laue there can be no more doubts about the stability of atoms (Jeong *et al*, 2013a, 2013b; Jeong *et al*, 2014). It would be natural for Rutherford to inform Bohr about this discovery. Someone in Manchester laboratory could have exclaimed for instance a declaration to the effect – *Eureka! I have seen Laue's photographs, they show tiny atoms with absolute certainty atoms positioned in perfect order. Natural atoms are resistant to change, no problems with stability* *etc, etc*. Such can be the jolt that inspired Bohr to get busy with the atom theory in June of 1912. There is no known published record of such remarks by Rutherford or others and there appears to be no mention of receiving such intimation by Bohr himself. However in Part-1 of trilogy as he sets the stage to discuss stability of atoms Bohr writes "… an atomic system occurring in nature…have absolutely fixed dimensions…" in 1912-1913 how would one know with "absolutely fixed" (atomic) anything? The best one could get would have been from "Laue". Furthermore, in Part-2 [without any direct references] Bohr invokes "…by the interference observed in recent experiment on diffraction of Rontgen rays in crystals…" . Clearly, here in the middle of the trilogy in print, Bohr acknowledges that he knew about X-ray's & crystals. It will be interesting to locate original correspondence on the subject between Rutherford and the others at or around Manchester from that period.

It appears that at least circumstantially Bohr was at the right place at the right time. He also had the means, and "Laue-news" could have been the "secret" trigger that got him started in the quantum atom race, in which he appears to eventually beat the early starter Nicholson.

Remarkably, arguably Nicholson appears to have become a statistics of the zeroth theorem (Jackson, 2008) or the Matthew effect (Merton, 1968, 1988); either way Nicholson's fortunes have been in retrograde ever since.

7. Summary

In this article we have outlined a story line tracing the development of the quantum theory of atoms with subplots (i) one was the observation that X-rays provided the first direct evidence into the structure of the atom, (ii) the second, Nicholson's contributions in introduction of the scale and quantization of angular momentum, plus its association with Planck's constant has not been fully appreciated and (iii) that in addition to prompting the Braggs, the sensational news of Laue's discovery activated Bohr's impetus dash into quantum atoms. The Laue-Brrag nexus in the summer of 1912 is well documented and confirmed, unfortunately that to Bohr is absent. However it is clear from his publications that at least by the time of the trilogy Bohr was aware of Laue's discovery. The historian of philosophy John H. Arnold (Arnold, 2000) has noted "Origins are simply where we pick up the story … where we wearily draw to a close … history allows us to demur … there have always been many courses of action"; John Arnold is correct, often times there are "many ways of being". When did Bohr learn the new of Laue's discovery and did he find it inspiring are questions for future researchers. Perhaps in the archives in Manchester and Cambridge or Rutherford's collections one might find another way "of being" to this story.

8. Acknowledgements

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Table 1: List of invitees to the 1st Solvay conference (1911)

- H. A. Lorentz (Leiden), as Chairman.

From Germany

- W. Nernst (Berlin)
- M. Planck (Berlin)
- H. Rubens (Berlin)
- Sommerfeld (M¨unchen)
- W. Wien (W¨urtzburg)
- E. Warburg (Charlottenburg).

From England

- Lord Rayleigh (London, did not attend)
- J. H. Jeans (Cambridge)
- E. Rutherford (Manchester)

From France

- M. Brillouin (Paris)
- Madame Curie (Paris)
- P. Langevin (Paris)
- J. Perrin (Paris)
- H. Poincar´e (Paris)

From Austria

- Einstein (Prag)
- F. Hasen¨ohrl (Vienna)

From Holland

- H. Kamerlingh Onnes (Leiden)
- J. D. van der Waals (Amsterdam)

From Denmark

- M. Knudsen (Copenhagen)

Table II: List of Physics Nobel Prize Awards since its Inception to 1930

- 1930 -Sir Chandrasekhara Venkata Raman
- 1929-Prince Louis-Victor Pierre Raymond de Broglie
- 1928-Owen Willans Richardson
- 1927-Arthur Holly Compton, Charles Thomson Rees Wilson
- 1926-Jean Baptiste Perrin
- 1925-James Franck, Gustav Ludwig Hertz
- 1924-Karl Manne Georg Siegbahn
- 1923-Robert Andrews Millikan
- 1922-Niels Henrik David Bohr
- 1921-Albert Einstein
- 1920-Charles Edouard Guillaume
- 1919-Johannes Stark
- 1918-Max Karl Ernst Ludwig Planck
- 1917-Charles Glover Barkla
- 1916-No Nobel Prize was awarded this year. The prize money was allocated to the Special Fund of this prize section.
- 1915-Sir William Henry Bragg, William Lawrence Bragg
- 1914-Max von Laue
- 1913-Heike Kamerlingh Onnes
- 1912-Nils Gustaf Dalén
- 1911-Wilhelm Wien
- 1910-Johannes Diderik van der Waals
- 1909-Guglielmo Marconi, Karl Ferdinand Braun
- 1908-Gabriel Lippmann
- 1907-Albert Abraham Michelson
- 1906-Joseph John Thomson
- 1905-Philipp Eduard Anton von Lenard
- 1904-Lord Rayleigh (John William Strutt)
- 1903-Antoine Henri Becquerel, Pierre Curie, Marie Curie, née Sklodowska
- 1902-Hendrik Antoon Lorentz, Pieter Zeeman
- 1901-Wilhelm Conrad Röntgen

Table III: Age of the Principal Characters at the Time of Breakthrough Mentioned in this Article

- Charles Glover Barkla, 29 years (experiment)
- Antoine Henri Becquerel, 44 years (experiment)
- Niels Henrik David Bohr, 28 years (theory)
- William Lawrence Bragg, 22 years (theory & experiment)
- William Henry Bragg, 50 years (experiment)
- Albert Einstein, 26 years (theory)
- Arthur Erich Hass, 26 years (theory)
- Max von Laue, 33 years (theory)
- Jean Baptiste Perrin, 39 years (experiment)
- Max Karl Ernst Ludwig Planck, 41 years (theory)
- Wilhelm Conrad Röntgen, 50 years (experiment)
- Heinrich Daniel Ruhmkorff, 48 years (experiment)
- Joseph John Thomson, 41 years (experiment)

A Quantitative Summary of Table III

- In this very selective non-random sample:
- Experimentalists are typically older; the 8 “experiment” entries: range 22 – 50 yr., mean 40.4 yr., median 42.5 yr.
- Theorists are typically younger; the 5 “theory” entries: range 26 – 41 yr., mean 30.8 yr., median 28 yr.
- Statistics of all 13 entries:
- Range 22 – 50 yr., mean 36.7 yr., median 39 yr.