THE INTERNATIONAL JOURNAL OF HUMANITIES & SOCIAL STUDIES

Why Bohr's Atom in 1913 and a New Assay of the Trilogy

Yeuncheol Jeong
Sejong University, Seoul, South Korea
Timir Datta
University of South Carolina, Columbia, South Carolina, USA

Abstract:
Hundred years ago, X-ray diffraction discovered by Laue and his associates working in Sommerfeld's group at Munich allowed one to directly 'see' stable atoms for the first time. Bohr became certain of "absolutely fixed dimensions" and permanence of "actual atoms" from Laue's discovery. Confident of atomic stability, Bohr must have been inspired to develop his own atomic theory. Ever since then, the legacy of Bohr is thus immense and pervasive, extending even beyond the confines of science. This is the first historical observation of existing evidence to provide synergy between Bohr's work and Laue's discovery.

1. Introduction

Specialization is the mantra in contemporary physics. Absolutely, but it is no myopia. For a full appreciation of various fields in physics is still essential for real breakthroughs, the synergy of disparate ideas has always been indispensable for the growth of scientific knowledge. For instance, a broad understanding from gauge symmetry breaking in superconductivity (amongst the lowest energy scales) to the high-energy physics of massive particles was critical for the success at the LHC last year. The 2013 Nobel Physics award to Professors Francois Englert and Peter Higgs also honors such creative synergy; before their achievement, Charles Day has already paved a way for the theoretical development from Yang-Mills non-abelian gauge theories, together with Nambu's application of spontaneous symmetry breaking, Goldstone's no-go theorem, Phil Anderson's brilliant cancellation of zero-mass problem, and other numerous contributions that all finally culminated in the 2013 prize. In this respect, in an article, "No physicist is an island", in the New York Times on October 8, 2013, Sean Carrol has explored the relevance of the single prize itself in contemporary physics. The article raised serious questions of who gets final credit; in particular, why not Gerald Guralnik, Dick Hagen, or Tom Kibble for the 2013 award, or what about the thousands of experimentalists involved.

The year 2013 was the centennial for Bohr's atomic theory and publication of his trilogy papers (Bohr, 1913a,b,c), a celebrated intellectual landmark of the last century as one of the highest individual intellectual achievements in the last century. This spectacularly successful theory, spawned in less than a year, was heralded by Bohr's abrupt switch in research interest during the summer of 1912. However, a historically important point has almost always been overlooked, namely, what suddenly turned Bohr's attention to atom models during June 1912. What sort of synergy from disparate ideas did he utilize to achieve such a tremendous impact in the growth of knowledge? Thus, it is natural to ask what triggered Bohr to suddenly get passionate about the quantum atom. Pursuant of the answer, we also advance a novel appraisal of trilogy's impact among its cited authors.

2. X-Ray Diffraction Patterns

Hundred years ago, an astonishing discovery made by Laue and his associates working in Sommerfeld's group at Munich made on the 28th of April in 1912, *inter alia*, allowed one to directly 'see' stable atoms for the first time. Sommerfeld declared an 'official deposition' on it in early May and formally presented it to the Physical Society of Gottingen, shortly after publication by the Bavarian Academy on the 8th of June. The exciting news of this discovery could have arrived in UK from Munich by preprints. As John Thomas recently pointed out, "[already] in the nineteenth century, it was common practice for physical scientists – and possibly others- to distribute reprints of their important papers to others across the globe" (Thomas, 2012b, p.12956). It has also been suggested by him that during the 250th anniversary celebration of the Royal Society in London in July of 1912, the German representative, W. Voigt of Gottingen, must have also spoken about the discovery. Furthermore, now it is confirmed that W. Henry Bragg at Leeds, UK, got Laue's news thru a letter sent on June 26th (1912) by a friend Lars Vegard, then residing in Wurzberg, Germany (Thomas, 2012b, p.12947). This news of Laue's discovery of course electrified the Braggs (W. Henry and W. Lawrence) into immediate action.

Although Laue spots were the most preeminent science breakthrough that year (Thomas, 2012a), initially his breakthrough was still blemished with confusion and was also questioned whether the physical explanations involved was correctly invoked by Laue himself. Coincidentally, this was a situation not very dissimilar from 'chemically sense, but physically nonsense' (Kragh, 2013) issues surrounding Bohr's own quantized atomic theory later. Harry Moseley, "the best of the young researchers that Rutherford ever had" at Manchester, wrote in his letter to his mother on 4th of Nov., 1912 that "the men who did the work entirely failed to understand what it meant, [and] ... an explanation [given by Laue's group was]… obviously wrong" (Heilbron, 1974, p.194). Nevertheless, Laue's discovery was so impressive that Moseley quickly readjusted his research plans, moved to spectroscopy and discovered Moseley's law. The Braggs also quickly demonstrated that the spots arose from interference of X- rays waves reflected layer-by-layer from atomic planes in the crystal. Whence, they determined the arrangement, size, charge and chemical identities of the atoms themselves. In rapid fire, the duo published a series of remarkable papers one after another. They transformed the diffraction experiment of Laue into a new tool to study atoms and their aggregates. Within two years, they would also win the physics Nobel Prize in 1915, just one year after Laue's, as the only father and son duo who shared the same Nobel Prize. Still, Lawrence is also the youngest (25 years old at the moment) Nobelist yet!

3. Impact of X-Ray on Bohr's Works

There are some leads as to when Rutherford's group at Manchester received Laue's news. C.G. Darwin was the resident mathematician in this group. Heilbron writes (Heilbron, 1974, p.71) " Darwin finished [his previous work] in April of 1912, and a month later […] had no pressing project in hand, and perhaps have already begun to think about X-ray diffraction". This implies that the news has in fact arrived in Manchester and "one month later" would be sometime in May or June.

In another work, Heilborn again describes (Heilbron, 1966, p.340) "at that moment […] the most exciting subject in physics [was] – X-rays, [… I]n July 1912, […] Moseley and Darwin were [also] interested in X-rays as a fundamental problem. […] [F]inally the master [Rutherford] was persuaded to let them try". So, Laue's discovery excited Moseley, "the best of the young people [who] Ruthereford ever had", enough to choose his own research, not in "the most striking contemporary investigation at Manchester, [that was] the elaboration of Rutherford's atom" (Heilbron, 1966, p.339), but in X-rays! His initial research was extremely important in showing that the nucleus contains only integer numbers of the elementary positive charges. This brilliant young man was expected to have a great career, but sadly Moseley ended up being killed in battle (August, 1915) at Gallipoli during WW-I, now honored and remembered by the eponymous, Moseley's law of X-ray spectra.

Unfortunately, unlike Moseley, we are unaware of any archival records on Bohr's response to Laue's discovery. However, seeing is believing; from Laue's photographs, Bohr can have no more doubts about physical reality and stability of atoms. *Eureka! They show tiny atoms, with absolute certainty, fixed in perfect order. Natural atoms are resistant to change, no problems with stability etc.* A remark or appreciation of this kind could have inspired Bohr.

In fact, a rapid rearrangement of Bohr's activities in June or July of 1912 has intrigued historians in the past. For example, in their article "Genesis of the Bohr Atom", Heilbron and Kuhn (Heilbron and Kuhn, 1969) asked "what suddenly turned his [Bohr's] attention … to atom models during June 1912". A perusal of Bohr's correspondence to this mathematician brother Harald may apprise us of this metamorphosis. Starting in late spring of 1912, on the 28th of May, in a rather brief note (~30 lines), he wrote (Nielsen, 1972, p.553), "what […] had occurred to me […] can explain certain difficulties […] in the electron theory of metals […] Thomson effect […] is of the wrong order of magnitude. […] [T]he specific heat of metals is not large at low temperatures […] [A] very interesting paper [...] by Stark […] gives […] the electric conductivity […] I am already thinking […] trying to write a little about it". His next dated 12th of May is much longer (~80 lines) and more technical and includes one trigonometric integral and two infinite series pertaining to the absorption and scattering of charged particles in matter. Also, *inter alia* he stated "I have not worked in the laboratory […] I have had to wait for some radium" (Nielsen, 1972, p.555) and "I surely hope [that my calculation] is fairly correct (I may send you some calculations to look over)" (Nielsen, 1972, p.557) and "I am thinking of trying soon to treat the electron theory […] corresponding to Stark's ideas" (Nielsen, 1972, p.559) and "I must first have the old things off my hands" (Nielsen, 1972, p.559). In summary, as of June 12th (1912), the mood in these two letters is casual with little sign of urgency. Bohr was taking care of old things, working on electron theory and charged particle scattering, when in doubt seeking Harald's expertise in mathematics.

4. Bohr's Secrets

The very next week, his mood had shifted and Bohr was edgy. All the minutia of electron theory and particle scattering are now cleared away - Bohr has found a new muse. On the 19th of June, he wrote (Nielsen, 1972, p.559) "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)." Oh, Bohr got secrets! But, what can there be to conceal? Wasn't he working on an improved theory of charged particle scattering, devoting all of his energy and extra time? Isn't working on the manuscript for "velocity of electrified particles" (Bohr, 1913d) justifiable and authorized? Besides, "also a secret" implies that there ought to be at least one more 'the original' secret. What was this secret?

Let us search for this secret in Bohr's own work, starting with the now famous June/July (1912) Manchester memorandum (Ulrich, 1981, p.140) to Rutherford, his post-doctoral mentor. In one calculation (Ulrich, 1981, p.140) in this memorandum, Bohr found the dissociation temperature of a simple 'diatomic molecule' by equating the thermal energy with the (classical) electrostatic potential energy of two elementary charges separated by hundred millionths of a centimeter (10^{-8} cm). The temperature came out to be about a hundred thousand degrees (10^5 K). Dissociation temperature of 100,000 degrees is far too high and renders the molecule to be improbably stable. Not making a single remark, Bohr proceeded to calculate the temperature again, but this time by associating the thermal energy with the (quantum) energy of three petahertz photons (3×10^{15} Hz). Here, Bohr introduced a numerical error of 10^{-2} for the ratio of Planck to Boltzman constants. Using this two orders of magnitude lower incorrect value, he found the dissociation temperature to be around hundred thousand degrees. Satisfied, Bohr wrote "and this gives again 10^5". Be that as it may, if he had used the correct value of the ratio, then this second (quantum) estimated temperature would have been more realistic 10^3 degrees, certainly not the same "again". Famously, Bohr pressed on ahead and hypothesized "that there for any stable ring (any ring occurring in the natural atoms) will be a definite ratio between the kinetic energy of an electron in the ring and the time of rotation" (Ulrich, 1981, p.137). Incidentally, perhaps unknown to Bohr, John Nicholson (whom Bohr had met at Cambridge University) had already published (Nicholson, 1912) that such a definite ratio leads to angular momentum quantization and hence to stable quantum states.

It seems that Bohr was firmly convinced of atomic stability and not bothered by extreme dissociation temperatures. Besides, there are many indications of his familiarity with Laue's work. For instance, in Part 1 of the trilogy, as Bohr sets the stage to discuss the stability of atoms, he invokes (Bohr, 1913a, p.4) "an atomic system occurring in nature […], the actual atoms in their permanent state […] have absolutely fixed dimensions". We ask in 1912-1913 how would one know of "absolutely fixed" (atomic) anything? The best one could get would have been from Laue's pictures. This new evidence for the existence of stable atoms was already discovered by Laue in late April of that year (1912) in Munich, Germany; Photographs of X-ray scattering from crystals -'Laue spots'- were the first visual proof for the physical existence of atoms arranged in a perfect geometric order. As a matter of fact, Bohr was in fact at Manchester along with Moseley during the time in question. The implication of Laue's discovery with Moseley and Bohr's sojourns in Manchester has never been properly noted before. Furthermore, in Part II, Bohr notes "the interference observed in recent experiment on diffraction of Rontgen rays in crystals" (Bohr, 1913b, p.500). Here, in the middle of the trilogy, he definitely knew about X-ray and crystals. His mentioning of both interference (a term used by the Braggs) and diffraction (by Laue) shows Bohr's full familiarity with the works of Laue and the Braggs. Thus, Bohr became certain of "absolutely fixed dimensions" and permanence of "actual atoms" from Laue's discovery. Thereby, confident of atomic stability, he must have been inspired to develop his own atomic theory.

In summary, Bohr's "secret" or 'the elephant in the room' appears to be Laue's discovery. To the best of our knowledge, this is the first historical observation of existing evidence to provide synergy between Bohr's work and Laue's discovery.

5. New Appraisal of the Trilogy

The most popular measures on the influence of scientific publications such as "citation index" or "impact factor" are only *a posteriori* indicators that assay after-trends amongst their readership. Such measures, however, don't seem to reflect the true strength of the trilogy. To appraise the "uber" impact of Bohr's articles, we tracked the post-trilogy Nobel recognition of the authors cited in these articles. Bohr showed an extraordinary skill in picking the most relevant and up-to date literature. The publication dates of the cited works range from 1896 to 1913.The trilogy papers cited a total of sixty five distinct (numbered) references from thirty one authors. Eleven of the cited authors (Bohr himself included) were later recognized by ten Noble prize awards, seven Laureates in physics and four in chemistry.

Eleven post-trilogy Nobel Laureates out of thirty one cited authors show an astonishingly high achievement factor, a 'gold standard' for others to measure up to. The legacy of Bohr is thus immense and pervasive, extending even beyond the confines of science. Culturally, the image of electrons as tiny planets orbiting around the nucleus is the signature icon of the nuclear age, seen in most logos of atomic organizations such as in that of IAEA. The spring head of the breakthroughs by Moseley as well as the Braggs was in fact Laue's discovery in April, 1912. We have argued that Bohr also was similarly inspired that summer. It was truly revolutionary for Bohr to be so bold to demand that the same quantum principles should apply to physics exactly the same way as to chemistry, hence by implication, to all of nature.

In retrospect, genesis of atomic quantization also has an interesting history of its own; the works of John William Nicholson predates Bohr. In his publications, Nicholson has already extended the idea of quantization to the angular momentum variable; hence, through quantization of energy states, guaranteeing the stability of Rutherford's nuclear atom. Quantized angular momenta would have a critical role in Bohr's work and in the trilogy papers. However, most textbooks credit only Bohr with the concept; e.g. the famous Landau-Lifsitz's lectures confidently refer to it simply as Bohr-Sommerfeld condition. Lamentably, Nicholson seems to have disappeared from physics literature, which may help perpetuate a winner-takes-it-all theme in sociology of science, the 'Matthew effect' in Bohr vis-a vis Nicholson.

However, the trilogy papers contributed positively to a host of other scientists. With the benefit of a century, today it is clear that the initial circumspections not withstanding, the breakthroughs a century ago arose from synergetic creativity, and the essential strengths of the discoveries from that era have passed the tests of time. The Physics Nobel award in 2013 is equally likely to leave a lasting legacy on the science community and reshape science and technology of the future generations.

6. References

1. Bohr, Niels, "On the constitution of atoms and molecules" Phil. Mag, 6, 1-25 (1913a)
2. Bohr, Niels, "On the constitution of atoms and molecules Part II.-Systems containing only a single nucleus", Phil. Mag., 6, 476 -502 (1913b)
3. Bohr, Niels, "On the constitution of atoms and molecules Part III.- Systems containing several nuclei", Phil. Mag., 6, 857-875 (1913c)
4. Bohr, Niels, "On the Theory of the Decrease of Velocity of Moving Electrified Particles on Passing Through Matter", Phil. Mag., vol. 25, 10-31 (1913d)
5. Nielsen, J. Rud, ed., Niels Bohr - Collected Work, Volume 1, North Holland, (1972)
6. Hoyer, Ulrich, ed., Niels Bohr - Collected Works, Volume 2, North Holland, (1981)
7. Heilbron, John,"The work of H.G.J. Moseley", History of Science Society, vol. 57, 336 (1966)
8. Heilbron, John, H.G.J. Moseley, The Life and Letters of an English Physicist 1887-1915, Univ. Of California Press, (1974)

9. Heilbron, John and Kuhn, Thomas, "The Genesis of the Bohr Atom", Historical Studies in the Natural Sciences Vol. 1, pp. vi, 211-290 (1969)
10. Kragh, Helge, “Niels Bohr between physics and chemistry”, Phys Today, 66, 37 (2013)
11. Nicholson, J. W., “The Constitution of the Solar Corona”, MNRAS, vol.72, 677-692, (1912)
12. Thomas, John Meurig, “The birth of X-ray crystallography”, Nature, 491, 186, (2012a)
13. Thomas, John Meurig, William Lawrence Bragg: The Pioneer of X-ray Crystallography and His pervasive Influence, Angew. Chem. Int. Ed. Vol. 57, (201v2b)