Nagaoka’s atomic model and hyperfine interactions

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Abstract: The prevailing view of Nagaoka’s “Saturnian” atom is so misleading that today many people have an erroneous picture of Nagaoka’s vision. They believe it to be a system involving a ‘giant core’ with electrons circulating just outside. Actually, though, in view of the Coulomb potential related to the atomic nucleus, Nagaoka’s model is exactly the same as Rutherford’s. This is true of the Bohr atom, too. To give proper credit, Nagaoka should be remembered together with Rutherford and Bohr in the history of the atomic model. It is also pointed out that Nagaoka was a pioneer of understanding hyperfine interactions in order to study nuclear structure.

Keywords: Nagaoka-Rutherford-Bohr atomic model (N-R-B model), the origin of hyperfine interactions

1. Introduction

Hantaro Nagaoka was a distinguished Japanese physicist living in the early 20th century. He was a member of the Japan Academy from 1906, and assumed its presidency after receiving the Order of Culture in 1937. He is so famous that there is supposed to be nothing more to be added to the Nagaoka archives. When it comes to the atomic model, however, things are not as they should be. A stereotyped picture, universally known as the Nagaoka “Saturnian” atom, has been disseminated; but it is so misleading that today many people have an erroneous picture of the Nagaoka atom, such as being a system involving a ‘giant core’ with electrons circulating just outside.

It was in 1996 that the author was astonished to find out about the extensive work of Nagaoka and his young collaborators concerning optical spectroscopic studies involving nuclear structure, which was indeed a precursor of hyperfine-structure studies that rapidly started in the 1930s. Their work had generally been forgotten by history, except for in the minds of a handful of Japanese science historians.

Figure 1 gives impressions of the ‘Japanese Journal of Physics 1923’ and Nagaoka-Sugiura-Mishima papers in Ref. 1. They had examined the structure of mercury lines of atomic spectra as well as those of other elements using an Echelon grating and Lummer-Gehrcke plates. In particular, experimental arrangements for crossing two quartz Lummer-Gehrcke plates at right angles to each other enabled them to have an accuracy of fractions of a milliangstrom by analyzing the crossed spectra thus obtained; those spectra showed a sequence of dots being composed of the contours of distributions of the light intensity that resulted from combining the two plates mentioned above. From the data shown in Fig. 1(b), they proposed a hypothesis that the Coulomb law does not hold in the vicinity of the atomic nucleus, suggesting the effect of nuclear vibrations. A typical example of the crossed spectra presented in Ref. 1 is shown in Fig. 1(c). Although their devices, log books and dry plates of the crossed spectra in Ref. 1 are missing, it may be worthwhile making available some remnants of their preliminary measurements, which have been found in the RIKEN Archives. Figure 2 shows some developed dry plates indicating clearly the date of measurements and the use of an Echelon grating and Lummer-Gehrcke plates.

This article aims to show that Nagaoka’s model of the atom and Rutherford’s are identical in view of their Coulomb potential related to the atomic nucleus. Even N. Bohr used the same potential to describe the orbit of atomic electrons. Simultaneously, the concept of hyperfine interactions is shown to have its origin in a 1904 Nagaoka paper titled “Kinetics of a System of Particles illustrating the Lines and Band Spectrum and the Phenomena of...
Radioactivity. Mention should also be made of a recent survey of Japanese high-school physics textbooks (1955–2012), which shows that, being different from the current tendency in Japan, the stereotyped Saturnian picture was rarely seen in any textbooks before 1980; instead, Nagaoka’s atomic model was described as being identical to Rutherford’s model.
The author has already published five articles on the Nagaoka model of the atom.\textsuperscript{6–10} The present article will be an elaborated paper based on these publications.

2. Nagaoka’s optical spectroscopy for the nuclear structure study

2-1. The origin of hyperfine interactions. W. Pauli first postulated that the atomic nucleus has a non-zero angular momentum (nuclear spin),\textsuperscript{11} which would provide hyperfine structure due to a magnetic dipole interaction in addition to that due to nuclear field effects (electric quadrupole interaction).\textsuperscript{3} I knew about his paper since my student days around 1960 thanks to a well-known textbook written by G. Herzberg (first published in Dresden, 1936),\textsuperscript{12} but never wanted to read it simply because it was written at a time when people did not yet know that the nucleus consists of protons and neutrons. At long last, in April 1996, I read it for the purpose of learning about Pauli’s mathematics, since I was concerned with the hyperfine structure anomaly,\textsuperscript{13,14} which is due to the finite size of the nucleus and its magnetization distribution. That was fruitless, because the paper had no mathematics at all, but I was astonished to find Pauli’s wonderful and excellent

![Fig. 2. Nagaoka’s preliminary measurements. (a) For Cu arc, dated 25. X. 1919, showing lines obtained with a Lummer-Gehrcke plate and an Echelon grating, the dry plate size in mm 108 x 82 x 2; (b) for N ion crossed spectra, the dots of which are barely seen, dated 4. XI. 1919, 110 x 40 x 2; (c) a measurement in the region of Hg 3663 Å, the line known well at the time, with the Lummer-Gehrcke plate B, dated 15. II. 1922, 55 x 30 x 2; (d) three lines identified in the region of Hg 3663 Å with an Echelon grating, dated 23. II. 1922, 82 x 30 x 2.](image-url)
introduction to the endeavor of Nagaoka and his young collaborators to study the nuclear field effects on the hyperfine structure.\textsuperscript{1)} Pauli wrote:

Kürzlich ist nun das Auftreten der Satelliten von Nagaoka und seinen Mitarbeitern, denen man die systematische Ausdehnung der Satellitenmessungen ins ultraviolette Gebiet und speziell bei Quecksilber ein umfangreiches, wertvolles Beobachtungsmaterial verdankt, mit dem Vorhandensein von verschiedenen Isotopen eines Elementes unter Zugrundelegung von speziellen Vorstellungen über den Kernbau und den davon herrührenden Abweichungen des Kernkraftfeldes vom Coulombschen Feld ihre Entstehungsursache. Ohne diese speziellen Vorstellungen und die besonderen Ansichten dieser Verfasser über den Zusammenhang der Satelliten mit den verschiedenen Isotopen eines Elementes sowie deren formelmäßige Darstellung der Abstände gewisser Satelliten für hinreichend zu halten, wollen wir hier den Gedanken Nagaokas und seiner Mitarbeiter versuchsweise in der allgemeinen Fassung aufnehmen, da die Satelliten in dem zusammenge setzten Bau des Kernes und den davon herrührenden Abweichungen des Kernkraftfeldes vom Coulombschen Feld ihre Entstehungsursache haben. Wir wollen überdies (als einzige hier eingeführte besondere Annahme über den Kernbau) voraussetzen, daß der Kern (von etwaigen speziellen Ausnahmefällen abgesehen) ein nicht verschwindendes resultierendes Impulsmoment besitzt. Dann müssen sich das Kerngebäude und das System der Außenelektronen, (dessen Teile ja infolge der viel stärkeren Wechselwirkung der Elektronen untereinander und der Quantenbedingungen als fest gegeneinander orientiert anzusehen sind), infolge der zwischen ihnen herrschenden Wechselwirkungskräfte in verschiedenbedingten, quantenmäßig bestimmten Orientierungen gegeneinander einstellen. Hierbei werden sich der Kernimpuls und der durch die Quantenzahl $j$ bestimmte Gesamtimpuls der Außenelektronen zu bestimmten, gegquantelten Werten des resultierenden Impulsmomentes des ganzen Atoms zusammensetzen. (pp. 741–742)

Pauli must have sensed formidable physics in the Nagaoka-Sugiura-Mishima paper;\textsuperscript{1)} otherwise, he would not have made such a long statement about their work. As can be seen from the above citation, he was so inspired as to postulate non-zero angular momentum of the atomic nucleus (nuclear spin) with which the atomic electrons possess a magnetic dipole interaction, giving additional effects to the atomic spectra. I wondered what on earth Nagaoka wrote. When I laid my eyes on his and colleague’s voluminous papers,\textsuperscript{1)} my heart rate shot up because I had never heard about their work before that moment. It was not known among physicists concerned with hyperfine interactions both at home and abroad. Later, it was learned that only a handful of science historians in Japan knew about it, as mentioned in Introduction.\textsuperscript{2)} They rightly pointed out the fact that Pauli attached great importance to the Nagaoka-Sugiura-Mishima papers\textsuperscript{1)} for the purpose of studying nuclear structure. But, unfortunately, none of us noticed that. Now, we can read the following in the Nagaoka’s concluding remarks (Ref. 1, 2nd paper):

The present research is of special interest as affording a means of investigating the nuclear structure from the examination of spectral lines, and though our knowledge of the nuclei is still vague, fresh light can be shed by the extension of spectroscopic research. The way of viewing the excitation of many non-series lines will open a wide field of investigation, not only in searching for the isotopes, but also for elucidating any unsolved problems of atomic structure.

This statement is almost the same as that which Pauli summarized in his letter paper.\textsuperscript{11)}

Wir möchten zum Schluß besonders hervorheben, daß uns auf Grund des vorliegenden Beobachtungsmaterials die hier diskutierte Hypothese über den Ursprung der Satelliten noch keineswegs als endgültig gesichert erscheint; wir möchten es sogar in keiner Weise für ausgeschlossen halten, daß sie sich noch als gänzlich irrig erweisen wird. Der Hauptzweck dieser Note ist jedoch, die Aufmerksamkeit der experimentellen wie der theoretischen Physiker auf die Satelliten der Spektrallinien zu lenken. Sollte sich nämlich andererseits die hier vorgeschlagene Auffassung der Satelliten als richtig herausstellen, so könnte man hoffen, aus einem vervollständigten und gemäß dem Kombinationsprinzip in Spektraltermen geordneten Beobachtungsmaterial in Zukunft auf rein spektroskopischem Wege über den Bau der Kerne etwas zu erfahren.
Legend has it that Pauli made relentless criticism toward anybody else’s physics. But that was not the case concerning Nagaoka. Amazingly, there is no trace of criticism when introducing the work of Nagaoka and his collaborators in Pauli’s paper. The author was greatly impressed and eventually was brought to the Nagaoka paper concerning so-called “Saturnian model” of the atom, i.e., the 1904 Nagaoka paper. And it was realized that Nagaoka intended to use optical spectroscopy to study the atomic nucleus in the very early days of atomic physics. Nagaoka assumed a geometrical point center of the atom, and wrote:

The refined apparatus recently introduced by Michelson and Lammer in spectrum analysis has revealed a complex crowding of lines where formerly a single line was supposed to exist. In the present system, we have supposed that \( \nu \) particles are arranged in a circle, but in the actual case the particles may be at slightly different distances from the attracting centre, which was identified with a geometrical point.

The hypothesis of a point centre would only be a rough approximation, and we have reason to believe that the complexity of the structure of spectral lines is a consequence most likely to be expected.

Where there are many series of spectra, we have to consider the same number of rings of particles, all of which may or may not lie in the same plane. The occurrence of doublets of elements of… (p. 453)

It is clear that for the first time he presumed the complexity of atomic spectra, i.e., satellites of major spectral lines, to be due to the finite size of the positively charged center of the atom. His statement “the hypothesis of a point center would only be a rough approximation, and we have reason to believe that the complexity of the structure of spectral lines is a consequence most likely to be expected.” is almost exactly the same that we make in an introduction to nuclear field effects concerning hyperfine interactions today. Further, he suggested that the rings of electrons might not lie in the same plane, that is to say, he was considering a spherical system of the atom. Let’s consider a heavy atom like Ra with a large number of electrons, which Nagaoka actually had in his mind; then, that would be obvious.

Indeed, ‘the origin of hyperfine interactions’ dates back to Nagaoka’s atomic model. The complexity of the structure of spectral lines had successively been observed since A. Michelson (1891) carried out precision measurements using an ingenious device, an interferometer. Nevertheless, nobody but Nagaoka actually imagined that this complexity might be associated with the finite size of the atomic nucleus.

In 1907 Nagaoka purchased a 35-plate echelon spectroscope constructed by Adam Hilger, Ltd., a London company. It was just three years after his 1904 paper that he obtained a top-grade echelon diffraction grating at that time. This clearly shows that Nagaoka was determined to devote himself to optical spectroscopy in order to analyze the complexity of the atomic spectra, which was later known as fine structures due to the electron spin-orbit coupling and hyperfine structures caused by the nuclear spin and shape.

2-2. International reputation for Nagaoka’s hyperfine spectroscopy. In the early 1920s there was nothing definite about the hyperfine structure of spectral lines. But, as mentioned above, the Nagaoka-Sugiura-Mishima work spurred Pauli to look for the nuclear magnetic effect, i.e., spin, in addition to their suggestion of electric field effects. Meanwhile, A.E. Ruark, who was an expert in optical spectroscopy, working for the American Bureau of Standard and wrote in collaboration with H.C. Urey “Atoms, Molecules and Quanta” (McGraw-Hill, New York, 1930), recognized excellence in the Nagaoka-Sugiura-Mishima measurements. He wrote:

The data of Nagaoka, Sugiura, and Mishima covered a wider range than those of any other authors, and have been used, except where otherwise noted, in the hope that a higher degree of internal consistency might be obtained. Professor J.A. Anderson very kindly sent me some unpublished measurements of the lines… These were made from plates obtained by…, these excellent data of measurements are found to be substantially in agreement with those of Nagaoka, Sugiura, and Mishima. (p. 979)

By around 1930 the hyperfine structure was widely perceived both experimentally and theoretically. In 1931, German physicists H. Schüler and E.G. Jones reported that they carried out an experiment to study hyperfine structures of mercury spectral lines, and found the Nagaoka-Sugiura-Mishima measurements to be in good agreement with theirs. It should be stated that one of the German authors, Schüler, and Th. Schmidt for the
first time observed a large change in the isotope shift between $^{154}$Sm and $^{152}$Sm, pointing out a fundamental change in building-up of the nucleus,\textsuperscript{20} that is to say, a proposed shape change from spherical to deformed, three decades before nuclear physicists realized that fact in the 1960s (see, for example, Ref. 21, p. 534).

From the Ruark and Schüler-Jones papers it is clear that the Nagaoka-Sugiura-Mishima work had become internationally well accepted as excellent data on hyperfine structures. Regrettably, however, it seems that no Japanese physicists were aware of this fact. Authentic reference-books, such as that of Landolt-Börnstein, cite optical measurements concerning hyperfine structures only starting from the 1930s. This may be one of the reasons why younger generations did not have access to the Nagaoka-Sugiura-Mishima work. Eventually, their work was forgotten by history.

As can be seen from a short note by N. Bohr, who first suggested the possibility of a nuclear field effect on the $S$-term of the series of atomic spectra,\textsuperscript{22} people in the 1920s could hardly imagine that optical spectroscopy would provide nuclear-structure information, because Rutherford\textsuperscript{1)} showed the dimension of the atomic nucleus to be extremely small (ca. $3 \times 10^{-12}$ cm) compared with the dimensions of the orbits of the electrons (of the order $10^{-8}$ cm). It is very much likely that Nagaoka’s young collaborators had the same difficulty to understand what their mentor really wanted to tell them. After their publications, they drifted apart to study the mass shift, which has nothing to do with nuclear structure. This can be seen, for instance, in a textbook written by Condon and Shortley (see Ref. 23, p. 420). This book, which was first published in 1935, reads as follows in section 2: Local nuclear fields, Chapter XVIII The Nucleus in Atomic Spectra:

\begin{quote}
Data on differences in spectra associated with different isotopes of heavy elements is being accumulated rapidly at present and may in the future prove an important source of knowledge about the nucleus, but at present not much more can be said than that reasonable assumed departures from the Coulomb law in the neighbourhood of the nucleus can account in order of magnitude for the observed effects.
\end{quote}

They made no reference to the Nagaoka-Sugiura-Mishima work, but only to Pauli. However, their comments concerning atomic spectroscopy in the future as an important source of knowledge about the nucleus and probable departures from the Coulomb law are almost the same as what Nagaoka wrote.\textsuperscript{3)} (See the 1st citation from Pauli in subsection 2-1.) Despite Nagaoka’s foresight, his collaborators were getting out of the tide. In the end, Japanese physicists could not make significant contributions to help with building the foundation (nuclear spin, magnetic dipole moment, and electric quadrupole moment) of the nuclear shell model devised independently in 1949 by M.G. Mayer and by H.D. Jensen and co-workers.\textsuperscript{24)}

In the early 1930s, hyperfine interactions were firmly established in terms of quantum mechanics by W. Bertlett (1931), G. Breit and I.I. Rabi (1931), G. Racah (1932), and J.E. Rosenthal (1932), so that one could extract nuclear spins and moments independently of nuclear models, which led to the nuclear shell model, as mentioned above. This subsection title may sound strange to those who are acquainted with Nagaoka’s “Saturnian model” only. Attention should be paid, however, to the fact that not only did Nagaoka suggest the cause for the complexity of spectral lines, hyperfine interactions in modern terms, but he also started optical spectroscopy to verify it. D.A. Freiburger, an American science historian, nicely wrote:\textsuperscript{15)}

\begin{quote}
The use of Nagaoka’s experimental data in the work of other physicists remained his most important contribution to the international physics community during his many years of spectroscopic research and the best example of this is perhaps Wolfgang Pauli. (p. 685)
\end{quote}

3. The Nagaoka model of the atom

In his 1904 paper,\textsuperscript{3)} Nagaoka assumed a geometrical point center of the atom to describe the orbits of atomic electrons revolving around the center. In his introductory remark we read:

\begin{quote}
The system, which I am going to discuss, consists of a large number of particles (electrons) of equal mass arranged in a circle at equal angular intervals and repelling each other with forces inversely proportional to the square of distance (Coulomb law); at the centre of the circle, place a particle of large mass attracting the other particles (electrons) according to the same law of force. (Comments in the parentheses are given by the author. Note the wording underlined, too.)
\end{quote}
It should be noted that he did not mention anything about the dimension of the central entity, but only its mass. Nevertheless, science historians and popular science writers have assigned a ‘giant core’ to the Nagaoka atom, just like a ‘Saturn system’; some people are fond of showing a picture of Saturn to illustrate the Nagaoka atom. They probably wanted to refer to Nagaoka’s preliminary letter paper announcing his full paper (the 1904 Nagaoka paper) to come, where he said: “at the centre of the circle is placed a large particle attracting the other particles forming the ring according to the same law of force.” A “large particle” is quite different from a “particle of large mass.” Instead of showing a picture like a Saturnian system, one should follow his full paper faithfully. Here, it should be reminded again that Nagaoka said: “We have to consider the same number of rings of particles, all of which may or may not lie in the same plane.” This statement suggests that he was considering the system in a three-dimensional way, which is different from the Saturnian system considered by Maxwell, as he stated in the introduction of the 1904 paper. This point is not taken into account by a large number of authors of the Nagaoka atom.

Recently, a fine monograph of the history of atomic models in the context of quantum physics, “Compendium of Quantum Physics,” was published, where K. Hentschel wrote “Atomic Models, Nagaoka’s Saturnian Model” (pp. 22–23). His term “the earliest published quasi-planetary model of the atom” is interesting and acceptable in light of the Saturn system considered by Maxwell, as he stated in the introduction of the 1904 paper. He did not specify a ‘giant core’ to the Nagaoka atom in his illustration, but still insisted on “Saturnian,” saying: “a large, massive, positively charged sphere.” This current statement made by a distinguished science historian is misleading because it gravely distorted what Nagaoka mentioned in his 1904 paper: “at the centre of the circle, place a particle of large mass” (p. 445); “the attractive centre by a positively charged particle” (pp. 445–446); and “the attractive centre, which was identified with a geometrical point” (p. 453).

A fascinating book addressed to general readers appeared in 1994 with an introduction by a superstar, S. Hawking, being supported by CERN. Unfortunately, their illustration of the Nagaoka atom is a stereotyped picture similar to Saturn. It may also be worth mentioning an article by L.M. Brown and Y. Nambu: “Physicists in Wartime Japan.” They correctly pointed out the essence of the Nagaoka model: In 1903 Nagaoka proposed a model of the atom that contained a small nucleus surrounded by a ring of electrons. This “Saturnian” model was the first to contain a nucleus, discovered in 1911 by Ernest Rutherford at the Cavendish Laboratory in Cambridge, England. (p. 66. Note that, actually, the discovery was made at the University of Manchester in England.) Still, here appears the popularized term “Saturnian,” from which one could hardly imagine such a small nucleus at the center of the atom.

Let’s think about why so many people like to refer to ‘Nagaoka’s Saturnian model.’ Probably, this is due to the fame of H. Poincaré. To begin with, it would be worthwhile coming back to two old articles with positive views of the 1904 Nagaoka paper. First, before the Nagaoka paper was published in Phil. Mag. in May 1904, O. Lodge introduced Nagaoka’s epoch-making idea in the appendix (part added in February 1904) to a publication of his Romanes Lecture at Oxford, June 1903. He wrote: The above may be taken as representing roughly and crudely the kind of tentative view held for instance by J.J. Thomson. A slightly modified view, favoured provisionally perhaps by Professor Poynting, and likewise it appears by a Japanese physicist, Professor Nagaoka, would concentrate the positive electricity at the central point, thereby endowing it with considerable mass; but then the motion of the electrons would be subject to the inverse-square law; hence their periods would be different at different distances. Professor Nagaoka, however, would not consider this a disadvantage, for he treats them as forming constituents in a Saturn’s ring; and there might be several such rings, corresponding to the different lines in the spectrum.

An indication of these very modern speculations is appended to this lecture in order to illustrate the present lines of inquiry, and to emphasize still further the cautionary clauses in the lecture that views advocated are not to be regarded as more than provisional.

Lodge did not mention explicitly the Coulomb potential of the central point that was assumed to be a geometrical point, but it seems that he was well aware of its uniqueness. (From the date that he made additions, he must have had refereed Nagaoka’s manuscript submitted to Phil. Mag. probably in
January 1904. Otherwise, he could not say “at the central point” because what Nagaoka wrote in his preliminary letter paper, published in February 25, was: “at the centre of the circle is placed a large particle.” It seems most likely that Nagaoka’s manuscript was the one presented orally at the Tokyo Physico-Mathematical Society held on December 5, 1903, and published in the society proceedings, where one can see “the hypothesis of a point centre.” If so, it would be an interesting subject to study why there are considerable differences between the 1904 Nagaoka paper and the one in the proceedings.)

In 1905, H. Poincaré published a review article titled “La valeur de la science: œuvres philosophique;” In the Chap. IX L’avenir de la physique mathématique he made a special remark on the Nagaoka’s proposal, saying that it was an eye-opener to glimpse the secrets of nature. We read:

Les lois sont plus simples, mais elles sont de toute autre nature et pour ne citer qu’une de ces différences, pour les harmoniques d’ordre élevé le nombre des vibrations tend vers une limite finie; au lieu de croître indéfiniment. De cela on n’a pas encore rendu compte, et je crois que c’est là un des plus importants secrets de la nature. Un physicien japonais H. Nagaoka a récemment proposé une explication; les atomes seraient, d’après lui, formés d’un gros électron positif entouré d’un anneau formé d’un très grand nombre d’électrons négatifs très petits. Telle la planète Saturne avec son anneau. C’est là une tentative fort intéressante, mais pas encore tout à fait satisfaisante; cette tentative il faudrait la renouveler. Nous pénétrerons pour ainsi dire dans l’intimité de la matière. Et au point de vue particulier qui nous occupe aujourd’hui, quand nous saurons pourquoi les vibrations des corps incandescents diffèrent ainsi des vibrations élastiques ordinaires, pourquoi les électrons ne se comportent pas comme la matière qui nous est familière, nous comprendrons mieux la dynamique des électrons et il nous sera peut-être plus facile de la concilier avec les principes. (p. 227)

Although he said that there were some flaws in Nagaoka’s papers, Poincaré noted as well as Lodge that Nagaoka’s attempt would be an interesting means to study the atomic system in the future. Actually, history progressed in that direction. It is deplorable, however, that following Nagaoka’s preliminary letter paper rather than the 1904 Nagaoka paper, Poincaré wrote, as can be seen from the above citation: a large, positively charged electron encircled by a large number of negative electrons like the Saturn ring. Today, Poincaré is a scientist known internationally much more than Lodge. Because of this and his fame, the English version of his review article has been printed repeatedly to date, and it seems that most writers follow Poincaré’s statement without consulting the 1904 Nagaoka paper. This may have resulted in the stereotyped misleading picture of the Nagaoka atom. However, Nagaoka himself should be responsible for that, too, because he called his model “Saturni” occasionally, though he did not like that at all (see section 6).

Concerning the ‘atomism’ in Europe, the situation was chaotic around the time when Nagaoka was considering the atom. According to Ref. 27, in Germany, for example, a number of influential scientists, such as E. Mach, H. Hertz and W. Ostwald, stubbornly resisted atomism; atoms were not real, maintained Hertz, they were merely imaginary objects that were a useful means of explaining certain phenomena. In Japan no scientists senior to Nagaoka had favourable opinions concerning his atomism, too. However, it is understandable that in Europe the Nagaoka model of the atom had generated much interest among leading scientists, like Lodge and Poincaré, who were seeking a breakthrough in atomism from philosophy to physics. It is of interest to note that even a German translation of his manuscript was received for publication in Phys. Z. on May 24, 1904, and published in August. (Note: No parts containing “Saturni” were translated, except for “The system differs from the Saturnian system considered by Maxwell...” and, unlike the 1904 paper, a messy part about the atomic mass was included.)

Even today everybody will first have a classical picture to describe a microscopic phenomenon, but can quantize it as he/she wishes: the correspondence principle. When we describe the motion of electrons around the nucleus, or a particle approaching the nucleus, today, we use the Coulomb potential of a positively charged nucleus, which is exactly the same as what Nagaoka did.
conduct experiments in that direction because he was a man of independence. His spirit is vividly demonstrated by his calligraphy, 稔糟 嘗勿 (Copying the original is most detestable). Instead, as originally intended, he enthusiastically pursued an untrodden realm, optical spectroscopy for nuclear structure study that resulted in valuable observations by which Pauli was inspired to assume nuclear spin.

4. Identity between Nagaoka and Rutherford atoms

The Nagaoka potential used to describe the kinetics of particles in the atom is the Coulomb potential of a geometrical point center of the atom that is given by $V(r) = \frac{e^2}{r}$, where $r$ is the distance from the point center and $e$ is a positive charge of the center. The Rutherford potential is the same as that seen in the following. He wrote:

$$X = Ne \left( \frac{1}{r^2} - \frac{r}{R^3} \right),$$
$$V = N e \left( \frac{1}{r} - \frac{3}{2R} + \frac{r^2}{2R^2} \right).$$

The 1st term in the potential $V$ is the Coulomb potential of the point center of the atom; the remaining terms come from the uniform distribution of electrons that is negligibly small compared with the 1st term. Note that at their time the atomic number was not yet established, though they knew that the normal atom was electrically neutral.

From their contexts it is evident that $E = Ne$. Consequently, the nuclear part of their potential is exactly the same. There is no reason at all to differentiate between the Nagaoka model and the Rutherford model. Figure 3 provides a pictorial comparison of their models in light of the Coulomb potential that they used.

Rutherford must have read the 1904 Nagaoka paper in bewilderment, while finding the Coulomb potential of the core of the atom to be the same as that which he assumed for a point center. Referring to Nagaoka, he wrote:

It is of interest to note that Nagaoka has mathematically considered the properties of a
“Saturnian” atom which he supposed to consist of a central attracting mass surrounded by rings of rotating electrons. He showed that such a system was stable if the attracting force was large. From the point of view considered in this paper, the chance of large deflection would practically be unaltered, whether the atom is considered to be a disk or a sphere. It may be remarked that the approximate value found for the central charge of the atom of gold (100e) is about that to be expected if the atom of gold consisted of 49 atoms of helium, each carrying a charge 2e. This may be only a coincidence, but it is certainly suggestive in view of the expulsion of helium atoms carrying two unit charges from radioactive matter. (p. 688)

Just before submitting this paper to Phil. Mag., Rutherford replied to Nagaoka’s letter,32) saying that “You will notice that the structure assumed in my atom is somewhat similar to that suggested by you in a paper some years ago.”33) Probably, Nagaoka expected that Rutherford would describe this similarity publicly in his coming paper.4) But, as can be seen from the above citation, there is no straightforward mention of the similarity between their atomic models. Rather, Rutherford implied that the Nagaoka atom was a disk-like system, calling it a “Saturnian” atom. This may be one of the reasons why people are likely to believe that their models are different. In view of the Coulomb potential they used, it is hardly acceptable that such a statement as Rutherford made is a fair reference to Nagaoka, though some people considered that it was proper;33) or that Nagaoka might have been grateful for it.2)

As discussed in subsection 2-1 and section 3, there is no doubt that Nagaoka mathematically considered a spherical atom with a positive point-charge at the center, saying that the rings of electrons may not lie in the same plane. It may be said, therefore, that, unlike his letter to Nagaoka,33) Rutherford did not care thoughtfully about Nagaoka’s priority in an idea of the atom with a positive charge at the center. Nagaoka must have been offended by Rutherford’s way of referring to the Nagaoka atom, since there was no trace of any contacts between them during the following decade. It is very unnatural when taken into account Nagaoka’s admiring letter to Rutherford.32) One thing should be remembered, however: in his letter Nagaoka proudly mentioned “my model of Saturnian atom” in which physicists in Bologna were much interested. Rutherford might have had it in mind to exploit this statement of Nagaoka in writing his paper.4)

It is no wonder that physicists and their students in Bologna welcomed Nagaoka with a bow when he visited the University of Bologna in 1910,34) because quite a few European physicists remembered Nagaoka as prospering from a highly praised “Saturnian” atom since Lodge and Poincaré drew attention to Nagaoka’s ingenious idea of the atom.3) Around the beginning of the 20th century, the Thomson model (so-called “plum-pudding model”)35) was widely accepted, while Nagaoka proposed a model of the atom that was extremely different from the former.

As Lodge and Poincaré foresaw, infant atomic physics developed in that direction (the atom with a nucleus). Finally, it culminated in success as Rutherford and his collaborators conducted a decisive experiment.4),36) Perhaps, Nagaoka was proud of that. But it seems that Rutherford was not so sympathetic to the Nagaoka atom. Nagaoka was lamenting about that to his last years.37)

The author, as a nuclear physicist, admires Rutherford’s achievements, but could not help questioning his personality when it comes to a matter of priority. He was born talented without doubt and, according to D. Wilson,35) he was a man of self-righteousness — so much so that, in later years, due to his priority-obsessed mind, he had developed acrimonious relationships with W. Ramsay and F. Soddy, both Nobel Prize winners in chemistry, who were once research collaborators at the beginning of Rutherford’s career (see Ref. 33, pp. 198–200, pp. 231–237). Wilson wrote (p. 163): “there was at times some acerbity between them.” It is also known that Rutherford would not give P. Villard credit for the discovery of γ rays for about ten years, until Rutherford was awarded the Nobel Prize in chemistry in 1908.33) So, too, as for the Nagaoka atom he did not make any exception; he did not credit for Nagaoka’s idea that the atom consists of a highly charged large-mass point center and electrons orbiting around it in a three-dimensional way.

As pointed out in section 3, the 1904 Nagaoka paper3) is considerably different from its preceding paper that was read before the Physico-Mathematical Society, Tokyo, on December 5, 1903 and published in the Society proceedings.30) Because of this, one should avoid or be careful in referring to the Nagaoka model of the atom by Ref. 30, and his successive papers that appeared in Nature,25) which are apparently based on Ref. 30.
5. High school physics textbooks in Japan

Two years ago a survey of high school physics textbooks in Japan was conducted to see how Nagaoka and his contribution to the early stage of atomic physics were described during the last 50 years. It is of interest to note that there were no textbooks that mentioned Nagaoka’s Saturnian model from 1955 to 1964; 50% Nagaoka atomic model and 50% no mention of Nagaoka at all; the Nagaoka model has been described ever since in such a way that the Rutherford model of the atom is identical to the Nagaoka model. However, Nagaoka’s Saturnian atom with a ‘giant core’ appeared gradually in textbooks. And after an extensive biography of Nagaoka was published, which emphasized Nagaoka “Saturnian” atom, showing a picture of the Saturnian system, the tendency to describe the Nagaoka model started remarkably to change. Now, the “Saturnian” atom is dominant in textbooks by almost 80% and about 20% the Nagaoka model or no mention of Nagaoka at all. It is deplorable that the Nagaoka model that is identical to the Rutherford model is fading away from textbooks.

Mention should be made of the fact that representative textbook writers who described the Nagaoka model and the Rutherford model as being the same were prominent physicists, such as S. Tomonaga, M. Nogami, K. Ariyama, K. Husimi, S. Kaya, T. Nishikawa, and G. Tominaga. The following is a typical example of explanations made by them:

The atom consists of a small positively charged core, i.e., the nucleus and the surrounding electrons. This structure is somewhat similar to the solar system, since an attractive force between the nucleus and electrons is caused by the Coulomb law, being inversely proportional to the square of the distance between them. This kind of atomic structure was first suggested by Nagaoka and confirmed experimentally by Rutherford. (Translated by the author from Japanese Ref. 38.)

Similarly, Rutherford could have made such a reference to the Nagaoka model in Ref. 4. If he had done this, the world would probably have been quite different in presenting the achievements of Nagaoka and Rutherford during the early days of atomic physics. Unfortunately, the authors of a biography of Nagaoka did not pay attention at all to the fact that in the past there were a large number of physicists who wrote our high school physics textbooks, while stating the identity of the Nagaoka model and the Rutherford model.

Both models of Nagaoka and Rutherford concerning the atom are classical ones, being inevitably not free from any radiation loss by orbiting electrons. Both of them understood this. However, they had intuitions mathematically and experimentally, respectively. The Bohr model based on the quantum theory was obviously developed from the classical model during Bohr’s visits (1912–13) to Rutherford’s laboratory, the University of Manchester. So such a wording as Rutherford-Bohr atomic model is commonly used in the textbooks published in the West (see, for example, Refs. 12, 26, 39). In Japan, on the contrary, a large number of physicists used to regard the Rutherford model as being identical to the Nagaoka model, i.e., the Nagaoka-Rutherford model, probably because they knew their Coulomb potential of the atomic center to be exactly the same, as pointed out above. By taking these points into account, it should be appropriate to propose a new wording: Nagaoka-Rutherford-Bohr atomic model.

Right after Bohr’s trilogy, a complete set of papers concerning the Bohr model, Rutherford wrote a paper titled “The Structure of the Atom.” Needless to say, he referred to the Bohr model. He also made mention of the Kelvin model as well as the Thomson model, but no mention of the Nagaoka model at all. Why? The author would like to leave that to the readers to decide. There is no way to deduce the same Coulomb potential from either the Kelvin model or the Thomson model. Their models are, therefore, basically different from those of Nagaoka, Rutherford, and Bohr.

In the first part of the trilogy, Bohr wrote:

Let us consider a ring consisting of \( n \) electrons rotating round a nucleus of charge \( E \), the electrons being arranged at equal angular intervals around the circumference of a circle of radius \( a \). (p. 20)

This statement is physically the same as that which Nagaoka made in his 1904 paper. It is interesting to note that Bohr employed the same notation, \( E \), for the charge that Nagaoka used for the charge concentrated at a geometrical point center of the atom. It seems that Bohr wanted to signal his respect to Nagaoka without making an explicit reference. He knew that his mentor, Rutherford, did not like to
refer to Nagaoka any longer. At that time, without
the mentor’s cover letter, young fellows could not
submit their papers to Phil. Mag., for instance. Their
papers were always communicated by Prof. XXX.

Bohr further continued:

*The total potential energy of the system consisting
of the electrons and the nucleus is*

\[
P = -\frac{ne}{a}(E - es_n),
\]

where \( s_n = \ldots \)

The 1st term is equivalent to the potential energy
\(-E \sum_1^\infty \) given by Nagaoka to the atomic center that
was identified with a geometrical point.\(^3\) He must
have been aware that his Coulomb potential was
exactly the same as Nagaoka’s. Therefore, it seems
natural that he wanted to send the copies of the
trilogy to Nagaoka immediately after its completion,
as is stated below.

6. Concluding remarks

It is time to remember Nagaoka together with
Rutherford and Bohr. The Coulomb potential of the
atomic nucleus, which is the essential basis of their
models of the atom, is the same.

On the occasion of the 50th anniversary of
Bohr’s atomic model, a commemorative volume\(^{42}\)
consisting of the Bohr’s trilogy of the atomic model
was published: “On the Constitution of Atoms and
Molecules with an introduction by L. Rosenfeld.”
With much respect, Rosenfeld mentioned Nagaoka
as a pioneer of the atomic model with its core being
positively charged. In concluding his remark, he
wrote:

> Let me end, much as I stated, with a bow to the venerable Japanese pioneer Nagaoka. From the latter Bohr received an interesting post-card with Lagrange’s portrait and the mention “Newton festival, 1913,” explained by a manuscript note: “Newton-festival is held every year on Newton’s birthday (Dec. 25th) in commemoration of his works and his successors.” The text of the card is as follows:

Tokyo, Dec. 27, 1913

Dear Sir,

Hearty thanks for your kindness in sending me several papers on atomic structure; it seems
to be intimately connected with Saturnian atom,
with which I was occupied about ten years ago.

Yours truly,

H. Nagaoka

Rosenfeld reminded us that Bohr sent copies of
his famous trilogy to Nagaoka as soon as its 3rd paper
Part III was published in November 1913, and
Nagaoka lost no time in writing to thank Bohr for
his thoughtfulness. This episode shows that Bohr had
profound reverence for Nagaoka. To the contrary,
there is no trace of Rutherford’s having sent a copy of
his paper\(^4\) to Nagaoka. Along with his paper “The
Structure of the Atom”,\(^40\) Rutherford’s remark on a
“Saturnian” atom,\(^4\) which was seemingly made to
differentiate his model from Nagaoka’s, has most
likely played a decisive role in history. (Nagaoka’s
card reminds us that sometimes he wrote “Saturnian”
to show his atomic model in spite of the fact that he
had tried to avoid “Saturnian,” calling “an electron atom/electron atoms” instead,\(^43\) or emphasizing
“my positively charged nucleus.”\(^44\) And he abhorred
incessant requests to write something on the
“Saturnian” atom.\(^37\)) Year by year Rutherford was
becoming more and more famous, and it is known
that he especially emphasized the difference between
his atom and Nagaoka’s Saturnian atom wherever he
gave lectures.\(^33\) Ironically, Nagaoka’s fame concern-
ing a “Saturnian” atom has been derived from the
work of Rutherford, and as pointed out in Refs. 6
and 10, Nagaoka has been alienated from Rutherford
and Bohr even in Japan. Now we should acknowledge
Nagaoka as the venerable pioneer leading to the
contemporary atomic model, as stated by Rosenfeld.

Rosenfeld did not mention anything about
Nagaoka’s spectroscopic studies, but one should
remember that in his paper\(^3\) Nagaoka showed his
intention to figure out the complexity of the atomic
spectra (fine structures and hyperfine structures) in
which Bohr was interested, too, unlike Rutherford.
Science historians are likely to say that Nagaoka
abandoned his “Saturnian” model of the atom (the
1904 Nagaoka paper)\(^3\) and turned to spectroscopy in
order to understand the structure of the atom. This
is wrong. Nagaoka continued spectroscopic studies
of the atom with a highly charged point center that
he presumed to be a rough approximation in the
paper;\(^3\) that is to say, he considered the finite size
of the atomic nucleus and its effects on atomic
spectra. After a painstaking two decades, he and his
collaborators published extensive measurements of hyperfine structures of various atoms, which were made at RIKEN. Their pioneering work attracted internationally a lot of professional interest. The most significant of all was Pauli, who was so inspired as to propose nuclear spin in addition to their field effects. Indeed, the 1904 Nagaoka paper is the origin of contemplating hyperfine interactions.

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References
1) Nagaoka, H., Sugiura, Y. and Mishima, T. (1923) The fine structure of mercury lines and the isotopes. Jpn. J. Phys. 2, 121–162; Nagaoka, H. and Sugiura, Y. (1923) Spectroscopic evidence of isotropy. Jpn. J. Phys. 2, 167–278; Nagaoka, H., Sugiura, Y. and Mishima, T. (1924) Isotopes of mercury and bismuth revealed in the satellites of their spectral lines. Nature 113, 459–460.
2) Itakura, K., Kimura, T. and Yagi, E. (1973) Nagaoka Hantarō Den (Biography of H. Nagaoka), supervisor Fujioka, Y., Asahi Shimbun sha, Tokyo (in Japanese).
3) Nagaoka, H. (1904) Kinetics of a system of particles illustrating the line and the band spectrum and the phenomena of radioactivity. Phil. Mag. 7, 445–455.
4) Rutherford, E. (1911) The scattering of α and β particles by matter and the structure of the atom. Phil. Mag. 21, 669–688.
5) Bohr, N. (1913) On the constitution of atoms and molecules, Part I Binding of electrons by positive nuclei. Phil. Mag. 26, 1–25; Bohr, N. (1913) Part II System containing only a single nucleus. Phil. Mag. 26, 476–502; Bohr, N. (1913) Part III System containing several nuclei. Phil. Mag. 26, 857–875.
6) Inamura, T.T. (2014) Why not have Nagaoka–Rutherford–Bohr model? BUTSURI 69, 652–653 (in Japanese).
7) Inamura, T.T. (1997) Nagaoka’s optical spectroscopy: pioneer nuclear-structure study. J. Spectr. Soc. Japan 46, 123–124 (in Japanese).
8) Inamura, T.T. (2000) Optical spectroscopy by Hantarō Nagaoka—pioneer nuclear-structure study. Hyp. Interact. 127, 31–34.
9) Inamura, T.T. (2008) Beyond Saturnian model—pioneer nuclear-structure study by Hantarō Nagaoka. BUTSURI 63, 61–62 (in Japanese).
10) Inamura, T.T. (2015) Resurrection of Nagaoka’s atomic model. HOUSHAKAGAKU 31, 55–63 (in Japanese).
11) Pauli, W. (1924) Zur Frage der theoretischen Deutung der Satelliten einiger Spektrallinien und ihrer Beeinflussung durch magnetische Felder. Naturwiss. 12, 741–743.
12) Herzberg, G. (1944) Atomic Structure and Atomic Spectra. 2nd ed. Dover Publications, New York.
13) Bohr, A. and Weisskopf, V.F. (1950) The influence of nuclear structure on the hyperfine structure of heavy elements. Phys. Rev. 77, 94–98.
14) Ramsey, N.F. (1985) Molecular Beams, Oxford University Press, Oxford.
15) Freiburger, D.A. (2002) Building a Japanese research tradition in physics: Hantarō Nagaoka and the spectroscopy. Nuncius Annali di Storia della Scienza XVII, 673–689.
16) Nagaoka, H. (1950) Memoirs Proc. Phys. Soc. Japan (later BUTSURI) 5, 323–328.
17) Takamine, T. (1951) Memorial writing: Prof. Hantarō Nagaoka and optical spectroscopy. KAGAKU 21, 145–146 (in Japanese).
18) Ruark, A.E. (1926) The fine structure and Zeeman effect of complex mercury lines. Phil. Mag. S7, 1, 977–995.
19) Schüler, H. and Jones, E.G. (1932) Hyperfeinstrukturen und kernmomente des quecksilbers II. Z. Phys. 74, 631–646.
20) Schüller, H. and Schmidt, Th. (1934) Über eine neue ersehnbene bei dem isotopen des samariums. Z. Phys. 92, 148–152; Schüler, H. and Schmidt, Th. (1935) Über abweichungen des atomkerns von der kugelsymmetrie. Z. Phys. 94, 457–468.
21) Bohr, A. and Mottelson, B.R. (1975) Nuclear Structure Vol. II. W.A. Benjamin, Inc., Reading.
22) Bohr, N. (1922) The difference between series spectra of isotopes. Nature 109, 746.
23) Condon, E.U. and Shortley, G.H. (1991) The Theory of Atomic Spectra. Cambridge University Press, Cambridge.
24) Bohr, A. and Mottelson, B.R. (1969) Nuclear Structure Vol. I. W.A. Benjamin, Inc., New York.
25) Nagaoka, H. (1904) On a dynamic system illustrating the spectrum lines and the phenomena of radioactivity. Nature 69, 392–393; Nagaoka, H. (1904) A dynamical system illustrating the spectrum lines. Nature 70, 124–125.
26) Greenberger, D., Hentschel, K. and Weinert, F. eds. (2009) Compendium of Quantum Physics. Springer, Heidelberg.
27) Fraser, G., Liljestol, E. and Sellevåg, I. (1994) The Search for Infinity. Mitchell Beazley, London.
28) Brown, L.M. and Nambu, Y. (1998) Physicists in wartime Japan. Sci. Am. 279 (6), 66–73.
29) Lodge, O. (1904) Modern Views on Matters. 3rd ed. Oxford. (See appendix.).
30) Nagaoka, H. (1904) Motion of particles in an ideal atom illustrating the line and band spectra and the
phenomena of radioactivity. Proc. Tokyo Math-Phys. Soc. 2, 92–107; (trans. Gradenwitz, A.) (1904) Über ein die linien und bandenspektren, sowie die erscheinungen der radioaktivität veranschaulichendes dynamisches system. Phys. Z. 5, 517–521.

31) Poincaré, H. (1905) La Valeur de la Science. Paris; (http://gallica.bnf.fr/ark:/12148/bpt6k2071994/f1.image); (trans. Halsted, G.B.) (2001) The Value of Science. Modern Library, Random House, Inc., New York.

32) Badash, L. (1967) Nagaoka to Rutherford, 22 February 1911. Phys. Today 20 (4), 55–60.

33) Wilson, D. (1983) Rutherford SIMPLE GENIUS. MIT Press, Cambridge, Massachusetts.

34) Nagaoka, H. (1912) Reports on a tour of European Physics Laboratories in 1910 (V), Tokyo Buturi Gakko Zasshi (Tokyo college of Physics Journal), June, 242–249 (in Japanese).

35) Thomson, J.J. (1904) On the structure of the atom: an investigation of the stability and periods of oscillation of a number of corpuscles arranged at equal intervals around the circumference of a circle; with application of the results to the theory of atomic structure. Phil. Mag. 7, 237–265.

36) Geiger, H. and Marsden, E. (1913) The laws of deflexion of α particles by large angles. Phil. Mag. 25, 604–623.

37) Nagaoka, H. (1950) My recollection of research into atomic nucleus. KAGAKUASAHI, January, 22–25 (in Japanese).

38) Tominaga, G. et al. (1978) Fundamental Physics I, a high school textbook. Kairyudo, Tokyo (in Japanese).

39) See, for example, Becker, R. (1982) Electromagnetic Fields and Interactions. Dover Publications, New York.

40) Rutherford, E. (1914) The structure of the atom. Phil. Mag. 27, 488–498.

41) Lord Kelvin (Thomson, W.) (1902) Molecular dynamics of a crystal. Phil. Mag. 4, 139–156.

42) Rosenfeld, L. (1963) On the Constitution of Atoms and Molecules: N. Bohr, 1913. Munksgaard, Copenhagen; W.A. Benjamin, Inc., New York.

43) Nagaoka, H. (1904) The structure of an atom. Proc. Tokyo Math-Phys. Soc. 2, 240–247; Nagaoka, H. (1905) Dispersion of light due to electron-atoms. Proc. Tokyo Math-Phys. Soc. 2, 280–289; Nagaoka, H. (1905) Mutual action of electron-atoms. Proc. Tokyo Math-Phys. Soc. 2, 316–320; Nagaoka, H. (1905) Virial of molecular forces due to electron-atoms, the characteristic equation and the Joule-Kelvin effect. Proc. Tokyo Math-Phys. Soc. 2, 335–340.

44) Nagaoka, H. (1938) In memory of Sir Ernest Rutherford, pioneer of radioactivity research. KAGAKUCHISHIKI, January, 46–50 (in Japanese).

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