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Janne Rydberg – his life and work

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Abstract

The Rydberg formula is emblematic of atomic spectroscopy. We review here the personal background, research accomplishments, and academic career of its discoverer, Janne Rydberg. Although his formula is often introduced as a generalization of the hydrogenic Balmer formula, Rydberg's work was independent of Balmer's, and displayed great ingenuity and a rare ability to recognize hidden patterns in complex numerical data. Although his discoveries attracted wide attention, experimental physics was then considered inseparable from measurement, and the fact that Rydberg's insightful formulations used the data of others impeded his academic career. Although Rydberg did not live to see the full theoretical implications of his discoveries, the vigorous study of Rydberg atoms continues today.
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1. Introduction

One of the great pioneers of atomic physics, Johannes (Janne) Robert Rydberg, was born on 8 November 1854 in Halmstad on the west coast of Sweden. His father Sven, a merchant and minor ship owner, died when Janne was only four years old. The family was left in a difficult economic situation. However, Janne was able to study for 9 years and finish his secondary schooling in 1873. He then entered the Lund University where he received a bachelor's degree in 1875. He continued with his main topic, mathematics and in 1879 he defended his doctoral thesis, dealing with the theory of conic sections. This work was soon complemented by another investigation, of algebraic integrals to algebraic functions, and in 1881 he was appointed "docent" (assistant lecturer) in mathematics. In parallel with his mathematical studies he worked as a teaching assistant at the Physics institute in Lund. His first physics paper

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dealt with friction electricity and he became docent in physics in 1882.

2. Rydberg's first scientific efforts

Already as a student he was particularly interested in the periodic system of the chemical elements introduced by D.I. Mendeleyev. At that time R.W. Bunsen and G.R. Kirchhoff had already been performing spectral analyses of various elements and obtained a wealth of wavelength data. This would soon become an extremely promising field of research.

Rydberg's main interest was indeed the periodic system and he published his first paper on this topic in 1884. It was followed by many other papers and Rydberg regularly returned to such problems. In those days it was already known that the system of spectral lines emitted when an element was introduced into a flame or electric arc was characteristic for each element. Rydberg assumed that these line spectra could be effective clues in his studies directed at revealing the real nature of the periodic system.

3. Studies in spectroscopy

The spectroscopic material, as obtained from observations, was in the form of a wealth of tables with spectral lines, apparently without any regularity and spread out over the spectrum. Initially such data were of limited use for Rydberg's research. His first task was to find a system for arranging the spectral lines. It was already known that the spectra of various elements could be quite different. For instance, the spectrum of iron (Fe) was very complicated with lots of lines, whereas those of the alkalies (Li, Na, etc.) and alkaline earths (e.g. Be, Mg) were relatively simple.

To begin with, Rydberg discovered that it was possible to sort the spectral lines belonging to an element in a number of different series, where the lines followed each other with a regularly decreasing difference and intensity. He put numbers on the various lines in a given series, with 1 for the line with the longest wavelength, 2 for the next line, etc. and tried to find a formula that could express the wavelengths or frequencies as a simple formula that included integers. When trying to draw the relation between wavelengths and order numbers he found that the curve resembled a hyperbola. Therefore he tried to express the frequency as a constant term reduced by a variable term, the denominator of the latter being a linear function of the order number. A little later he found that there was better agreement with experimental data if the denominator was a quadratic function, and this was the form that he now used for his series formula.

This detail in the derivation is interesting because it shows that Rydberg could not have started from Balmer's formula for the hydrogen spectrum [1]. Otherwise he could have started from the quadratic form. Balmer published his formula in 1885, some years before Rydberg's first publication dealing with atomic physics. However, it seems to be clear that Rydberg derived his formula without knowing anything about Balmer's work. Only when he had derived his equations he realized that Balmer's formula was a specific case of his result.

In September 1887 Rydberg wrote to the Royal Swedish Academy of Sciences (KVA) and asked for financial support from a fund belonging to the Academy. An appendix to this application contained a summary of his results, all of which were later formally published. The complete report of his research on the systematics of spectra "Recherches sur la constitution des spectres d′emission des elements chimique" was submitted to KVA in 1889 and was printed a year later [2]. In 1886 Rydberg married Lydia Eleonora Mathilda Carlsson, the daughter of a medical official. They had two daughters and a son.

When Rydberg compared the formulae which he had derived for the various series in a given element, he found that the constant term for a certain series had the same value as the first running term in another series. An important relation between the various series was thereby found. The wavenumbers could now be expressed as the difference between two terms of the same form, where the denominator is a quadratic function of a running integer and the numerator is a constant number, which has the same value for all series. It was also found that this number returned, with the same value for all elements. Rydberg has described his results in the following way.

"In all spectra which have been investigated so far, the strongest lines form series, and these can be approximated by means of the formula

$$n = n_0 - N_0/(m + \mu)^2 \quad (1)$$

where n is the wavenumber of the line ($1/\lambda$), N_0 a constant with the value of 107,921.6 while n_0, m and μ are constants which are specific for the series". (It is interesting to note that the wavenumber, later usually denoted σ, was introduced by Rydberg.) He also rewrote the formula in the following, now well-known way

$$n/N_0 = 1/(m_1 + \mu_1)^2 - 1/(m_2 + \mu_2)^2 \quad (2)$$

an expression that points towards the famous combination principle of Ritz [3]. The value of the constant N_0, which Rydberg assumed to be identical for all chemical elements, was computed by him using the known wavelengths for the hydrogen atom, which resulted in the value 109,721.6 given above. Later measurements have yielded the value 109,677 and it is also known that the value varies from element to element, being 109,737 for infinite nuclear mass. The constant N_0 is known as the Rydberg constant R_∞.

Rydberg had thus revealed a remarkable relation between the various chemical elements and he had also arrived at a simple synthesis for previously unsystematized numerical material for the spectra of atoms. His results were received with great admiration in several countries and Rydberg was immediately considered by the spectroscopic community as a leading physicist.

However, Rydberg realized that his formulas were approximate and that they just provided a formal description of the spectra. The physical meaning of the formulae was not understood, but the solution came several years later when Niels Bohr published his theory on the constitution of atoms [4]. Rydberg's spectral terms could now be identified with the energy contents for an atom in its various quantum states. Furthermore, Rydberg's constant came as the natural unit for measurements of atomic energies. Modern atomic theory gives as a first approximation the same description of atomic spectra as Rydberg could derive from his purely chemical analysis of the experimental material. With ingenious intuition and a remarkable ability to discover relations in complex numerical data – and without the support of theories – Rydberg managed to find the rational form that has remained the basis for all subsequent studies of atomic spectra.

4. Application for a chair in physics

In spite of Rydberg's international recognition he encountered problems in Sweden. In 1897 a chair as professor in physics became available at Lund University. Rydberg and five other Swedish scientists sent in their applications, and the candidates were evaluated and ranked by three experts, one Danish and two Swedish professors. After much work the Swedish experts concluded that while Rydberg's scientific results were excellent his discoveries were based on data obtained by other scientists! And since the chair was supported to be in experimental physics, his qualifications were not sufficient. However, the Danish expert, C. Christiansen, was strongly in favor of Rydberg, whom he also encouraged to contact some foreign experts for additional evaluation of his achievements. Rydberg followed this advice and received very strong and enthusiastic recommendations from the leading spectroscopists Heinrich Kayser and Carl Runge in Germany. Even the Lund University was impressed and now supported Rydberg for the chair. All relevant documents were sent to King Oscar II and the Swedish government in Stockholm who had to make the final decision. After a long consideration the King and government decided, on 21 September 1900, to appoint Viktor Adolf Bäcklund, whose fields of research were mechanics and mathematical physics, to professor. He had also applied for the chair but he was not even ranked by the three experts who had decided that his merits in physics were not sufficient. However, it has been pointed out later that Bäcklund was a close friend of Oscar II, a quite cultural monarch. This example shows that it can be very difficult to evaluate scientific results, to choose between a competent candidate who has made detailed studies and a person with original ideas that will open new fields for research. The following developments have shown that Rydberg's contributions belong to the latter category.

The new professor, Bäcklund, now became responsible for all teaching in physics. Since he wanted to concentrate on his own fields, he needed someone who could teach courses in experimental physics. Therefore he worked hard to find a position as extra professor to Rydberg for this purpose, and this was approved by the government in March 1901. Efforts were continued to raise this position chair to full professor, which finally succeeded in January 1909. At the age of 54 years and after about 25 years of scientific activity Rydberg had reached his goal. During several previous years when Rydberg with a modest salary was waiting for a permanent position, he was also working as an accountant in a savings bank in Lund. His unique skill in handling piles of complicated numbers must have been quite useful for the bank.

5. Last years

As already mentioned, Rydberg entered the field of atomic spectroscopy in connection with his studies of the periodic system of elements. The great problem, to which he always returned, was to find a simple formula which could describe the periodicity of the chemical and physical properties of the elements and explain the elusive secrets of the periodic system. Rydberg soon found that atomic weights of elements were not suitable as an independent variable for the periodic system. Instead he introduced integers (atomic numbers) to indicate the positions of the elements in the system, and he was probably the first scientist to do this. But even here he encountered major problems. At that time, when many elements had not yet been found, there was no method which allowed one to establish the order number in a unique way. Such investigations kept Rydberg busy during many years, and while he must have been frustrated, he still published a wealth of papers from 1884 to 1913 on such problems. In this context the spectral studies can be considered as an episode. But it must be underscored that the latter work has been extremely important for the development of atomic physics, whereas his large scale-studies of the periodic system are of minor significance. Despite clever handling with details and an admirable formal elegance this work was neither correct nor important. We now know why these investigations of the periodic system failed. It was only with E. Rutherford's discovery of the atomic nucleus, N. Bohr's atomic theory and H.G. Moseley's results for X-ray spectra that it became possible to establish the correct atomic number for each chemical element. The final solution to Rydberg's great problem came much later, with the exclusion principle of W. Pauli, which explains the number of electrons in periodically arranged shells.

Rydberg was not destined to work as a full professor for a long period. Already in 1911 he had a stroke, and for several years he suffered from a weak heart and blood circulation problems. In 1915 he had to resign from his position because of bad health and he spent the last three years of his life in a hospital. Soon after his 65th birthday, on 28 December 1919, he died in Lund of a brain hemorrhage. A few months before his death, on 26 June 1919, he was elected Foreign member of the Royal Society.

In these days it appears surprising that he was not elected to the Royal Swedish Academy of Sciences. However, he was nominated for the 1917 Nobel prize in physics by a Swedish astronomer, Carl Charlier, but no award was made in that year. The German physicist Phillip Lenard (Nobel laureate 1905) nominated Rydberg for the 1920 prize but this was not considered because Nobel prizes are not awarded posthumously. It still shows that Rydberg's scientific work was highly considered in Europe.

As a professor Rydberg had several excellent students, in particular Manne Siegbahn (1886–1978) who was acting professor when Rydberg's health was failing, and became full professor in 1915 when Rydberg had to retire. In Lund Siegbahn carried out exceptional work in X-ray spectroscopy which was rewarded with the Nobel prize in 1924 "for his discoveries in the field of X-ray spectroscopy".

Rydberg was considered by many of his contemporaries as a complicated person and his sadness was apparent, but his modesty and kindliness of heart were also appreciated. His successor Siegbahn has mentioned Rydberg's sense of humor.

6. The Rydberg conference in 1954

About 50 years ago, in July 1954, the Rydberg Centennial Conference on Atomic Spectroscopy was held in the Physics Department, Lund University. The time and place of the conference were chosen with a view to commemorate the hundredth anniversary of the birth of Janne Rydberg. The Conference was organized by Professors B. Edlén, L. Minnhagen and N. Ryde. It was attended by physicists and astrophysicists, including the Nobel prize winners N. Bohr and W. Pauli as well as A. Bohr, G. Herzberg, A. Kastler and B. Mottelson (who all would be awarded the Nobel prize between 1966 and 1975). The list of speakers included many other distinguished scientists, J. Brossel, R.H. Gartstang, W.R.S. Garton, J.L. Greenstein, P. Jacquinot, E. Hylleraas, P.F.A. Klinkenberg, H. Kopfermann, H.G. Kuhn, W. Lochte-Holtgreven, J.E. Mack, W.F. Meggers, C.E. Moore-Sitterley, G. Racah, G.F. Series, A.G. Shenstone, and several others. The Proceedings have been published [5]. Of the many exciting articles we here mention those by Niels Bohr and Wolfgang Pauli. Bohr discussed in detail "Rydberg's discovery of the spectral laws" and praised Rydberg's pioneering work, so important for all the later progress, whereas Pauli's topic "Rydberg and the periodic system of the elements" also showed the periodic system drawn in spiral form once published by Rydberg. Pauli pointed out that it was basically correct except for the fact that Rydberg had assumed the existence of two elements between H and He, namely Nebulium and Coronium. It was later found that the spectral lines of these "elements" were forbidden lines in ionized nitrogen and oxygen (explained by I.S. Bowen) or highly ionized iron, appearing in the solar corona (the corona problem was solved by B. Edlén).

7. The Rydberg constant

It is well known that Bohr was able to express the Rydberg constant in terms of the mass m and charge e of the electron and the constants c (speed of light in vacuum) and h (Planck's constant). Over the years a huge amount of measurements have been carried out and the precision of R_∞ has constantly increased. The work includes accurate measurement of some wavelengths in neutral hydrogen, nowadays by laser techniques. Correction must then be made for the reduced mass factor $(1 + m_e/M)$ to bring it to a value appropriate to a nucleus with infinite mass, and for fine and hyperfine structures, radiative effects, as well as nuclear volume and QED effects [6]. The most recent value is 109,737.31568549 (83) cm^{-1} [7].

A better value of the proton radius would be needed to further improve the value of R_∞.

8. Rydberg atoms

In these days, more than 80 years after Rydberg's death, so-called Rydberg atoms are being eagerly studied. These are assumed to be atoms with one valence electron in states with high values of the principal quantum number n. The important properties of these states are n-dependent, binding energy (n^{-2}), orbital radius (n^2), fine-structure interval (n^{-3}), geometric cross section (n^2), radiative lifetime (n^3), etc. [8]. The Rydberg states are found in interstellar space and they are used in laser physics and microwave technology. Rydberg states are also found in highly charged ions. In tokamak devices such states are populated by charge exchange spectroscopy between neutral atoms and multiply ionized impurity ions in the plasma. This process will often leave the impurity ions in high n, l states which decay by photon emission. A similar process takes place in beam-foil spectroscopy experiments where the fast ions leaving the foil are in high Rydberg states. A combination of beam-foil and tokamak spectroscopy was applied to study the spectrum and energy levels in C IV with great success [9].

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