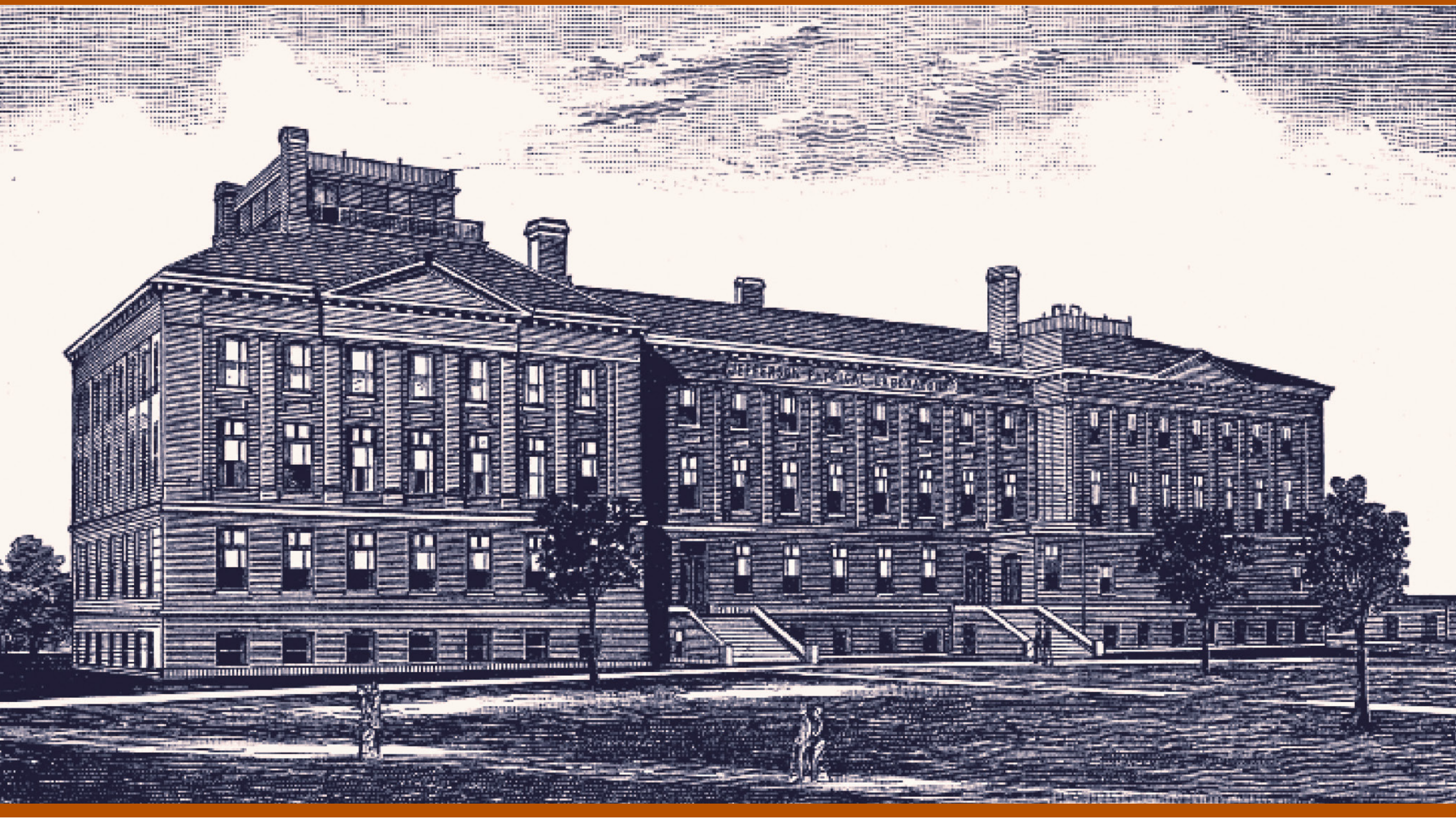


HISTORICAL FOCUS

Theodore Lyman, Pioneer of Ultraviolet Vacuum Spectroscopy

By Paul Horowitz

Pulling out his watch at the end of a talk at the Physical Society in the first decade of the 20th century, Lyman remarked “And now, gentlemen, this story which I have told you in seven minutes represents the work of exactly seven years.” And what was it that he had labored over so long? The meticulous development of satisfactory techniques for optical spectroscopy in what we now call the “extreme ultraviolet” (EUV: wavelengths shorter than about 100 nm). Those labors are encapsulated in Lyman’s lab notebook (Figure 1); and, in addition to pioneering techniques that would inform the field for decades, he discovered the spectral lines that bear his name.

BALMER'S FORMULA

To put Lyman's work in context, let's step back twenty years, to the remarkable achievement of Johann Balmer, a Swiss mathematician whose part-time teaching job at a girls' school allowed him to follow his interest in mathematical puzzles. Balmer was also acting as a docent at the university, where his colleague Prof. Hagenbach encouraged him to explore the relationship of the four known optical spectral lines of hydrogen (measured precisely by August Ångström). In his 1885 paper,[1] with a leap of intuition, he arrived at the formula:

$$\lambda = \mathrm{B}\,\frac{m^2}{m^2 - n^2}\ \text{Å} \qquad (1)$$

where B (which he called "the fundamental number of hydrogen"; it's now called the Balmer constant) is 3645.6Å. Balmer knew he was on to something, noting the excellent agreement with Ångström's measurements:

line	formula	measured	difference	*m,n*
H_α (C-line)	6562.08	6562.10	+0.02	3,2
H_β (F-line)	4860.8	4860.74	−0.06	4,2
H_γ (near G)	4340	4340.1	+0.1	5,2
H_δ (h-line)	4101.3	4101.2	−0.1	6,2

He didn't stop there. He predicted the wavelengths of the next five possible combinations (*m,n*=7,2, 8,2, etc.), and having been informed by Hagenbach that they had already been measured(!), he noted that "the agreement is striking in the highest degree." Going further, he speculated[2] about spectral lines corresponding to values of n greater than 2, which are in the infrared and which we now know as the Paschen and Brackett series, etc. Interestingly for our narrative about Theodore Lyman, he did not mention n=1. Those lines lie in the ultraviolet, and, owing to atmospheric absorption, are not observable in a spectrometer operating in ambient air.[3] They were not seen on Earth before Lyman.

ATOMIC PHYSICS AT THE TURN OF THE CENTURY

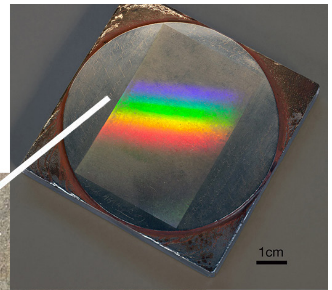
Before continuing, it's worth reminding the reader that the physics of the atom at the turn of the century was, well, unsophisticated. Electrons had just been discovered (by J.J. Thomson, 1897), but the discovery of protons had to await the Geiger–Marsden experiment (deflection of alpha particles by a gold foil, 1909) and Rutherford's realization of a compact nuclear charge (1911). What models there were included primarily Thomson's 1904 "plum pudding" (rings of electrons embedded in a diffuse cloud of positive charge), described in a 29-page article replete with elaborate orbital calculations, and in which radioactivity is caused by electron orbit instabilities. Bohr's atom was fifteen years in the future, and quantum mechanics another decade further.

Figure 1: Lyman's laboratory notebook, chronicling his decade of pioneering work in vacuum-UV spectroscopy. Over a century ago, the Harvard Coop was evidently the go-to place for school supplies. [Harvard University Archives]

[1] "Notiz über die Spectrallinien des Wasserstoffs" (A Note on the Spectral Lines of Hydrogen), *Annalen der Physik und Chemie* 25, 80–87 (1885). (English translation available at https://web.lemoyne.edu/giunta/balmer.html)

[2] "None of the hydrogen lines which correspond to the formula when n = 3, 4, and so on, and which may be called lines of the third or fourth order, is found in any spectrum as yet known; they must be emitted under entirely new relations of temperature and pressure if they are to become perceptible.

[3] As Lyman later remarked, "So steep is the rise of this absorption that, while the line λ 1940 [1940Å, or 194 nm] may be photographed through 14 metres of air, the region beyond λ 1750 is entirely absorbed by an air column 1 cm. long." The longest wavelength of the Lyman series (*m,n* = 2, 1, "Lyman- α") is well below that, at λ = 1215.67Å, and cannot be observed except in a vacuum (hence the term "vacuum ultraviolet").



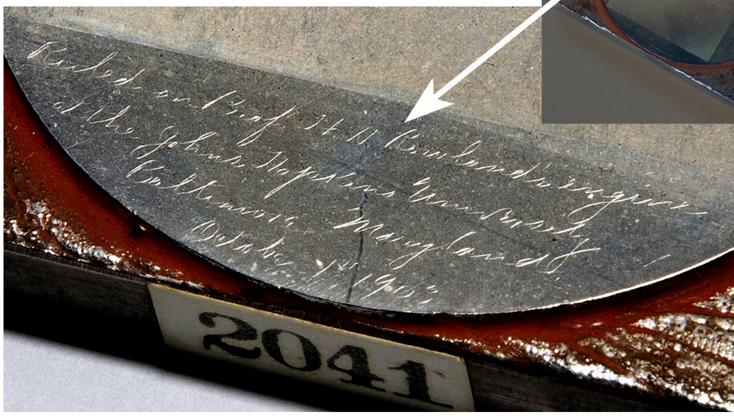


Figure 2 (top right): This is the concave grating that Lyman used to find the "Lyman series" of spectra. It was ruled by John Brashear on a precise concave piece of "speculum," a hard bronze-like tin/copper alloy that could be polished. [Reproduced with permission of the Collection of Historical Scientific Instruments (CHSI), Harvard University.]

Figure 3: A closeup of the scribed legend on the grating of Figure 2, above: "Ruled on Prof. H.A. Rowland's engine / at the Johns Hopkins University / Baltimore Maryland / October 1903." On the other edges are written "Grade AE (highest)," "15028 lines to 1 inch / 3 ft. 2" focus," and "Plate prepared by the / John A. Brashear Co. Ltd / Allegheny Pennsylvania / U.S.A." [Reproduced with permission from CHSI.]

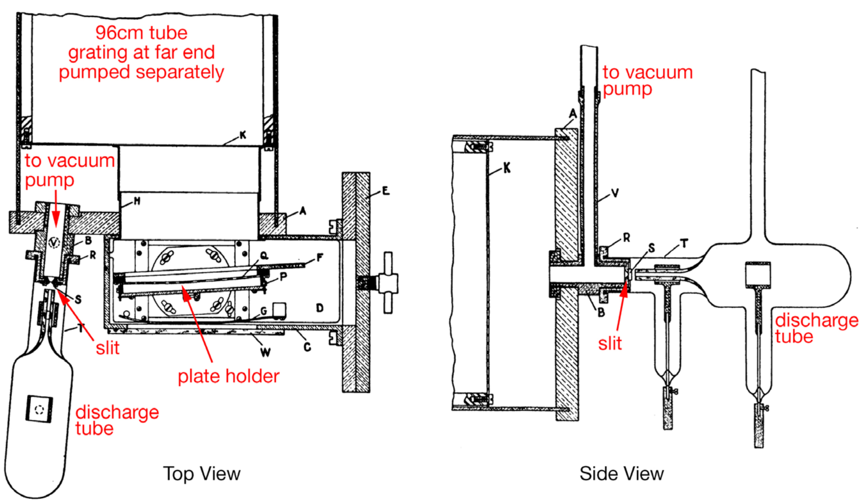


Figure 4: Lyman's windowless vacuum EUV spectrograph. Pumping directly downstream of the slit preserves the vacuum in the meter-long tube. [From Lyman, T., *The Spectroscopy of the Extreme Ultra-Violet*, 2nd ed. (Longman, 1928).]

ENTER THEODORE LYMAN IV

It was in this era that the young Lyman, in 1897, received his A.B. at Harvard, where he had taken an optics course from Prof. Wallace Sabine[4] that diverted him from his earlier interest in electrical engineering. Sabine was Lyman's advisor for his doctorate research, for which he suggested the topic of ultraviolet spectroscopy. The field had progressed down to about 1250Å in pioneering work by Walter Schumann,[5] with a spectrograph operating in vacuum. He used fluorite (crystalline CaF2) instead of glass for the optical components (prism, lenses, windows) because it went furthest into the ultraviolet. However, as Lyman later determined, fluorite's transmission ends abruptly around 1250Å, and could not be used to observe the $n = 1$ ("Lyman series"). An additional problem with his prism spectrograph was that the index of refraction of fluorite at these short wavelengths was not accurately known.

Following a suggestion from his advisor Sabine, Lyman replaced Schumann's refractive prism with a concave reflection grating (a "Rowland grating," Figures 2 and 3), thus establishing an accurate wavelength scale while also eliminating both EUV-blocking fluorite components (lens and prism). However, there was still the fluorite window that separated the vacuum spectrograph from the glowing gas-filled discharge tube. Lyman's solution was to eliminate that, also: he joined the discharge tube directly to the spectrograph, with a vacuum pump exhausting the residual gas leaking through the ~25 μm slit (see

[1] "Notiz über die Spectrallinien des Wasserstoffs" (A Note on the Spectral Lines of Hydrogen), *Annalen der Physik und Chemie* 25, 80–87 (1885). (English translation available at https://web.lemoyne.edu/giunta/balmer.html)

[2] "None of the hydrogen lines which correspond to the formula when $n = 3, 4$, and so on, and which may be called lines of the third or fourth order, is found in any spectrum as yet known; they must be emitted under entirely new relations of temperature and pressure if they are to become perceptible.

Figures 4 and 5). To calibrate the resulting spectra he used a clever dual-slit arrangement, which allowed the overlaying of two spectra with known offset.

A facile description, benefiting from hindsight, conceals the many wrong turns and technical difficulties that bedevil experimental science, and particularly so in an era lacking the accoutrements we now take for granted. The above paragraph represents the work of some seven years, and in the opening paragraph of his 1906 *Astrophysical Journal* paper Lyman remarks:

"The description has been made with some minuteness in the hope that an exact knowledge of the conditions necessary to success may prove of value to investigators who work in this field. Some attention has also been given to earlier and imperfect forms of the apparatus. For the author wishes, by flagging the pits into which he has fallen, to prevent other investigators from similar accidents."

Indeed, in this 34-page article he devoted 22 pages to a description of the experimental technique (with seven pages of spectra and tables, and five pages of introduction and summary).

Among the many difficulties, maintaining a good vacuum and preparing gas samples of high purity were among the most troublesome: leaks were common and vacuum pump technology was primitive (see Figure 6).[6] In Lyman's notebooks, with their many notations of failing vacuum (manually measured with a McLeod gauge), you get a sense of continuing frustration. Contamination with air, or moisture, or outgassing from the wall

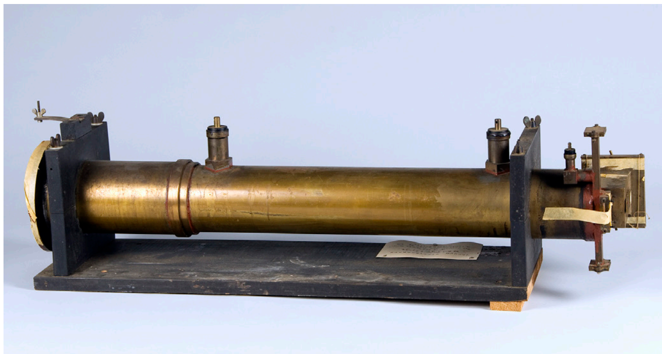


Figure 5: A vacuum UV spectrograph, likely the very one used to discover the Lyman spectra of hydrogen. The light source and film were mounted on the right side, with the concave grating at left. Two vacuum ports are seen along the tube, with an additional double-ended pumping port positioned just behind the light source at right (where the red "Glyptal" sealing material can be seen). [Reproduced with permission from CHSI]

Figure 6: Vacuum technology circa 1920: the Holweck pump [Reproduced with permission from CHSI]

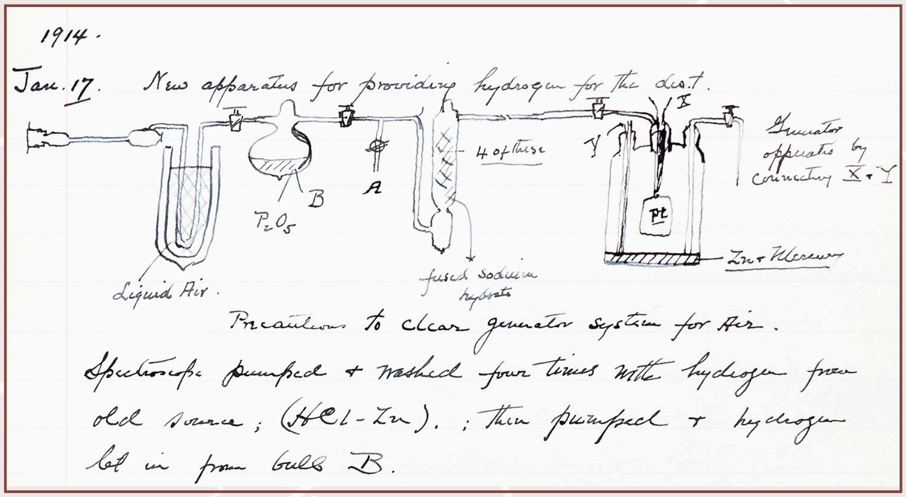
[3] As Lyman later remarked, "So steep is the rise of this absorption that, while the line λ 1940 [1940Å, or 194 nm] may be photographed through 14 metres of air, the region beyond λ 1750 is entirely absorbed by an air column 1 cm. long." The longest wavelength of the Lyman series (m,n = 2, 1, "Lyman- α") is well below that, at λ = 1215.67Å, and cannot be observed except in a vacuum (hence the term "vacuum ultraviolet").

[4] The founder of architectural acoustics, see *Harvard Physics Newsletter* 2023, p. 16; also available at https://www.physics.harvard.edu/sites/projects.iq.harvard.edu/files/physics/files/2023-acoustics.pdf.

[5] Lyman's scientific trajectory was greatly influenced by Schumann, about whom he wrote a warm tribute in *The Astrophysical Journal* (39, 1, pp 1–4, 1914; DOI: 10.1086/142050).

[6] As related by David Webster in his AIP oral history (https://www.aip.org/history-programs/niels-bohrlibrary/oral-histories/4942), "Seven years of work, seven years of hard work. After all, he had to have high vacuum to get down to the region that he was interested in, and a much higher vacuum than anybody ever had before or was customary. I remember his pump well, he had a fore pump, and then his high vacuum pump was a big Archimedes spiral full of mercury, with a return passage, and it was about a foot in diameter, and maybe a foot or a foot and half long, it had about five or six turns, each turn half full of mercury, of course in a helix, and this thing would slowly turn around and the mercury would run around driving the air ahead of it, and he had to pump the whole spectrometer with that, and that took mighty good technique of making things, so that it would be vacuum tight, and then a great deal of patience pumping them out. Then, of course, finding the material for windows as far as he could use any, and then just using a discharge in hydrogen vapor with a narrow slit between it and the spectrometer, trusting that his pump could maintain a better vacuum in the spectrometer than there was in the discharge tube. That was really a heroic job."

materials was a constant companion. As he remarked in the 1906 *ApJ* paper, “The perfect dryness of the gas is necessary for the success of the work” – see for example his lab-notebook diagram (Figure 7). Another essential aspect of UV spectroscopy was the preparation of the film and developer in this pre-electronic era. Ordinary photographic film failed to register EUV, owing to the opacity of the gelatin emulsion. Lyman extended a technique for making gelatin-starved film (Figure 8, originally devised by Schumann for work down to 1250Å) to work ultimately down to 600Å.[7] And, like Schumann, he formulated his chemical developer.


1914.
Jan. 17. New apparatus for providing hydrogen for the dist.

Precautions to clear generator system for Air.
Spectroscope pumped + washed four times with hydrogen from old source; (HCl - Zn). ; then pumped + hydrogen let in from bulb B.

Figure 7: Removing moisture and contaminants from hydrogen gas. [Harvard University Archives]

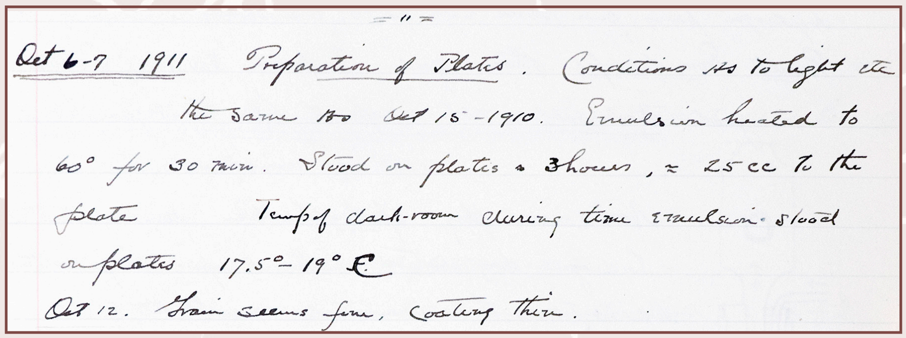

Oct 6-7 1911 Preparation of Plates. Conditions as to light etc the same as Oct 15-1910. Emulsion heated to 60° for 30 min. Stood on plates 3 hours, = 25 cc to the plate. Temp of dark-room during time emulsion stood on plates 17.5° - 19° C.
Oct 12. Grain seems fine, coating thin.

Figure 8: Lyman prepared his own “film” – a thin gelatin-starved silver-halide emulsion on a thin glass plate. [Harvard University Archives]

GETTING TO THE “LYMAN SERIES”

By 1904 Lyman had succeeded in finding and quantifying some 130 UV spectral lines with his spectrograph and its hydrogen discharge source. Among them is what later became known as Ly-α, which he listed as 1215.6Å (he was remarkably accurate: to six figures it is 1215.67Å). But he had no model in mind, and that line is not featured in any way. In fact, he states a disclaimer: “The author makes no claim that all of these lines belong to the spectrum of hydrogen.” For the next few years Lyman’s publications addressed things like absorption of UV by various solids and gases.

It wasn’t until brief notices in *Nature* 1914 (Ly-α and Ly-β) and 1915 (adding Ly-γ), and a 1916 full article in *ApJ* (“The Extension of the Spectrum Beyond the Schumann Region”) that Lyman announced the eponymous series. In his words, “Prominent in the spectrum of hydrogen is the line at λ1216 which forms the first member of a series predicted, on theoretical grounds, by Ritz. I have also found the two next members near λ1026 and 972.”[8] So it was the prediction of specific emission lines of hydrogen (Ritz’s generalization of the Balmer–Rydberg formula) that directed Lyman’s attention to a subset of the many spectral features he had been compiling (e.g., 362 of them, in his 1906 *ApJ* paper), until then unsupported by any model.

[7] From four expansive pages about plate preparation in Lyman’s *The Spectroscopy of the Extreme Ultraviolet* (1928): “The sensitiveness of the plates so prepared depends to a large degree on the temperature to which the emulsion is raised and the length of time during which it is exposed to this temperature: it is also somewhat dependent upon the temperature of the room in which the emulsion is allowed to settle. The perfection of the film as shown by its freedom from fog and streaks, as well as by its keeping quality, depends upon the purity of the solid ingredients and of the distilled water employed, a small amount of organic matter exercising a very prejudicial effect. The nature of the developer and its temperature also play an important role.”

[8] In the next paragraph he reports two other lines (at Å 1086 and Å 992) “. . . that always appear with a disruptive discharge in hydrogen,” and which he notes are accurately predicted by a modified Balmer formula that substitutes n + 0.5 for n; he opines that these are due to an impurity. That formula is due to a 1912 paper by Fowler, who attributes those lines to hydrogen; but it was nicely explained by Bohr, in a 1913 paper, as transitions to the n=3 orbital of doubly ionized helium.

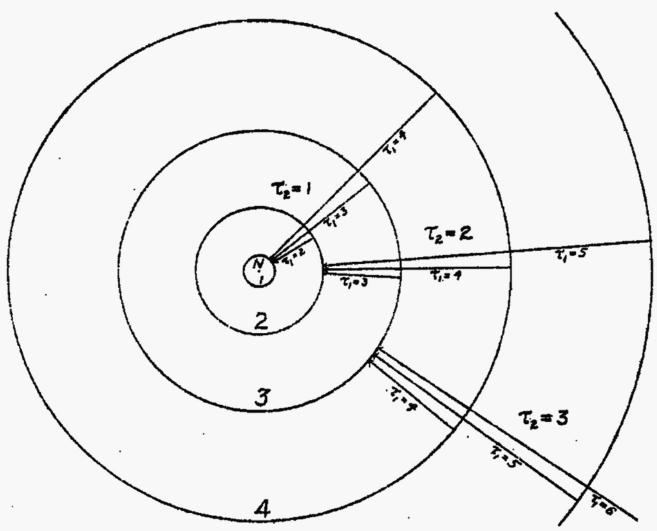
The electron radiates energy only when it changes from one steady state of vibration to another, and then one quantum of energy is released; that is, for a sudden shrinkage from orbit of τ_2 to τ_1, there must be a loss of energy W = $h\nu$ where ν is the frequency of the radiation.

$$h\nu = \delta W = W_{\tau_2} = W_{\tau_1} = \frac{2\pi^2 me^2 E^2}{h^2}\left(\frac{1}{\tau_2^2} - \frac{1}{\tau_1^2}\right)$$

$$\nu = \frac{2\pi^2 me^2 E^2}{h^3}\left(\frac{1}{\tau_2^2} - \frac{1}{\tau_1^2}\right).$$

In the case of hydrogen, $E = e$. We can then calculate the value of the constant $2\pi^2 me^2 E^2/h^3$ which is equal to 3.26×10^{15}. The well-known Balmer formula for the series of lines in the hyrogen spectrum is $\nu = K\,(1/\tau_2^2 - 1/\tau_1^2)$ in which K as determined by experiment is 3.29 times 10^{15}. This practical identity of Bohr's calculated value of the Rydberg constant and the experimental value is probably the greatest triumph of Bohr's work.

If the value 1 is assigned to τ_2, and a series of values, 1, 2, 3, etc., given to τ_1, the frequencies of a series of lines in the ultraviolet are determined. This series was not known at the time of Bohr's first work, but has since been found by Lyman of Harvard. (Not published.) The physical picture obtained of the production of this series of spectrum lines is as follows:



N represents the nucleus of the atom. The rings 1, 2, and 3 correspond to the orbits of the electron in the various steady states of motion. When an electron falls from one steady state to the next one of smaller radius of vibration, one quantum of energy is liberated. In the above spectral series, all the lines are formed by electrons falling from the second ring and beyond, all the way to the first ring. The first line in the series is due to an electron falling from the second to the first ring; the second line to an electron falling from the third to the first ring, and so on.

Figure 9: This 1915 paper by Harkins and Wilson may be the first published diagram of the Bohr atom, featuring the Lyman transitions to the ground state ("the first ring").

Figure 10: An undated photograph of Lyman's office. The portrait on the right is of his advisor, Wallace Sabine. [Scanned by the author from a 5"×7" glass negative.]

NIELS BOHR: HYDROGEN SPECTRA EXPLAINED

In a stunning paper[9] that reconciled the α-scattering compact nucleus of Rutherford with the Planck–Einstein quantized emission of radiation, the Danish physicist Niels Bohr put forward a semi-classical model of the atom that also incorporated Planck's constant h, a balancing act that required him to discard classical radiation from an accelerated charge. Bohr's atom had the light negative electrons in orbits around the compact and massive positive nucleus of Rutherford, but, to circumvent what he called "the inadequacy of the classical electrodynamics in accounting for the properties of [Rutherford-model] atoms," he posited that the orbits are stable (non-radiating), and that radiation is emitted only when an electron makes a transition from a higher to a lower state.[10]

And, *mirabile dictu*, when he calculated the wavelengths predicted by his atom model, setting the photon energy $h\nu$ equal to the difference of the potential energy of his quantized orbitals, $W_\tau=(2\pi^2me^4/h^2)(1/\tau^2)$ (he used τ instead of Balmer's m and n), it agreed with Balmer's formula if the lower energy state had $\tau=2$. Put another way, Bohr's atom's energy states, calculated from first principles, predicted that $B=2h^3c/\pi^2me^4$. Evaluating this expression (it's in cgs units, way better than SI for this kind of stuff) you get (with contemporary values of the constants) B=3645.1Å – *eureka*, Balmer's "fundamental number of hydrogen"![11] Bohr was not unmindful of

[9] Bohr, N., "I. On the Constitution of Atoms and Molecules," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 26, 151, pp 1–25 (1913); DOI: 10.1080/14786441308634955.

[10] He had initially assumed that the frequency of radiation was connected somehow to the orbital period of the electron, an assumption shared by Planck and Einstein. It was only after his attention was drawn to Balmer's formula that he saw the similarity (and exclaimed, "As soon as I saw Balmer's formula, the whole thing was immediately clear to me."). It goes like this: converting Balmer's formula (eq'n 1) to frequency, you get $\nu = c/\lambda = (n^2c/B)(1/n^2 - 1/m^2)$. But Bohr's energy states go like the inverse of squares of integers, so the Balmer formula suggested to him that the energy of the emitted radiation (Einstein: $h\nu$) is equal to the difference of energy of the two states.

[11] Bohr points out that you need to correct for the finite mass of the proton, a multiplicative factor of $1 + m_e/m_p$, or 1.000545, which I've not done here.

transitions to other final states, and remarked that "If we put τ_2=2 and let τ_1 vary, we get the ordinary Balmer series. If we put τ_2=3, we get the series in the ultra-red observed by Paschen and previously suspected by Ritz. If we put τ_2=1 and τ_2=4,5,... , we get series respectively in the extreme ultraviolet and the extreme ultra-red, which are not observed, but the existence of which may be expected." It is, of course, the spectra corresponding to τ_2=1 that were announced by Lyman in the following two years. Figure 9 may be the first published diagram showing the Bohr atom and the three spectral series (Lyman, Balmer, Paschen.

LATER WORK

By 1917 Lyman had succeeded in extending his spectroscopy down to 500Å, well beyond the most "refrangible" (a term used to signify "short wavelength") line of hydrogen (911.75Å, produced by an unbound electron falling to the ground state). A favorite gas was helium (whose spectral lines extend down to 230Å), which, however, had caused some early confusion because its singly-ionized spectrum is almost identical to that of hydrogen, and some lines of its doubly-ionized spectrum fit a Balmer-like formula with half-integer denominators (see footnote 8).

Lyman was clearly on a roll, but events half a world away put a stop to further discoveries as he joined the war in Europe. He found himself in the Signal Corps in France,[12] about which he later wrote "My military experience was one of the most interesting of my whole life."[13] Lyman returned in 1919, but by his own reckoning was unable to lead the field that he had pioneered: "When I was mustered out of the service in the spring of 1919 I found it impossible to resume my academic work or my research with any enthusiasm. It took some time for me to get back into harness. Meanwhile a number of people had entered the field of vacuum spectroscopy. I had lost the leadership and I never regained it. Moreover, the untimely death of Professor Sabine increased my administrative burdens." Wallace Sabine had been his inspiration to pursue physics and, later, his advisor, and Lyman was greatly saddened by his death. His portrait hung prominently in Lyman's office (Figure 10).

LYMAN LAB

Lyman was generous with his time and resources; as recounted by Frederick Hunt (AIP Oral Histories), "He seemed always the same, the proper Bostonian, and he was a very kind and very generous man. In 1931, I think I attended two meetings of the Acoustical Society of America – the fifth meeting in Camden, and I think the next one was in Rochester. Professor Lyman administered what was called 'a small travel fund' from which funds were made available to help pay my expenses to go to these meetings. As it turned out later, the travel fund was Lyman's back pocket."

As it became clear that the Jefferson Laboratory could not support the growing research activity, Lyman sought funds for a new laboratory, and then the design and construction of the "Research Laboratory of Physics." The timing was lucky: he raised the money

[12] With accounts like this: "Most men of my age who entered the service were occupied with office work generally in back areas. I had the good fortune to see some service in the field" and "In the spring, after a short tour of duty in the quiet area in front of Roul I took a flash ranging unit to the very active Chateau Thierry section. This was a most valuable experience; I was to some extent my own master, I was in constant communication not only with the American Divisions in the neighborhood, but with the French artillery intelligence, as well. I saw the German offensive rise to a maximum, I saw fortune turn toward the Allies. I took part in the second St. Mihiel offensive. Thereafter I was attached to the Second Army. I returned home in March '19 in command of a Battalion of over 1000 officers and men." (from *Theodore Lyman, 1874–1954: A Biographical Memoir* by Bridgman; see citation on p. 30)

[13] Lyman was a hereditary member of the military order of the loyal legion of the United States. Perhaps he acquired his casual attitude toward danger from his father, whose 400+ page account of his Civil War service (letters to his wife) included descriptions like this: "A battery was firing at one of ours and the shells coming over struck right among our infantry. They cut the pine trees about me in a manner I didn't like, and one burst close by, throwing the pieces round just as you see them in French battle pictures. All day there was firing. About eleven came General Meade and told me to go out at once to Mott and to get a written report from him, which I did; and a sharpshooter shot at me, which I hate – it is so personal. More by token, poor General Rice, a Massachusetts man and very daring, was to-day killed by a sharpshooter. The ball broke his thigh, and, when they amputated his leg, he never rallied." (from *Meade's Headquarters 1863-1865, Letters of Colonel Theodore Lyman From The Wilderness to Appomattox.* Selected and edited by George R. Agassiz)

before the 1929 market crash, and oversaw construction in 1930–31 when costs were depressed.[14] The new laboratory was completed in 1931, and Lyman was its first director (while continuing as director of Jefferson Lab, where his sub-basement grating room remained – see Figures 11 and 12); it was renamed Lyman Laboratory when he retired in 1947. The plaques in Figure 13 hang adjacent to the department office near the Lyman main entrance.

Figure 11 (above): A set of concrete stairs below this imposing hatch leads to the site of Lyman's sub-basement spectrograph laboratory.

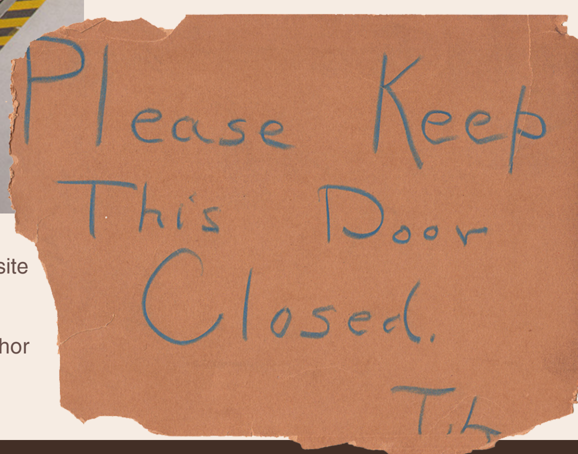


Figure 12 (right): This disintegrating cardboard placard was rescued by the author from the door to Lyman's grating room, during a destructive lab cleanup.

LYMAN'S LEGACY

Those who knew Lyman recall a proper Boston gentleman (the fourth generation of the name Theodore Lyman), one who "knew how to carry himself," even "majestic," a feeling nicely portrayed in the photograph of Figure 14. In later years he was seen walking the hallways carrying a wooden pole (with spike) in hand. What was he doing? Picking up cigarette butts (he feared for the safety of the wooden building)! Among his idiosyncrasies, as related by Edward Purcell, was that "he didn't know how to cope with a woman at Harvard." Alice Armstrong (in an AIP Oral History) put it amusingly:

[14] A similar happenstance of timing favored the construction of the great reflector at Palomar, nicely recounted in Ronald Florence's highly readable book *The Perfect Machine* (HarperCollins, 1995).

"His office was on the ground floor, at the end, and I think to get in and out of the building, I had to pass it. Well, I walked along the hall and a few times he might have come out of his office, walking along the hall in the opposite direction [and] I'd turn into a little gray mouse and scuttle along the floor on the opposite side of the hall, so he wouldn't see me." [15]

In addition to our beloved Lyman Laboratory, his scientific legacy extends beyond his pioneering techniques in EUV vacuum spectroscopy. Astronomers observe *Lyman Forests* (Figure 15) to deduce the prevalence and structure of galactic distribution at high redshifts. *Lyman ghosts* is the name given to false spectra caused by periodic ruling errors in diffraction gratings, discovered during his graduate years. His name adorns a crater on the moon's far side (Figure 16). And, in an example of his generosity toward students, in 1929 he granted the 20-year-old undergraduate Edwin Land a personal laboratory on the

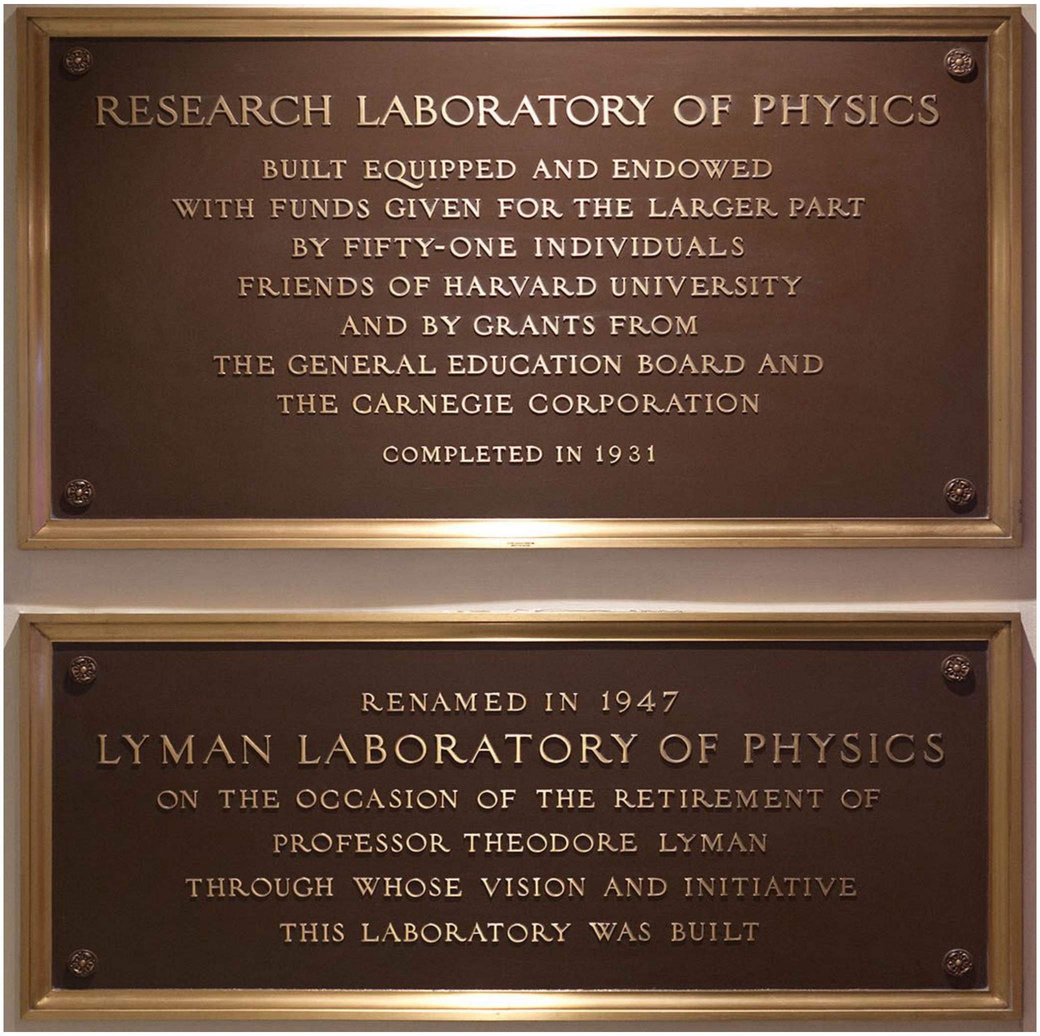


Figure 13: These plaques are prominently displayed in the entrance foyer of Lyman Lab.

[15] In an interview this year, Gerald Holton (at age 102!) provided context: Lyman was not at all misogynistic. He simply had not experienced women in science, partly because (1) there were very few, and (2) needing to prove themselves, women chose more difficult topics (publishing fewer papers, compared with the men who typically "sliced the sausage" [Holton's words] and turned out many). See, e.g., G. Sonnert and G. Holton "Career Patterns of Women and Men in the Sciences," *American Scientist*, 84 1, pp 63–71 (1996), and particularly the section "Women's Methodology: Perfectionism."

Figure 14: Theodore Lyman in his laboratory, examining a mercury-filled McLeod vacuum gauge, where the grating end of a meter-long spectrograph can also be seen. [Scanned by the author from a 4"×5" negative.]

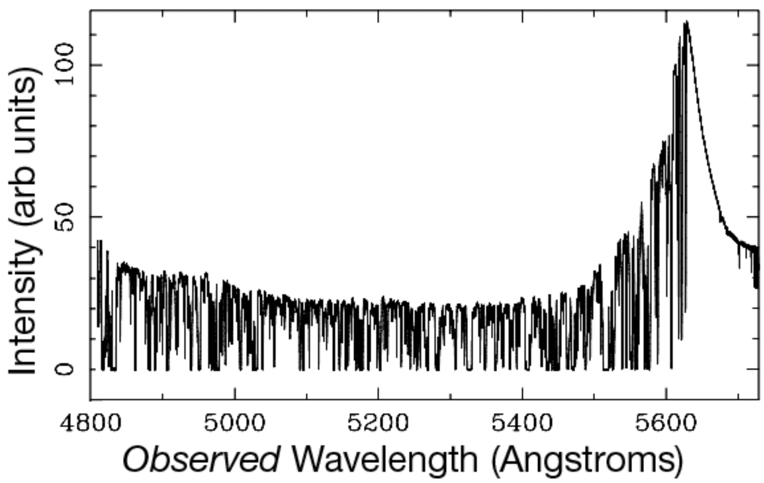


Figure 15: A "Lyman-¤ Forest" – spectrum of a distant quasar (Q1422+2309) whose 1216Å emission line (redshifted to ~5630Å) has been absorbed, on the short-wavelength side, by numerous intervening galaxies at progressively smaller redshifts. [After Rauch, M., "Lyman Alpha Forest," Encyclopedia of Astronomy and Astrophysics, 2001.]

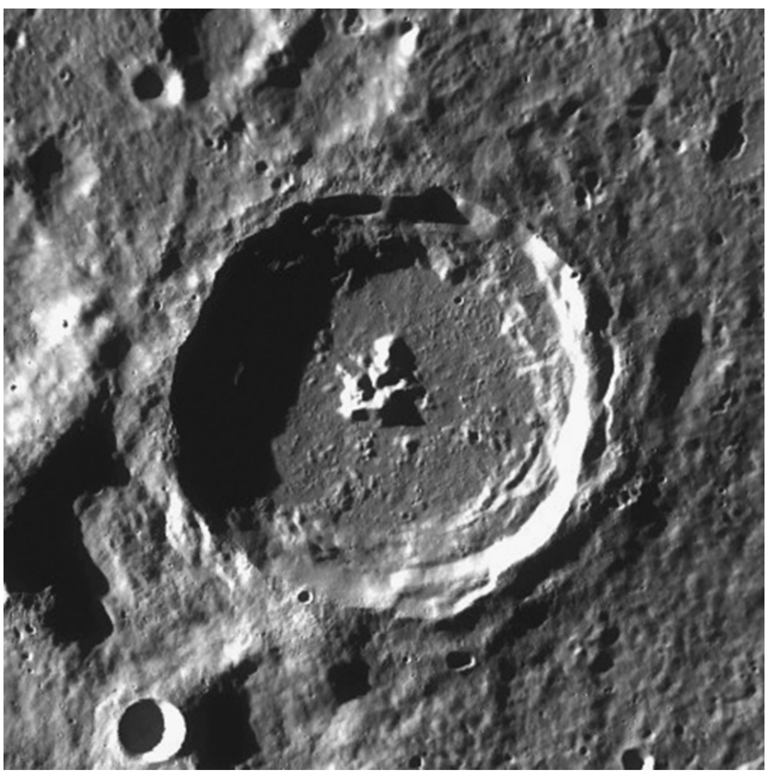


Figure 16: Lunar crater Lyman, on the farside at lunar coordinates 64.8°S, 163.6°E. [Photo from Lunar Reconnaissance Orbiter, July 2009]

3rd floor of Jefferson to work on his invention of plastic polarizer.[16] In his seventies Lyman suffered from deteriorating health; he died in 1954, at the age of 79. He is buried in the Mount Auburn Cemetery, on a hillock near his relatives (Figure 17). He was a member of numerous scientific societies (among them the National Academy of Sciences and the Royal Institution of Great Britain), and a recipient of the Rumford Medal (AAAS), the Elliott Cresson Medal (American Philosophical Society), and the Frederick Ives Medal (American Optical Society).

SOURCES AND REFERENCES

In addition to the references cited in the text and footnotes, the following were used in the preparation of this short history:

• Bridgman, P.W., *Theodore Lyman, 1874–1954: A Biographical Memoir* (National Academy of Sciences, 1957);

• Craig, P. Wayne, "On the Wing of a Butterfly, *Johann J. Balmer* (1825–1898)," *Helvetica Chimica Acta*, 96, 2304–16 (2013);

• McElheny, Victor K., *Edwin Herbert Land, 1909–1991: A Biographical Memoir* (National Academy of Sciences, 1999);

• Schwarz, W.H. Eugen, "100th Anniversary of Bohr's Model of the Atom," *Angew. Chem. Int. Ed.*, 52, 12228–38 (2013);

• Sara Schechner, Sara Frankel, and Harvard University's Collection of Historical Scientific Instruments;

• The Harvard University Archives;

• miscellaneous journal articles and other online sources;

• and helpful conversations with Jacob Barandes and Gerald Holton.

[16] Land maintained a warm relationship with Harvard thereafter. The Science Center was funded with his gift, which he preferred not to be publicly acknowledged; and the Rowland Institute of Science, endowed as an independent research laboratory in a beautiful structure whose design and construction was personally overseen by Land, became the Rowland Institute at Harvard in 2002.

Figure 17: Lyman's gravesite (highlighted) at Mount Auburn Cemetery, adjacent to that of his grandparents Theodore Lyman II and Mary Elizabeth Lyman. Henry and Elizabeth Cabot are his brother and sister-in-law, and Henry's daughter Cora married the Boston surgeon Richard Warren. Its location is Pilgrim Path–705–GUS; cemetery ID 52835039. An easy way to find it is to use the astonishing app "what3words," where it's found at swift.nature.factor. (For a wonderful introduction to the app, see the talk by the founder at https://egconf.com/videos/chris-sheldrick-co-founder-ceo-what3words-eg12.)