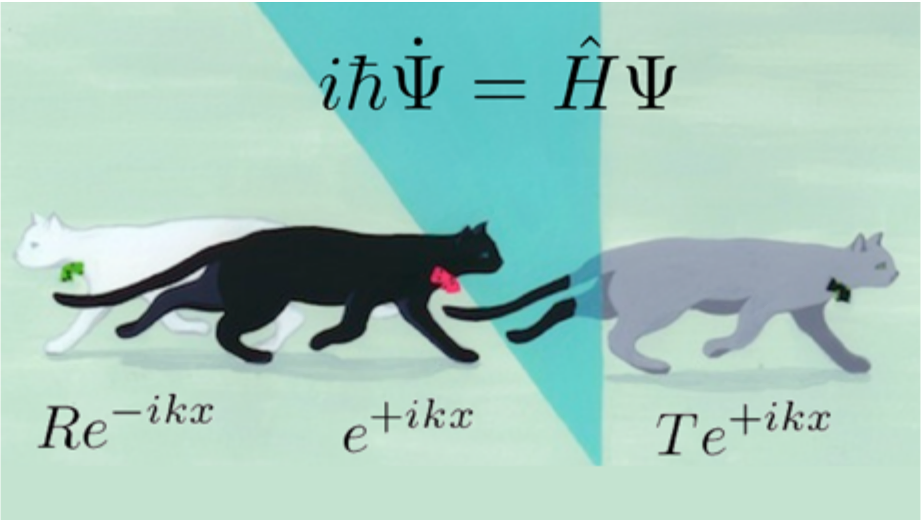
Exploring Quantum Physics

Coursera, Spring 2013 Instructors: Charles W. Clark and Victor Galitski

Quantum Theory: Old and New

Part II. Applications of the Bohr model



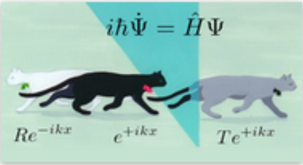
Quantum Theory: Old and New

coursera

UNIVERSITY OF MARYLAND

Exploring Quantum Physics

by Dr. Charles Clark and Dr. Victor Galitski



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Additional Materials

Mathematical References

For those who may want to brush up on their mathematics before or during the courses, we present **a short crash course on the math**

Original scientific literature

Some lectures draw on material from original scientific literature, which we provide here for the convenience of students.

- Atomic clocks and quantum computers
- The Bohr model of the atom
- Bose-Einstein condensation
- The discovery of deuterium
- The discovery of deuterium - a simplified account
- The green laser pointer
- The photoelectric effect
- Does quantum mechanics provide a complete description of physical reality?
- Young's double slit experiment and diffraction

Quantum Theory: Old and New

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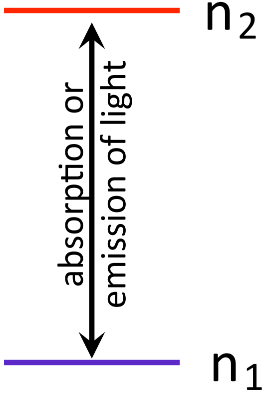
Niels Henrik David Bohr
1885-1962
1922 Nobel Prize in Physics
"for his services in the investigation of the structure of atoms and of the radiation emanating from them".

Bohr's stationary states of hydrogen-like atoms

$$E(n) = -\frac{1}{n^2}\frac{e^4 m_e}{2\hbar^2} = -\frac{1}{n^2}R_\infty hc$$

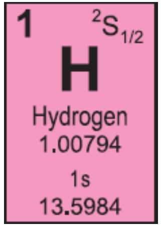


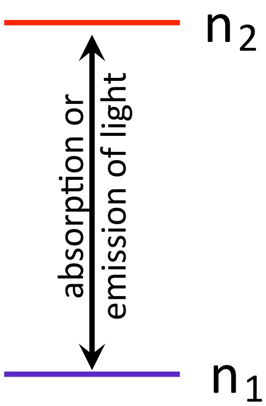
$$E(n_2) - E(n_1) = h\nu = \frac{hc}{\lambda}$$

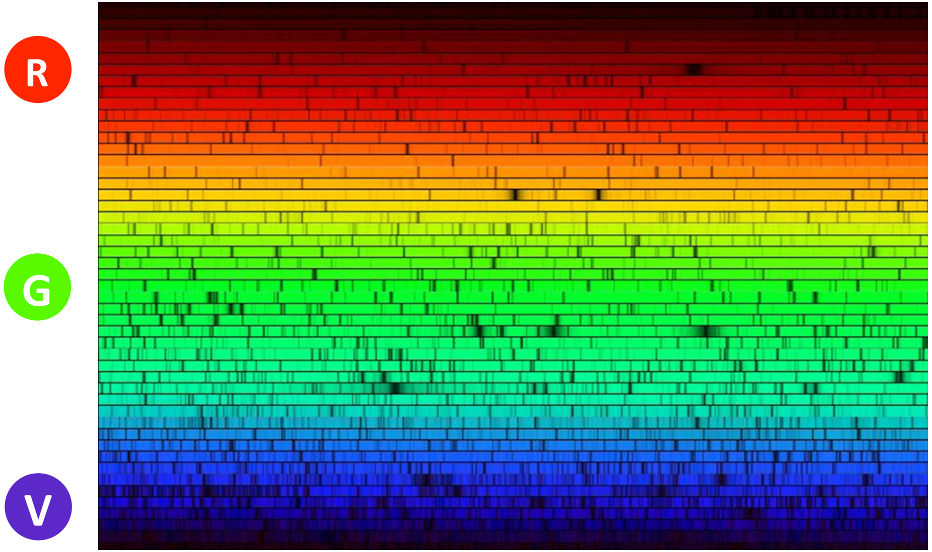
$$\frac{1}{\lambda} = R_\infty\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right]$$ Infinite nuclear mass

$$\frac{1}{\lambda} = R_\infty\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right]\frac{\mu}{m_e}$$

Balmer Series: $n_1 = 2$







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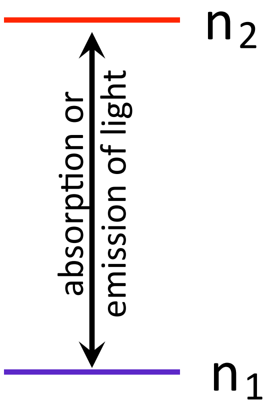
Bohr’s stationary states of hydrogen-like atoms

To within experimental uncertainty, the Bohr model gave the correct wavelengths for the Balmer series (n_1 = 2), the Paschen series (n_1 = 3), and the Pickering series in He^+ .



1914: Theodore Lyman finds 3 new lines with n_1 = 1 in the far UV spectrum of H

1922: Frederick Brackett finds a new infrared series with n_1 = 4

1924: August Pfund finds a new infrared series with n_1 = 5

1953: Curtis Humphreys observes the last *named* series, n_1 = 6

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Radio recombination lines from the largest bound atoms in space

S. V. Stepkin, A. A. Konovalenko, N. G. Kantharia and N. Udaya Shankar, *Monthly Notices of the Royal Astronomical Society* **374**, 852 (2007)

They observe radio-frequency absorption by carbon-like atoms in the cool tenuous medium located in the Perseus arm in front of the supernova remnant, Cassiopeia A (Cas A). These are associated with states with *n* up to 1009: atoms **a million times larger than hydrogen**. The Bohr transition frequencies are now seen to be valid over a range spanning $2.5 \times 10^{15} – 2.6 \times 10^{7}$ Hz: eight decades of frequency!

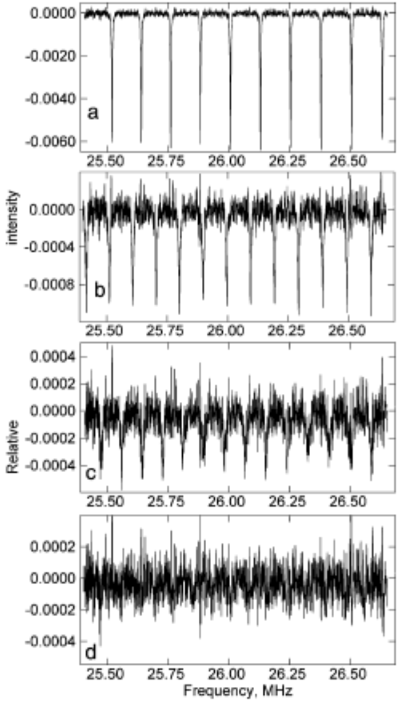

Figure 2. The series of α, β, γ and δ RRLs observed around 26 MHz in the direction of Cas A. Panel (a) shows α series C627…C636, panel (b) shows β series C790…C802, panel (c) shows γ series C904…C917, and panel (d) shows δ series C994…C1009.

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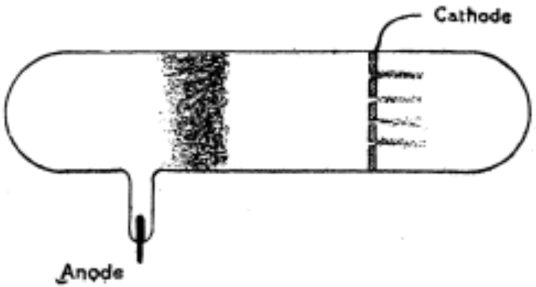
Joseph John Thompson
1856-1940
1906 Nobel Prize in Physics
"in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases".

Isotopes discovered by mass spectrometry



Motion of charged particle in electric and magnetic fields

$$m\ddot{\vec{r}} = e\vec{F} + e\dot{\vec{r}} \times \vec{B}$$

$$\ddot{\vec{r}} = \frac{e}{m}\left(\vec{F} + \dot{\vec{r}} \times \vec{B}\right)$$

Trajectory is a parabola that depends upon the charge-to-mass ratio e/m

Observation of ^{20}Ne and ^{22}Ne

“Bakerian Lecture- Rays of positive electricity,” J. J. Thompson, *Proc. Roy. Soc. Lond. A* **89**, 1 (1913)

Quantum Theory: Old and New

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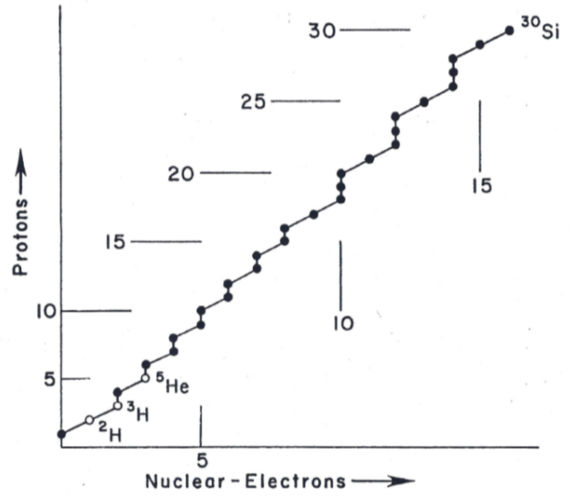
Harold Clayton Urey
1893-1981
1934 Nobel Prize in Chemistry "for his discovery of heavy hydrogen".

Today we know that isotopes are associated with different numbers of neutrons being present in nuclei of the same element.

In 1931, the neutron was not yet discovered. Most thought isotopes carried different numbers of protons and "nuclear electrons.

There were clues that a heavy isotope of hydrogen might exist. it could not be seen in mass spectrometry due to interference from the abundant molecular ion H_2^+.



Urey's isotope road map, from Ferdinand Brickwedde's memoir

Quantum Theory: Old and New

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1934 Nobel Prize in Chemistry "for his discovery of heavy hydrogen".

Harold Urey thought heavy isotopes of hydrogen might be detected in the optical spectrum of atomic hydrogen.

Bohr's theory, given some twenty years ago, permits the calculation of the Balmer spectrum of the heavier isotopes of hydrogen from this spectrum of hydrogen by the well-known theoretical formula for the Rydberg constant. The value of the Rydberg constant for the hydrogen isotopes can be calculated from the atomic weights of the isotopes and the known atomic weight of the electron. The expected wavelengths of the Balmer series, using the most recent determinations for the atomic weights of hydrogen, deuterium and tritium, and of the electron, are given in Table I.

"Some Thermodynamic Properties of Hydrogen and Deuterium," Harold C. Urey, Nobel Lecture (1934)

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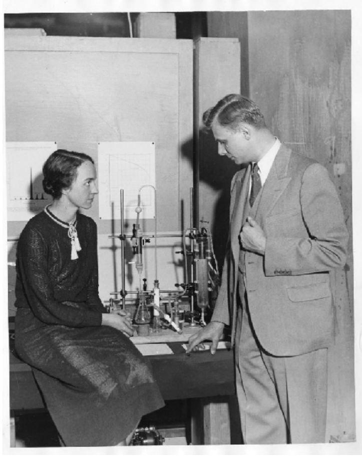
Smithsonian Institution



Marion Langhorne Howard Brickwedde (1909-1997) and F. G. Brickwedde with the apparatus for making heavy water.

The concept: evaporate liquid hydrogen. Presumably any heavier isotope will be less volaatile and will be concentrated in the residue

> "Urey approached me at the National Bureau of Standards in Washington, inviting me to join the search for a heavy isotope of hydrogen by evaporating 5- to 6-liter quantities of liquid hydrogen to a residue of 2 cm^3 of liquid to be evaporated into glass flasks and sent by railway express to Columbia University for spectroscopic examination. . . I was happy to cooperate and prepared by distillation of liquid hydrogen at the Bureau of Standards the samples of gas in which the heavy isotope was identified."

Ferdinand Graft Brickwedde, NIST memoir

Balmer Series: $n_1 = 2$

The Balmer β emission line of atomic hydrogen from three different samples of distillate

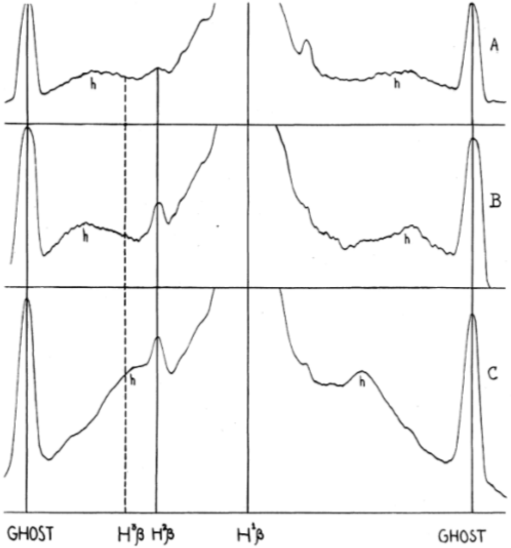
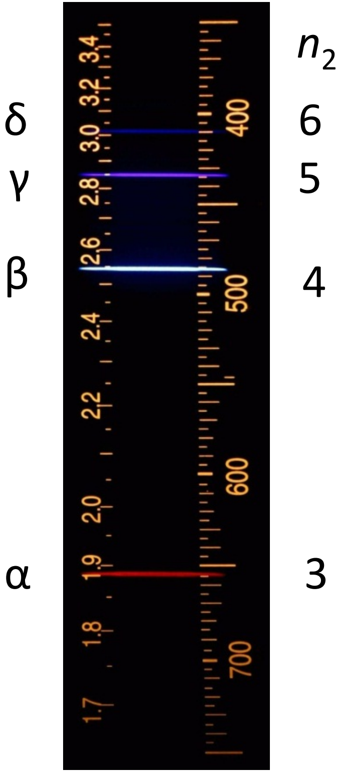
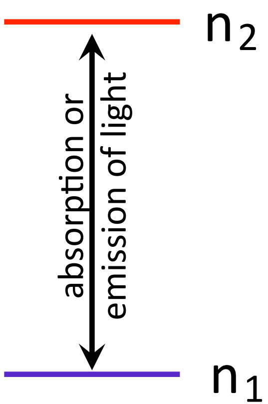


Fig. 4. Microphotometer curves of Hβ for (A) ordinary hydrogen (B) Sample II (C) Sample III. The calculated position of $H^3\beta$ is indicated although there is no evidence for its existence from these curves. The h's indicate regions of halation.

"A Hydrogen Isotope of Mass 2 and its Concentration," H. C. Urey, F. G. Brickwedde and G. M. Murphy, *Physical Review* **40**, 1 (1932)





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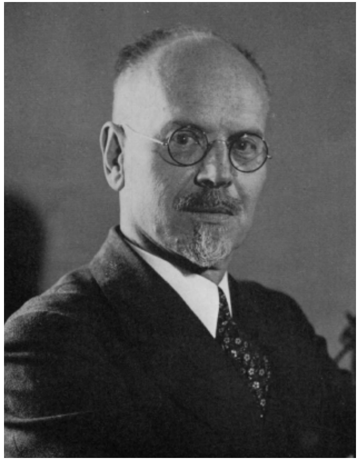

Edward Wight Washburn
1881-1934
Chief Chemist, National
Bureau of Standards

On the dawn of Thanksgiving Day, 1931, no one knew anything about the mass 2 isotope of hydrogen. A few months later, Edward Wight Washburn and Urey developed a means for producing it efficiently by electrolysis.

In 1934, the Norsk Hydro plant in Rjukan, Norway began producing heavy water on an industrial basis, and by1935, Norsk Hydro was shipping 99% pure heavy water at a price of $US 0.50/gram.

Deuterium and ultra-pure graphite were the only suitable moderators for a nuclear chain reaction. After the Nazi invasion of Norway in 1940, Norsk Hydro's heavy water production was dedicated to the Nazi nuclear power project. The events that followed are told in *The Heroes of Telemark.*