PHY2005
Atomic Physics

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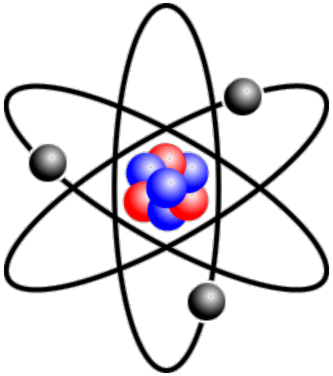
Atoms in physics



Atom: particles bound by Coulomb potential

Periodic Table of the Elements

Atomic Number	Boiling Point
Symbol	
Name	
Atomic Mass	

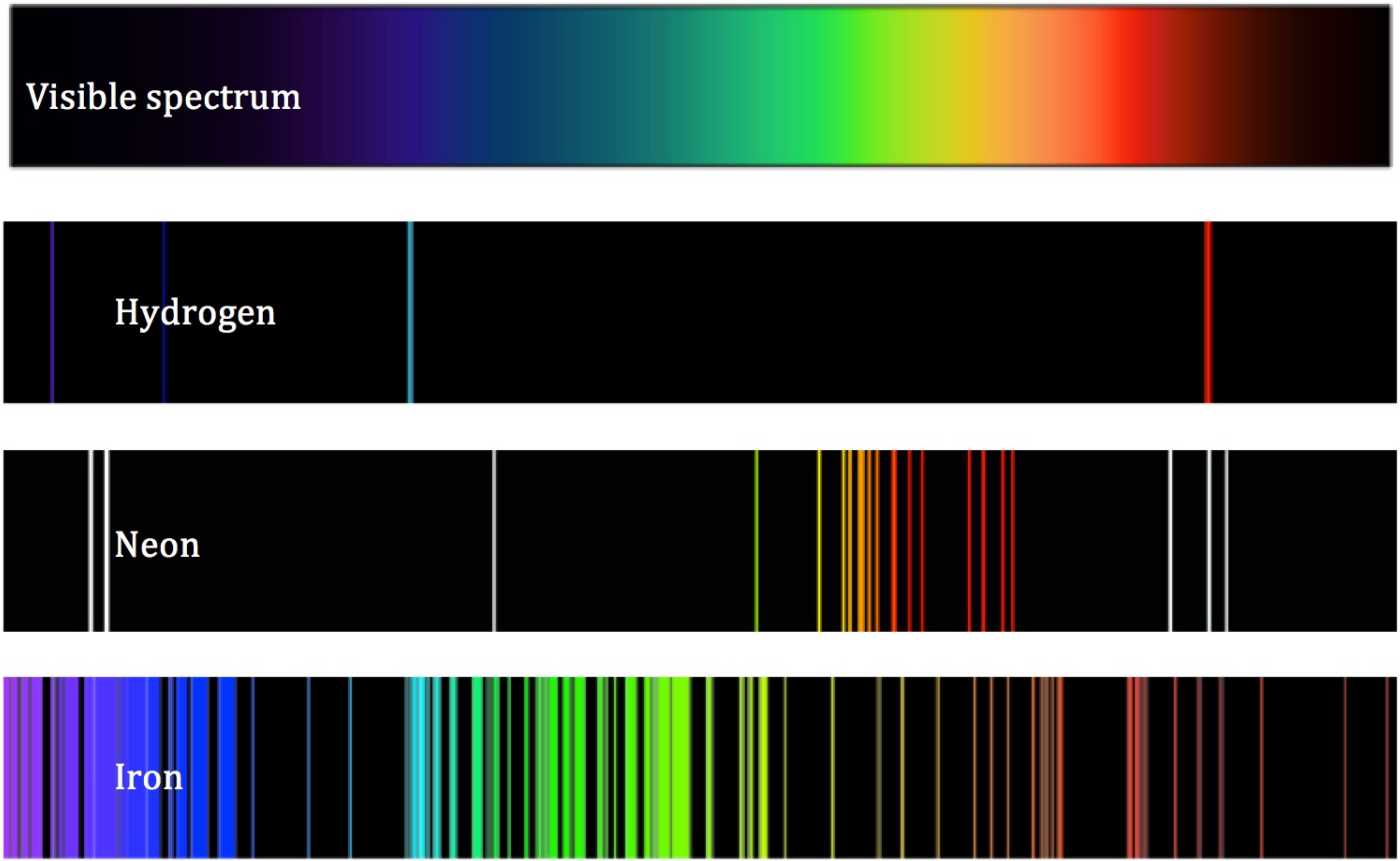
Normal boiling points are in °C.
SP = Triple Point
Pressure is listed if not 1 atm.
Allotrope is listed if more than one allotrope.

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 -252.762 **H** Hydrogen 1.008																	2 -268.93 **He** Helium 4.003
3 1342 **Li** Lithium 6.941	4 2471 **Be** Beryllium 9.012											5 4000 **B** Boron 10.811	6 graphite 3825 SP **C** Carbon 12.011	7 -195.798 **N** Nitrogen 14.007	8 -182.953 **O** Oxygen 15.999	9 -188.12 **F** Fluorine 18.998	10 -246.053 **Ne** Neon 20.180
11 882.940 **Na** Sodium 22.990	12 1090 **Mg** Magnesium 24.305											13 2519 **Al** Aluminum 26.982	14 3265 **Si** Silicon 28.086	15 white 280.5 **P** Phosphorus 30.974	16 444.61 **S** Sulfur 32.066	17 -101.5 **Cl** Chlorine 35.453	18 -185.847 **Ar** Argon 39.948
19 759 **K** Potassium 39.098	20 1484 **Ca** Calcium 40.078	21 2836 **Sc** Scandium 44.956	22 3287 **Ti** Titanium 47.88	23 3407 **V** Vanadium 50.942	24 2671 **Cr** Chromium 51.996	25 2061 **Mn** Manganese 54.938	26 2861 **Fe** Iron 55.933	27 2927 **Co** Cobalt 58.933	28 2913 **Ni** Nickel 58.693	29 2562 **Cu** Copper 63.546	30 907 **Zn** Zinc 65.39	31 2204 **Ga** Gallium 69.732	32 2833 **Ge** Germanium 72.61	33 616 SP **As** Arsenic 74.922	34 685 **Se** Selenium 78.972	35 58.8 **Br** Bromine 79.904	36 -153.34 **Kr** Krypton 84.80
37 688 **Rb** Rubidium 84.468	38 1382 **Sr** Strontium 87.62	39 3345 **Y** Yttrium 88.906	40 4409 **Zr** Zirconium 91.224	41 4744 **Nb** Niobium 92.906	42 4639 **Mo** Molybdenum 95.95	43 4265 **Tc** Technetium 98.907	44 4150 **Ru** Ruthenium 101.07	45 3695 **Rh** Rhodium 102.906	46 2963 **Pd** Palladium 106.42	47 2162 **Ag** Silver 107.868	48 767 **Cd** Cadmium 112.411	49 2072 **In** Indium 114.818	50 2602 **Sn** Tin 118.71	51 1587 **Sb** Antimony 121.760	52 988 **Te** Tellurium 127.6	53 184.4 **I** Iodine 126.904	54 -108.09 **Xe** Xenon 131.29
55 671 **Cs** Cesium 132.905	56 1897 **Ba** Barium 137.327	57-71	72 4603 **Hf** Hafnium 178.49	73 5458 **Ta** Tantalum 180.948	74 5555 **W** Tungsten 183.85	75 5596 **Re** Rhenium 186.207	76 5012 **Os** Osmium 190.23	77 4428 **Ir** Iridium 192.22	78 3825 **Pt** Platinum 195.08	79 2856 **Au** Gold 196.967	80 356.62 **Hg** Mercury 200.59	81 1473 **Tl** Thallium 204.383	82 1749 **Pb** Lead 207.2	83 1564 **Bi** Bismuth 208.980	84 962 **Po** Polonium [208.982]	85 337 **At** Astatine 209.987	86 -61.7 **Rn** Radon 222.018
87 677 **Fr** Francium 223.020	88 1737 **Ra** Radium 226.025	89-103	104 unknown **Rf** Rutherfordium [261]	105 unknown **Db** Dubnium [262]	106 unknown **Sg** Seaborgium [266]	107 unknown **Bh** Bohrium [264]	108 unknown **Hs** Hassium [269]	109 unknown **Mt** Meitnerium [268]	110 unknown **Ds** Darmstadtium [269]	111 unknown **Rg** Roentgenium [272]	112 unknown **Cn** Copernicium [277]	113 unknown **Uut** Ununtrium unknown	114 unknown **Fl** Flerovium [289]	115 unknown **Uup** Ununpentium unknown	116 unknown **Lv** Livermorium [298]	117 unknown **Uus** Ununseptium unknown	118 unknown **Uuo** Ununoctium unknown

Lanthanide Series	57 3464 **La** Lanthanum 138.906	58 3443 **Ce** Cerium 140.115	59 3520 **Pr** Praseodymium 140.908	60 3074 **Nd** Neodymium 144.24	61 3000 **Pm** Promethium 144.913	62 1794 **Sm** Samarium 150.36	63 1529 **Eu** Europium 151.966	64 3273 **Gd** Gadolinium 157.25	65 3230 **Tb** Terbium 158.925	66 2567 **Dy** Dysprosium 162.50	67 2700 **Ho** Holmium 164.930	68 2868 **Er** Erbium 167.26	69 1950 **Tm** Thulium 168.934	70 1196 **Yb** Ytterbium 173.04	71 3402 **Lu** Lutetium 174.967
Actinide Series	89 3198 **Ac** Actinium 227.028	90 4788 **Th** Thorium 232.038	91 4027 **Pa** Protactinium 231.036	92 4131 **U** Uranium 238.029	93 4174 **Np** Neptunium 237.048	94 3228 **Pu** Plutonium 244.064	95 2011 **Am** Americium 243.061	96 3100 **Cm** Curium 247.070	97 2627 **Bk** Berkelium 247.070	98 unknown **Cf** Californium 251.080	99 unknown **Es** Einsteinium [254]	100 unknown **Fm** Fermium 257.095	101 unknown **Md** Mendelevium 258.1	102 unknown **No** Nobelium 259.101	103 unknown **Lr** Lawrencium [262]

Alkali Metal | **Alkaline Earth** | **Transition Metal** | **Basic Metal** | **Semimetal** | **Nonmetal** | **Halogen** | **Noble Gas** | **Lanthanide** | **Actinide**

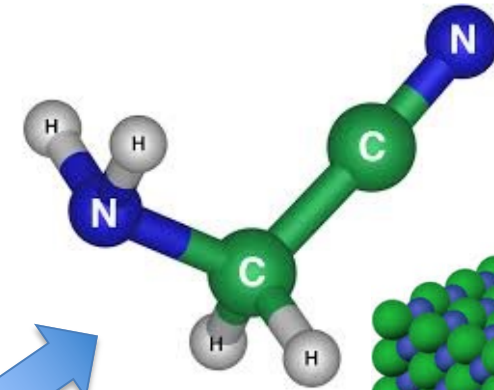
Very testable QM

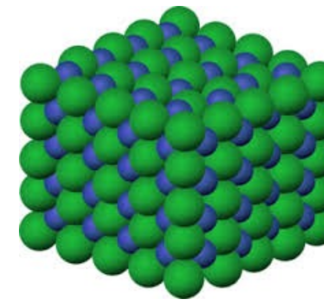


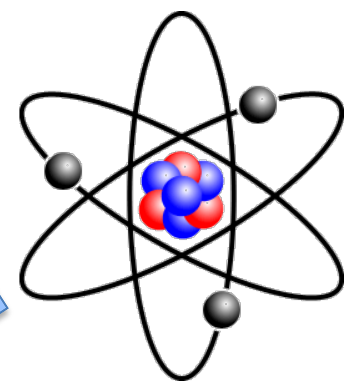
Very testable QM

"The spectrum of the hydrogen atom has proved to be the Rosetta stone of modern physics: once this pattern of lines had been deciphered much else could be understood" – Hänsch, Schawlow & Series (Scientific American, 1979)

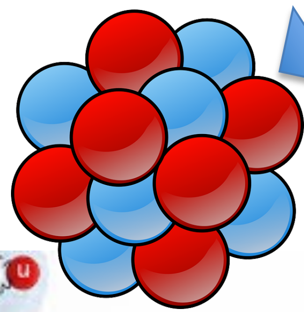
Atoms in physics



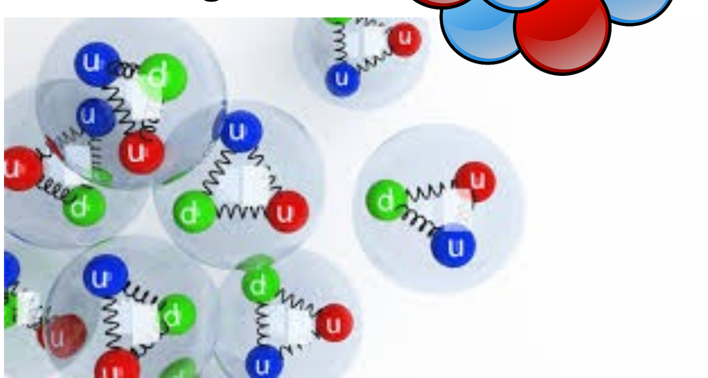




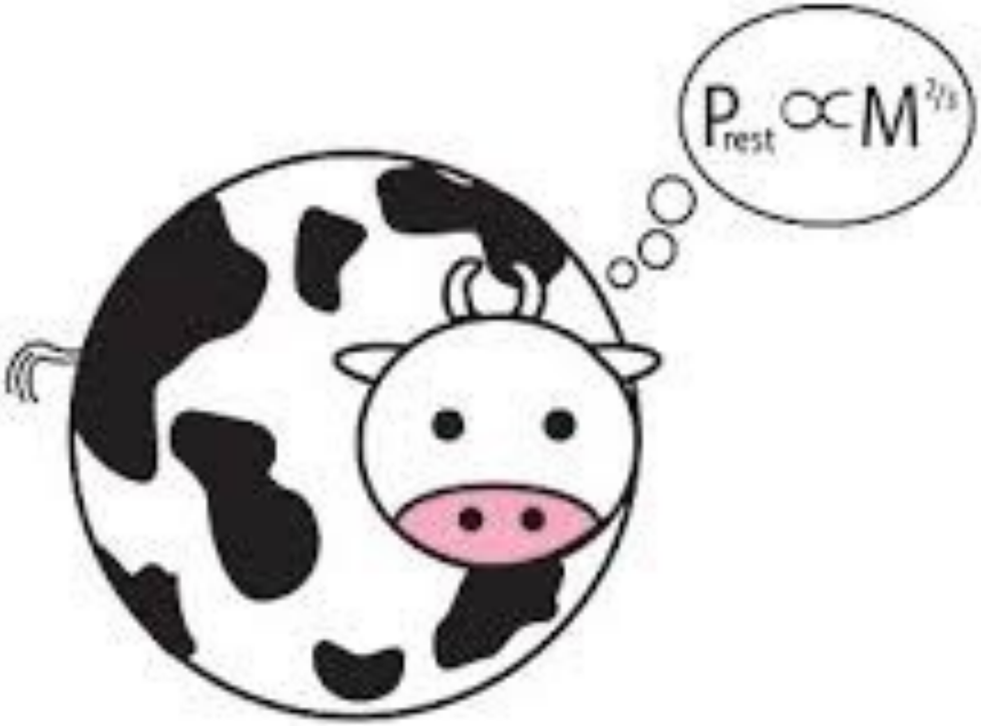
Molecular physics, solids, liquids: atoms are the building blocks



Nuclear and Particle physics: the strong force



How physics *really* works



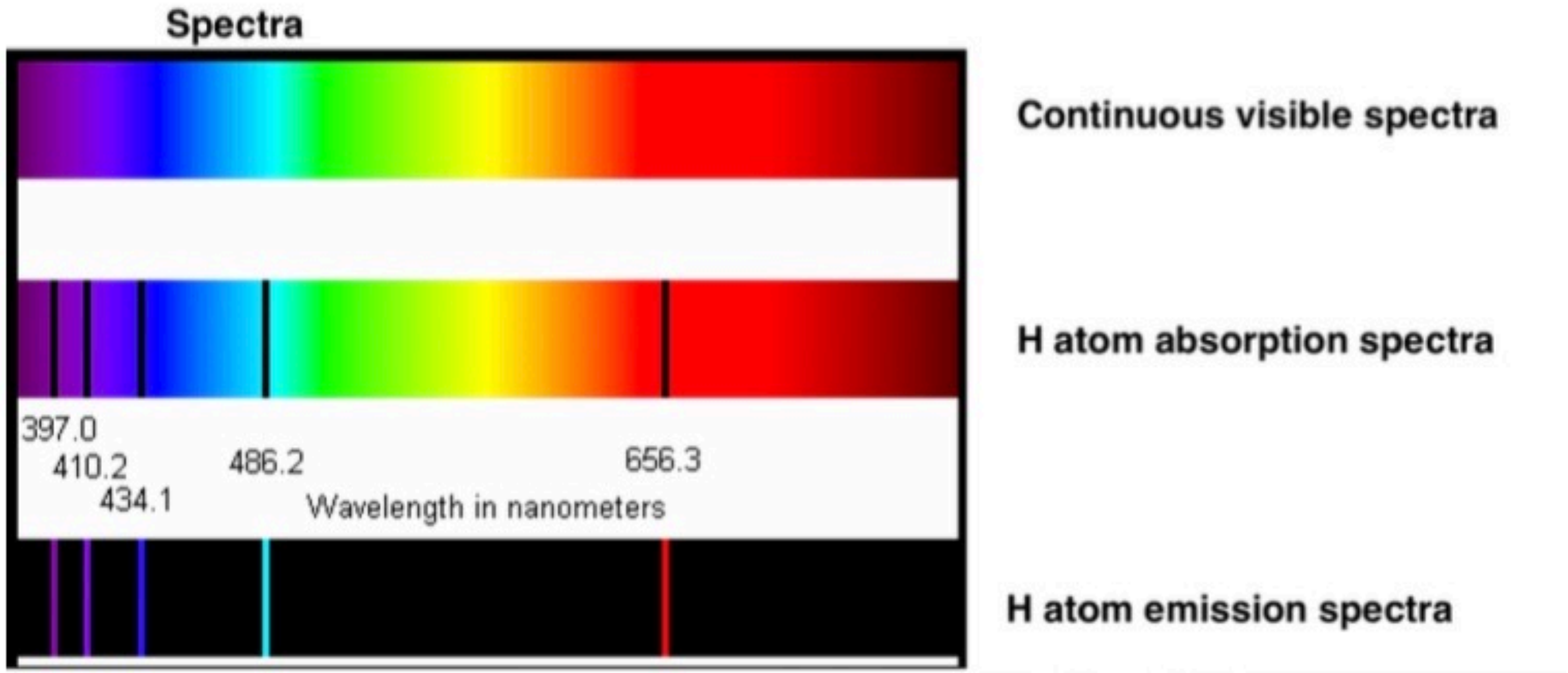
(2) Single-electron atoms

Learning goals

1. To revise the observed properties of the spectrum of the hydrogen atom.
2. To revise the postulates of the Bohr model, including how quantization is introduced to the model via a quantum number.
3. To revise the application of the Bohr model to calculate energy levels (and radii) in single-electron atoms.
4. To understand how the Bohr model can be applied to single-electron atoms with differing nuclear mass and/or differing nuclear charge.
5. To assess the quantitative accuracy of the Bohr model.
6. To understand limitations of the Bohr/Sommerfeld model of single-electron atoms.

Spectrum of hydrogen

Optical:

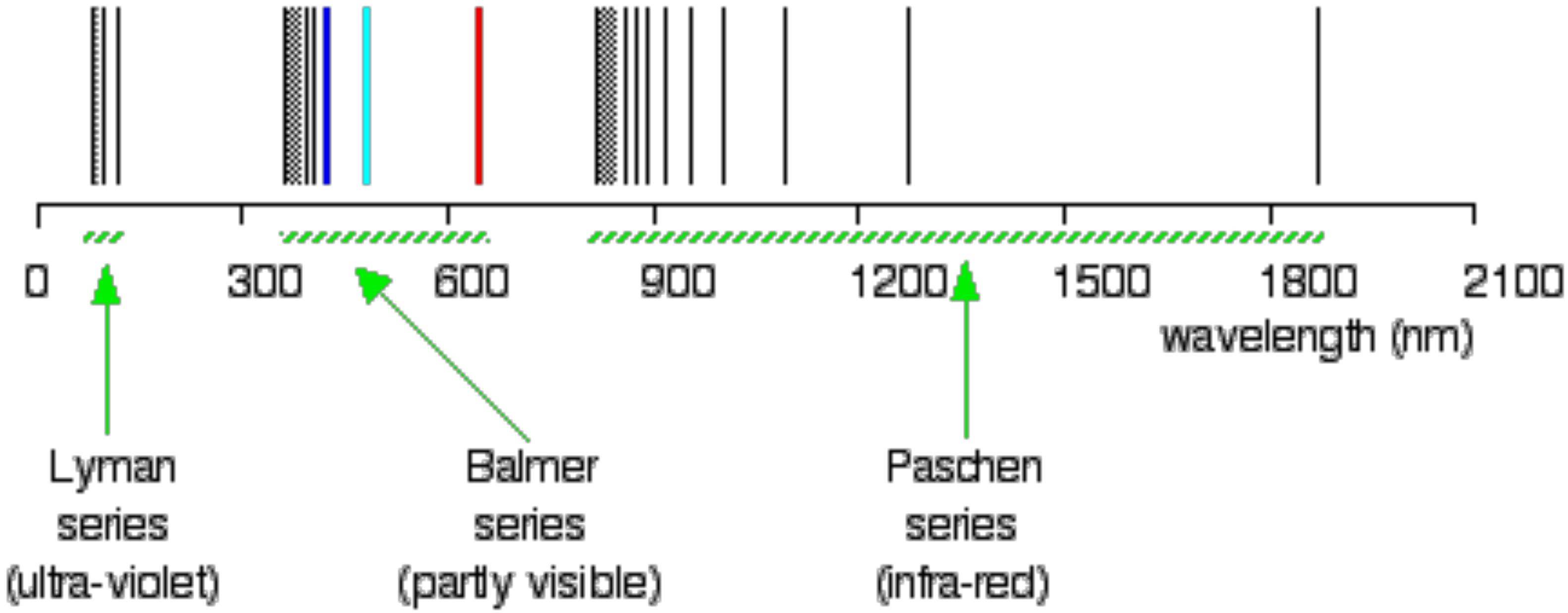


Spectrum empirically matched by Rydberg formula:

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \quad \text{for } n \geq 3$$

Spectrum of hydrogen

Ultraviolet, optical and infrared:



Spectrum matched by Rydberg/Ritz:

$$\frac{1}{\lambda} = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) \quad \text{for } n_2 > n_1$$

Spectrum of hydrogen

Ultraviolet, optical and infrared:

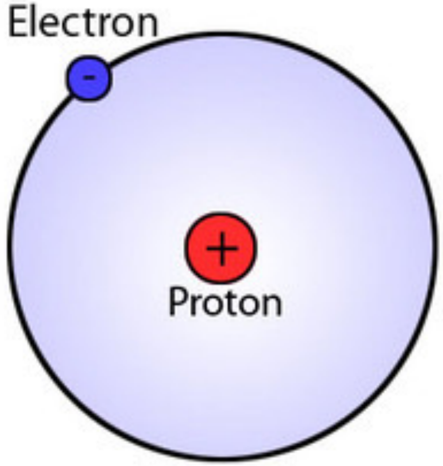
Series name	Region	n_1	n_2
Lyman	Ultraviolet	1	2 to ∞
Balmer	Visible	2	3 to ∞
Paschen	Infrared	3	4 to ∞
Brackett	Far IR	4	5 to ∞
Pfund	Far IR	5	6 to ∞

Table 1: Series of lines in the hydrogen spectrum.

Transitions within series named using Greek letter (α, β, γ etc.), starting from the longest wavelength.

Postulates of the Bohr model

1. Electron in “classical” circular orbit
2. Orbital angular momentum, L, is quantized
3. Electron does not radiate while in allowed state
4. Radiation emitted in transitions between states



Bohr formulae

Allowed states specified by principal quantum number, n. Energy and radius in each state obey:

$$E_n = -\left(\frac{1}{4\pi\epsilon_0}\right)^2 \frac{m_e Z^2 e^4}{2\hbar^2 n^2} \approx -13.6\ \mathrm{eV}\frac{Z^2}{n^2}$$

$$r = \frac{4\pi\epsilon_0 n^2\hbar^2}{m_e Z e^2} = a_0\frac{n^2}{Z}$$

$$a_0 \approx 5.3 \times 10^{-11}\ \mathrm{m}$$

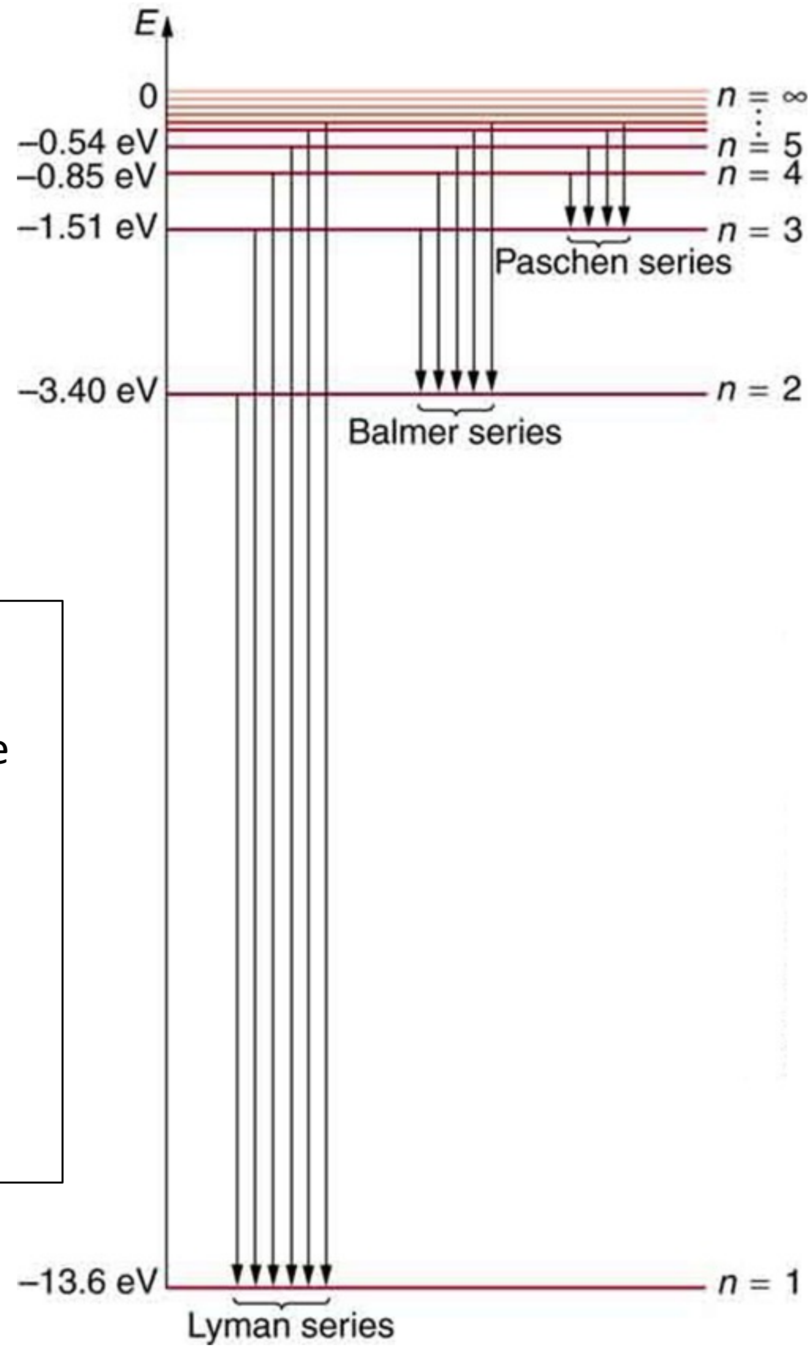
Wavelengths of transitions in the Bohr model

For photons emitted in transition between levels with quantum numbers n_i and n_f:

$$\frac{1}{\lambda} = \frac{\nu}{c} = \left(\frac{1}{4\pi\epsilon_0}\right)^2 \frac{m_e Z^2 e^4}{4\pi\hbar^3 c} \left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) = R_\infty Z^2 \left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

where $$R_\infty = \left(\frac{1}{4\pi\epsilon_0}\right)^2 \frac{m_e e^4}{4\pi\hbar^3 c}$$

Energy levels and transitions in hydrogen
("energy level diagram")



Note:

- here we are using energy scale "relative to ionization"
- common alternative to take "ground" state as E=0
- definition of energy scale particularly important for multi-electron atoms (later)

Reduced mass

To account for finite mass of nucleus, replace electron mass with *reduced mass* given by

$$\mu = \frac{m_e M}{m_e + M}$$

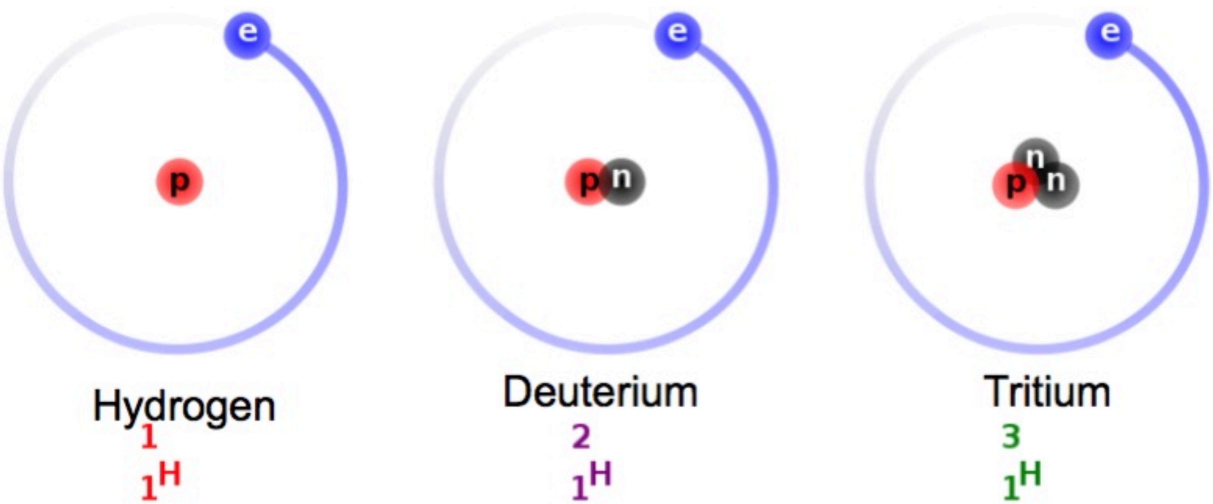
Equivalent to replacing the Rydberg constant with

$$R_M = \frac{\mu}{m_e} R_\infty = \frac{M}{m_e + M} R_\infty$$

Reduced mass

Although the effect of reduced mass is small (the proton mass is about 2000 times larger than the electron mass), it is measureable in spectra.

It is clearly seen as an isotope shift e.g. between the isotopes of hydrogen (differing number of neutrons in the nucleus).



Other single-electron atoms

The Bohr model can be applied to single-electron atoms, provided that the nuclear charge *Z* and the reduced mass μ are properly taken into account.

$$\frac{1}{\lambda} = \left(\frac{1}{4\pi\epsilon_0}\right)^2 \frac{\mu Z^2 e^4}{4\pi\hbar^3 c} \left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

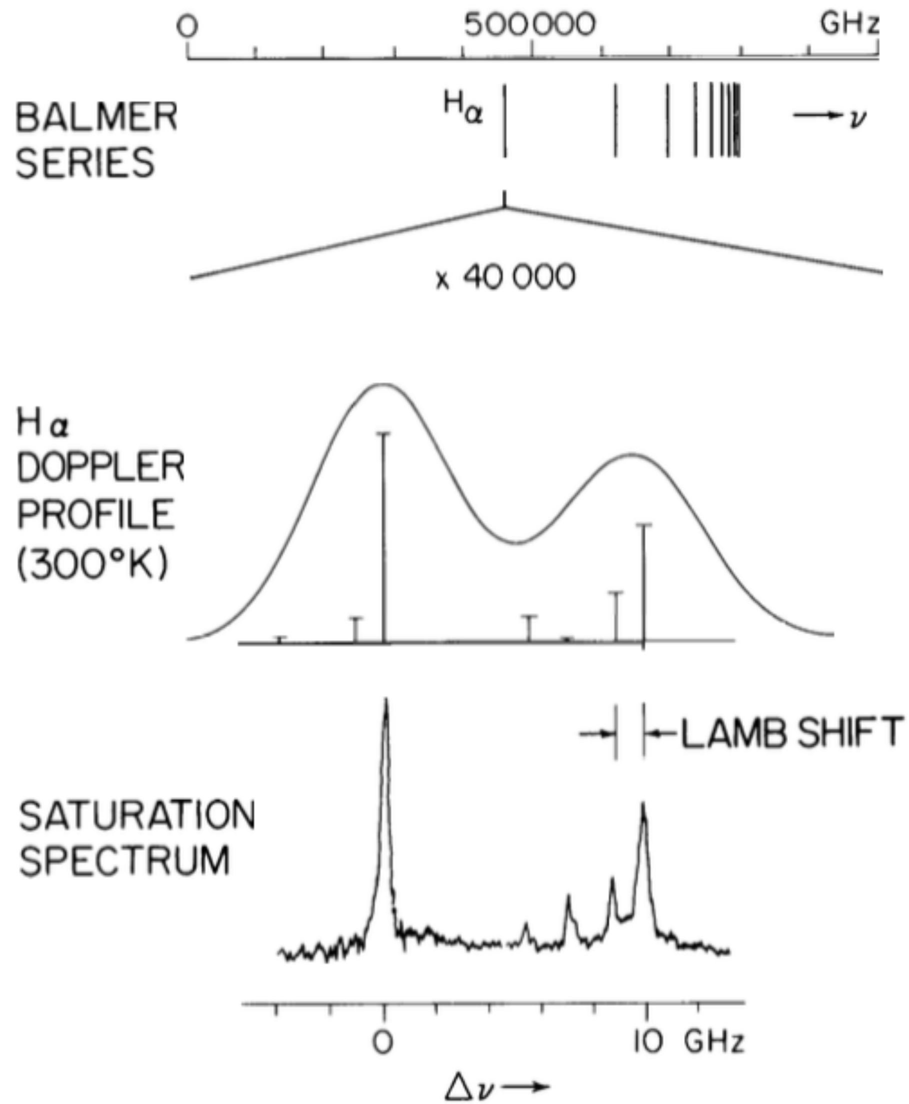
Includes single-electron ions, and exotic examples like positronium.

Table 2: Some single-electron ions and their nuclear charge.

single-electron ion	nuclear charge
He^+	$Z = 2$
Li^{2+}	$Z = 3$
Be^{3+}	$Z = 4$

Limitations of Bohr theory

Transitions of hydrogen have observed fine structure, which is not explained by the simple theory:



Limitations of Bohr theory

Transitions of hydrogen have observed fine structure, which is not explained by the simple theory:

Transition	principle quantum number change	Fine-structure components (nm)	Bohr theory (nm)
Balmer α	$n = 3 \rightarrow n = 2$	656.4522552 656.4537684 656.4584404 656.466464	656.4696
Balmer β	$n = 4 \rightarrow n = 2$	486.264130281 486.264488967 486.265465436 486.265570391	486.2737

Limitations of Bohr theory

Model can be extended (Sommerfeld) to elliptical orbits accounting for special relativity, allowing fine structure to be incorporated, up to a point.

However, such semi-classical treatments were superseded by more complete formulations of quantum mechanics, which are now well accepted.

In the next sections we will revise the quantum treatment of the single-electron atom and then consider multi-electron atoms.

Summary/Revision

- The spectra of single-electron atoms consist of regular series of lines with wavelengths described by the Rydberg formula.
- Bohr's semi-classical model describes the *quantized* energy and radii of electron orbits in the hydrogen atom and introduces a *quantum number*, n.
- The pattern of spectral lines predicted by the Bohr model agrees with the general observed properties of the hydrogen spectrum very well.
- The Bohr model makes simple, testable predictions for how the spectra of other single-electron atoms will behave, depending on the reduced mass and the nuclear charge.
- The simple Bohr model does not account for all properties of the hydrogen spectrum, however. In particular, more sophisticated approaches are need to understand *fine structure* in the spectral lines.