Emission Series and Emitting Quantum States: Visible H Atom Emission Spectrum

Experiment 6

#6 Emission Series and Emitting Quantum States: Visible H Atom Emission Spectrum

Goal:

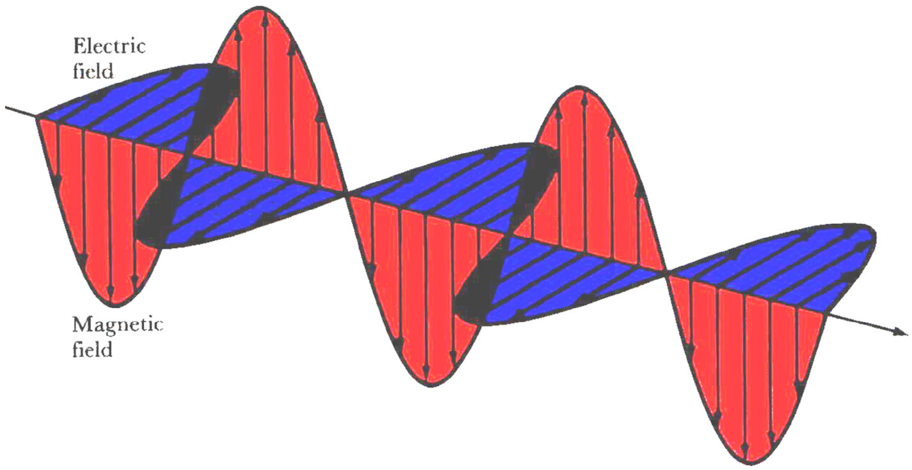
- To determine information regarding the quantum states of the H atom

Method:

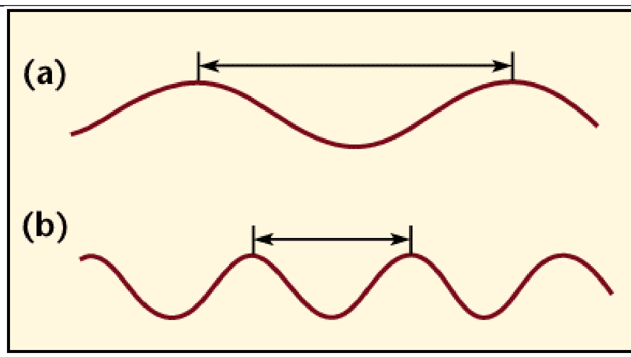
- Calibrate a spectrometer using He emission lines
- Observe the visible emission lines of H atoms
- Determine the initial and final quantum states responsible for the visible emission spectrum, as well as the Rydberg constant

Electromagnetic Radiation

Oscillating electric and magnetic fields

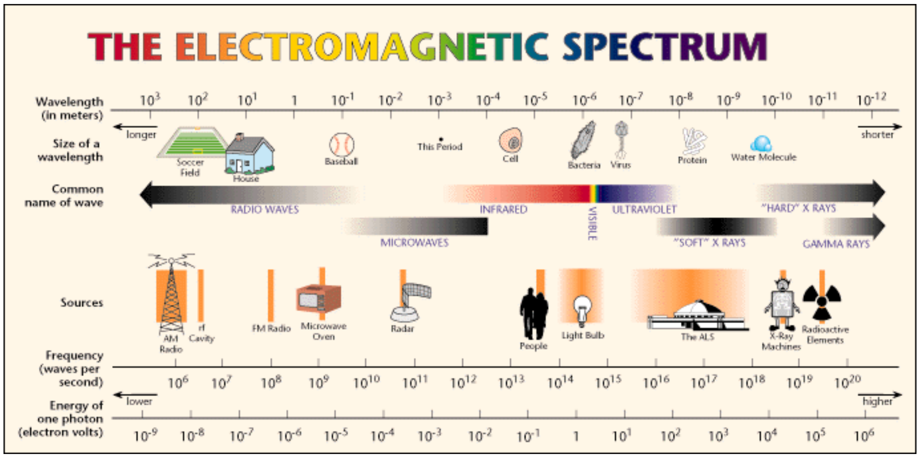


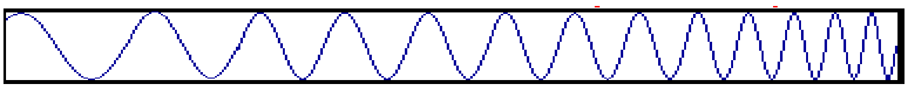
Light Energy



- Wavelength λ distance peak-to-peak
- Frequency ν oscillations per second
- Energy $E \propto \nu$ faster oscillation = more E

Electromagnetic Spectrum





Visible Emission

400 nm 500 nm 600 nm 700 nm

Wavelengths, λ, increase

Energies decrease

Electronic transitions (“e^- jumps”)

Dual Nature of Light/Relationships

1. **Wave** — wavelength, λ; frequency, ν
2. **Particle** — photon = "packet"; $E = h\nu$

h Planck's constant = 6.626×10^{-34} J·s
Units J = (J·s) (s^{-1})

c speed of light = 2.998×10^{8} m·s^{-1}
Units s^{-1} = (m·s^{-1})/(m)

$$E = h\nu$$

$$\nu = \frac{c}{\lambda}$$

Using the Equations

(a) Calculate the frequency of 460nm blue light.

$$\nu = \frac{c}{\lambda} = \frac{(2.99\times10^{8}\ \frac{\text{m}}{\text{s}})}{(460\ \text{nm})\left(\frac{1\ \text{m}}{1\times10^{9}\ \text{nm}}\right)}$$

$$= 6.52\times10^{14}\ s^{-1}$$

(b) Calculate the energy of 460 nm blue light.

$$E = \frac{hc}{\lambda} = h\nu$$

$$= (6.626\times10^{-34}\ J\cdot s)(6.52\times10^{14}\ s^{-1})$$

$$= 4.32\times10^{-19}\ J$$

Spectroscopy

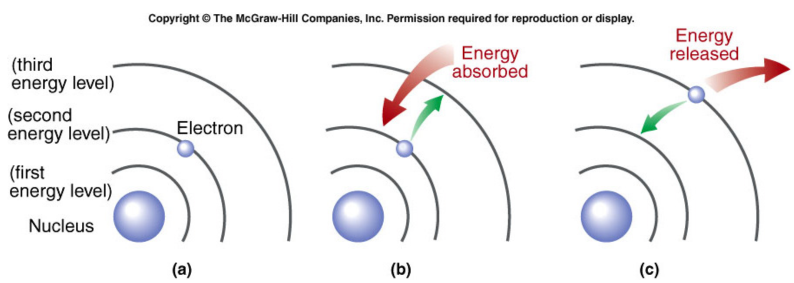
Spectroscopy: study of interaction of light with matter

hν: photon

1. **Absorption:** matter + hν → matter*
2. **Emission:** matter* → matter + hν

Energy change in matter: $\Delta E_{matter} = E_{h\nu}$

Discrete Energy Levels

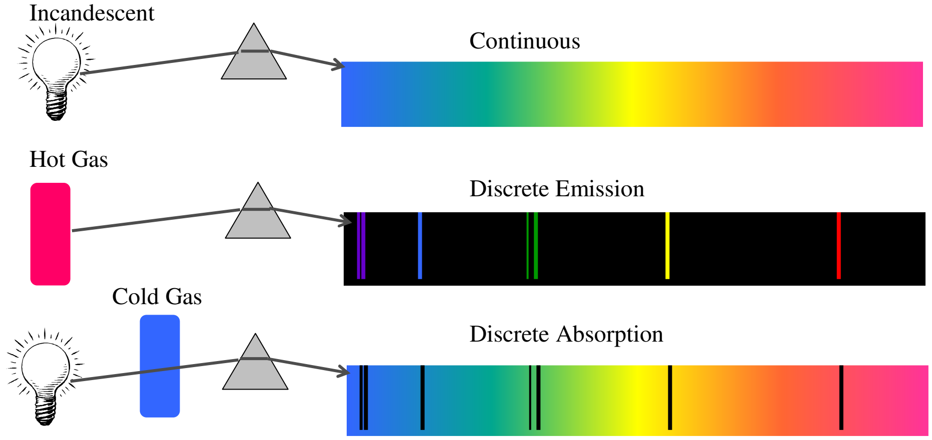


Ground state atom　Absorption　Emission

Observed energy level changes:

$$\Delta E = E_{h\nu} = E_{final} - E_{initial}$$

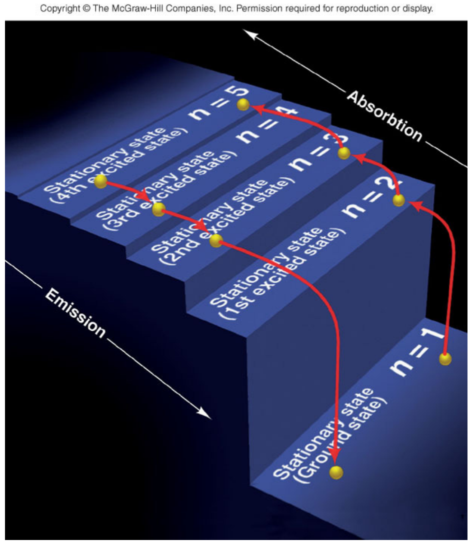
“Discrete” Atomic Emission



Atomic absorption: electrons excited to higher energy levels

Atomic emission: excited electrons lose energy

Quantized Energy Levels



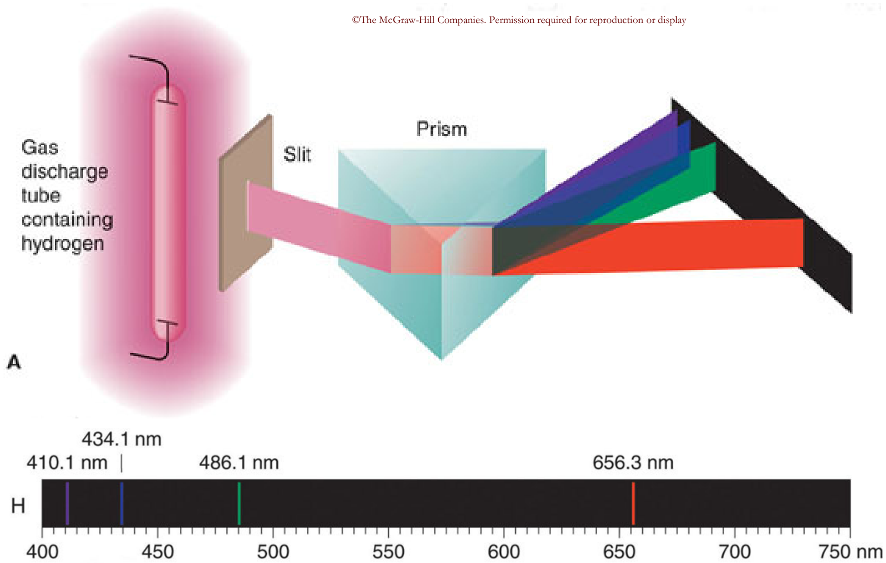
$$E_{h\nu} = \Delta E_{levels}$$

$$\Delta E = E_f - E_i$$

Absorption: $E_f > E_i$

Emission: $E_f < E_i$

Hydrogen Emission Spectrum



H atom emission

1) Electrical energy excites H — ***H + energy → H****
   - initial quantum state — $n_i = 2, 3, 4, 5, 6, \ldots$

2) H* loses energy — ***H* → H + hν***
   - final quantum state — $n_f = 1, 2, 3, \ldots$

   $n_f < n_i$

You observe several $\Delta E_{transitions}$ ≡ visible λs

- n_i's levels > n_f
- n_f end at same n_f

← You determine n_i's and n_f

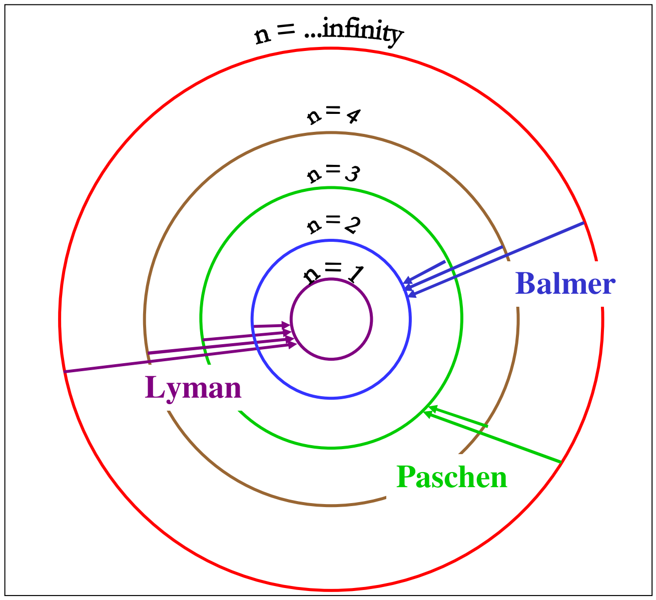
Hydrogen Atom and Emission

Ground State:

n = 1

Excited States:

n = 2, 3, 4, …



Rydberg Equation

General transition eq'n: $E_{h\nu} = E_f - E_i = \Delta E_{levels}$

Hydrogen atomic emission lines fit (***Rydberg eq'n***):

$$E_{h\nu} = R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

$R_H = 1.096776 \times 10^7 m^{-1} = 2.180 \times 10^{-18} J = 2\pi e^4 m/h^3 c$

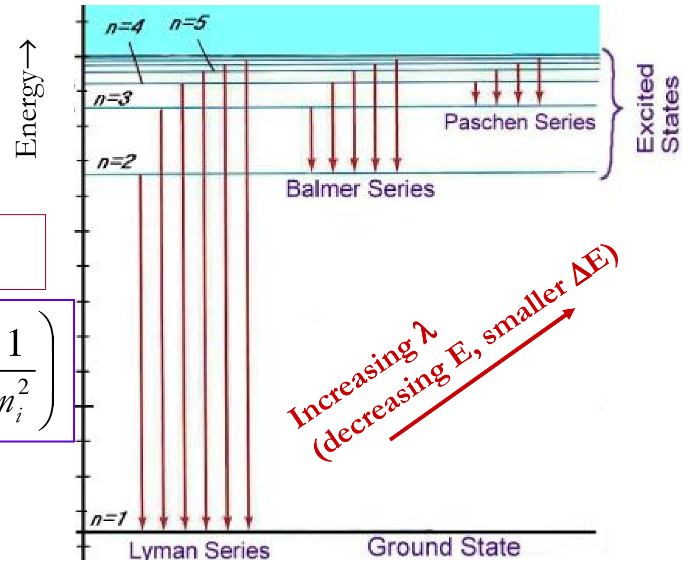
A "series" is associated with two quantum numbers:

Lyman:	$n_i = 2, 3, 4, \ldots$	$n_f = 1$
Balmer:	$n_i = 3, 4, 5, \ldots$	$n_f = 2$
Paschen:	$n_i = 4, 5, 6, \ldots$	$n_f = 3$

Hydrogen Atomic Emission

n = principal E states (principal quantum #s)

$$E_{h\upsilon} = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$



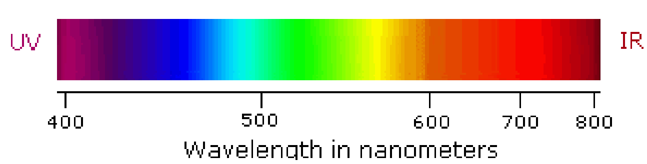
Part 1 Correlate color with wavelength

- Use lucite rod
- 20 nm intervals, 400–700 nm
- Boundary λs
- λ of max. intensity

λ, color

λ_{short}, λ_{long}

λ_{max}



Observe Hg atomic emission (handheld specs)

Part 2 Calibrate Spectrometer

Determine if measured wavelengths are "true"

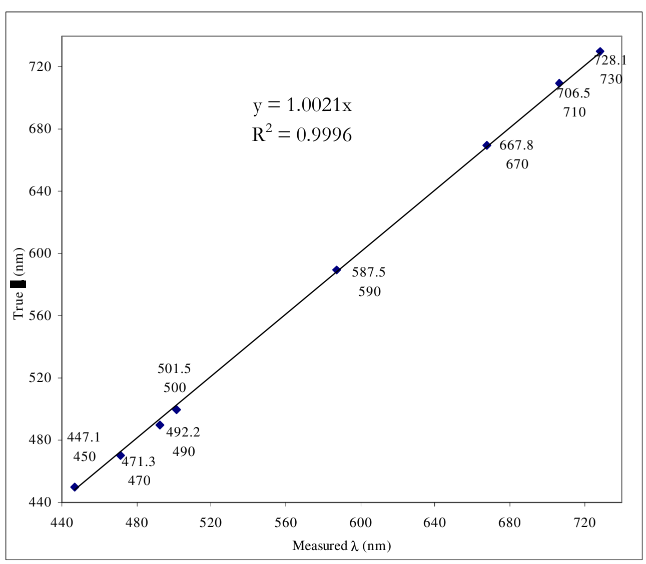
- Use He emission
- **Record λ_{msr} for lines**
- **Plot λ_{true} vs λ_{msr}**
- 7 or 8 lines

Color	**Accepted λ (nm)**	**Measured λ (nm)**
red	728.1	730
red	706.5	710
red	667.8	670
yellow	587.5	590
green	501.5	500
green	492.2	490
blue-green	471.3	470
blue-violet	447.1	450

Calibration Plot

$$slope = \frac{y_2 - y_1}{x_2 - x_1} = \frac{\Delta\lambda_{true}}{\Delta\lambda_{msrd}}$$

H atom emission:
- Multiply: λ_{msrd} by slope
- Converts: measured $\lambda \rightarrow$ true λ



Part 3 Record H emission λs

$$H_{2(g)} \xrightarrow{e^-} H^*_{2(g)} \rightarrow 2H^*_{(g)} \rightarrow 2H_{(g)} + h\nu_{(lines)}$$

$$H^*_{2(g)} \rightarrow H_{2(g)} + h\nu_{(bands)}$$

- Record color, λ_{msr} (3 or 4 lines)
- Determine λ_{true}
- Calculate $E_{h\nu}$ from λ_{true}

Units:
E in J
h in J·s
c in m/s
λ in m

color, λ_{msr}
λ_{true}
$E_{h\nu}$

$$E_{h\nu} = \frac{hc}{\lambda}$$

Questions/Data Analysis

1) Does your data match the Balmer series (it should; $n_{final} = 2$?)

2) What is $n_{initial}$ for each line?

3) What is your experimental R_H?

Hydrogen Lines / Analysis

Color	λ (nm)	ΔE (J)
red	660	3.0×10^{-19}
blue-green	490	4.1×10^{-19}
blue-violet	430	4.6×10^{-19}
violet	410	4.8×10^{-19}

$$E_{h\upsilon} = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) = \Delta E_{atom}$$

One way to think about the data

Are we observing the Balmer series, as predicted?

Balmer: $n_f = 2$ $3 \rightarrow 2$, $4 \rightarrow 2$, $5 \rightarrow 2$

These would be the three lowest energy transitions

Example data:

Literature λ (nm)	Color	Observed λ (nm)	ΔE (J)
410.1	violet	400	5.0E-19
434.0	blue-violet	430	4.6E-19
486.1	blue-green	500	4.0E-19
656.2	red	650	3.1E-19

Compare calculated ΔE to observed ΔE

$E_{H\ atom} \propto 1/n^2 = R_H/n^2$ so calculate ΔE between levels and compare to observed E's

Theoretical λ (nm)	Theoretical Color	Theoretical ΔE (J)	Observed λ (nm)	Observed Color	Observed ΔE (J)	% error
410.1	violet	4.84E-19	400	violet	5.0E-19	2.6
434.0	blue-violet	4.58E-19	430	blue-violet	4.6E-19	1.0
486.1	blue-green	4.09E-19	500	blue-green	4.0E-19	2.7
656.2	red	3.03E-19	650	red	3.1E-19	1.0

Experiment matches Balmer well (<5% error)

How? Plot ΔE_{atom} vs. $1/n_i^2$

Rearranged Rydberg equation fits:

$$y \quad = \quad m \quad x \quad + \quad b$$

$$\Delta E_{atom} = -R_H \left(\frac{1}{n_i^2}\right) + \frac{R_H}{n_f^2}$$

$$slope = -R_H$$

$$\text{y-intercept} = \frac{R_H}{n_f^2}$$

$$\text{x-intercept}: \quad \Delta E = 0$$

$$so: \quad \frac{1}{n_f^2} = \frac{1}{n_i^2}$$

Example plot data

$$y \quad = \quad m \quad x \quad + \quad b$$

$$\Delta E_{atom} = -R_H\left(\frac{1}{n_i^2}\right) + \frac{R_H}{n_f^2}$$

	Corrected λ			Balmer	
color	**nm**	E_f-E_i (J)	n_i	n_f	$1/n_i^2$
---	0	0	2	2	0.250
red	660	3.0E-19	3	2	0.111
blue-green	490	4.1E-19	4	2	0.063
blue-violet	430	4.6E-19	5	2	0.040
violet	410	4.8E-19	6	2	0.028
		y-axis			**x-axis**

Example Balmer Rydberg Plot

Slope (~R_H):

2×10^{-18}J

Close to R_H

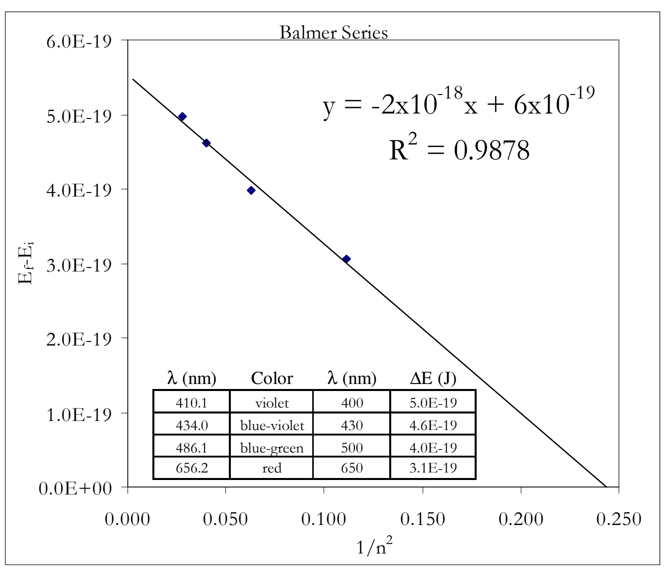
2.18×10^{-18}J

x-intercept:

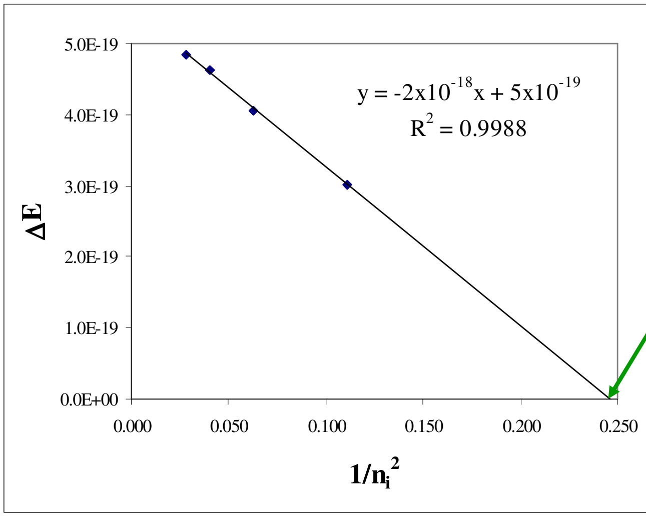
~0.24

Close to 0.25

~$1/2^2$



Balmer ($n_f = 2$) – plot ΔE vs. $1/n_i^2$



Good:

Slope ≈ $-R_H$

x-intercept:

$\sim 0.25 = \frac{1}{2^2}$

so

$n_f = 2$

This plot verifies our data – we observed the Balmer series!

As an extension (extra)

1) Data for:

Balmer ($n_f = 2$) or Paschen ($n_f = 3$)

2) Transitions are 3 lowest energy:

Balmer ($n_i = 5, 4, 3$) or Paschen ($n_i = 6, 5, 4$)

		Balmer			Paschen		
nm	E_f-E_i (J)	n_i	n_f	$1/n_i^2$	n_i	n_f	$1/n_i^2$
0	0	2	2	x-intercept	3	3	x-intercept
660	3.0E-19	3	2	0.111	4	3	0.063
490	4.1E-19	4	2	0.063	5	3	0.040
430	4.6E-19	5	2	0.040	6	3	0.028

Graphs

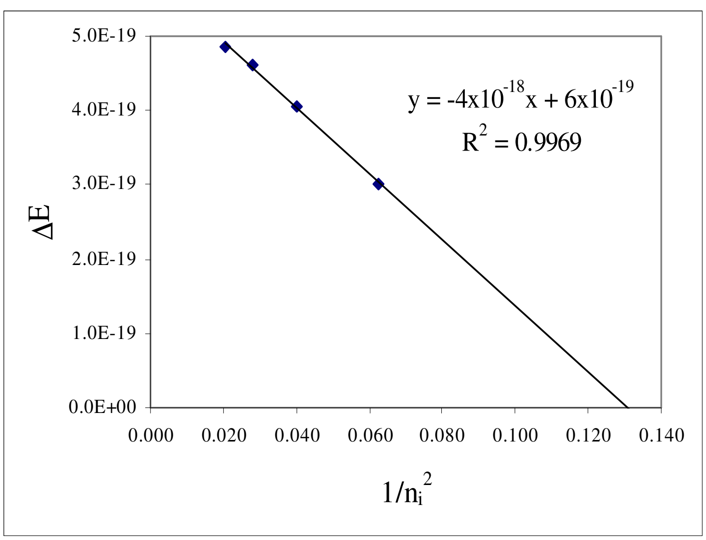
Prepare two graphs (Balmer and Paschen)

- x-axis should extend to x-intercept (y = 0)
- y-axis should be appropriate

Draw best-fit straight line

- Find slope (one should be close to $-R_H$)
- Find relative error in experimental R_H
- Match λ and **color** to n_i and n_f

Paschen ($n_f = 3$)

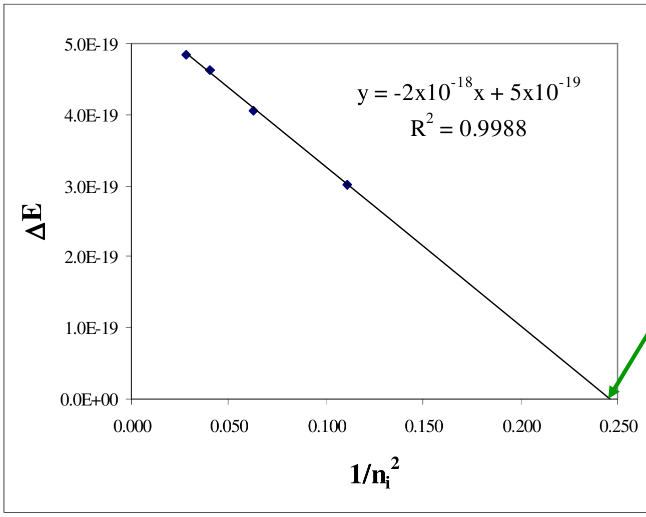


Not too good

Slope ≠ R_H

x-int. ≠ $1/3^2$

Balmer ($n_f = 2$)



Good:

Slope ≈ $-R_H$

x-intercept:

$\sim 0.25 = \frac{1}{2^2}$

so

$n_f = 2$

Example Balmer Rydberg Plot

Slope ($\sim R_H$):

2×10^{-18}J

Close to R_H

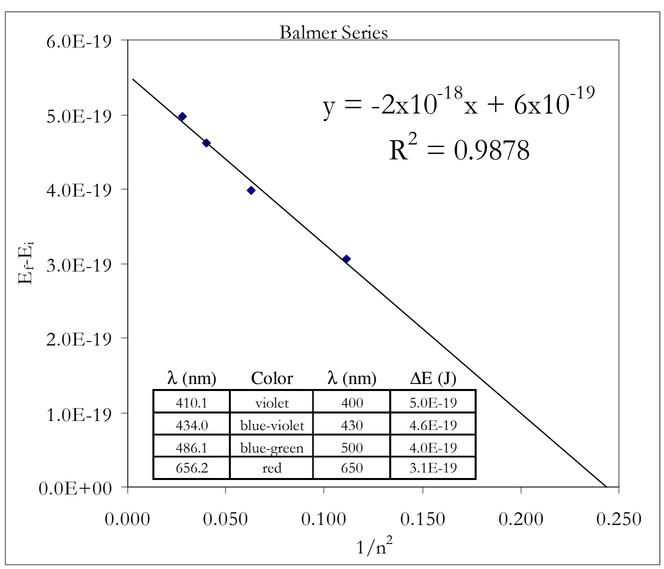
2.18×10^{-18}J

x-intercept:

~0.24

Close to 0.25

$\sim 1/2^2$



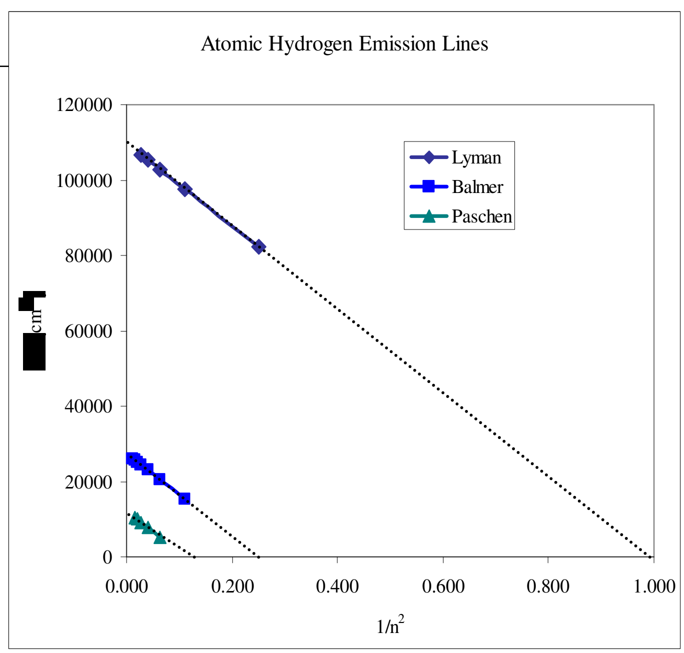
λ (nm)	Color	λ (nm)	ΔE (J)
410.1	violet	400	5.0E-19
434.0	blue-violet	430	4.6E-19
486.1	blue-green	500	4.0E-19
656.2	red	650	3.1E-19

Data

color	nm	E_f-E_i (J)	Balmer n_i	n_f
---	0	0	2	2
red	660	3.0E-19	3	2
blue-green	490	4.1E-19	4	2
blue-violet	430	4.6E-19	5	2

Experimental R_H: 2×10^{-18} J

$1/\lambda$ vs. $1/n_i^2$



Report

Abstract

Results

- 2a: Calibration data and plot
- 2b: Table
- Series plot (Balmer plot)
  depending on your analysis choice
- R_H and error from literature
- Predicted wavelengths and error

Sample calculations of:

- photon energy and Rydberg slope

Discussion/review questions