<table>
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<tr>
<th>Day</th>
<th>Topic</th>
<th>Notes</th>
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<tbody>
<tr>
<td>Fri.</td>
<td>8.4-.7 More Energy Quantization</td>
<td>RE 8.b</td>
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<td>Mon.</td>
<td>9.1-.2, (.8) P and En Multi-particle Systems</td>
<td>RE 9.a</td>
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<td>Tues.</td>
<td>9.3 Rotational Energy Quiz 8</td>
<td>HW8: Ch 8 Pr’s 21, 23, 27(a-c)</td>
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<td>Wed.</td>
<td>Review Exam 2 (Ch 5-8)</td>
<td>RE 9.b</td>
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<tr>
<td>Fri.</td>
<td>Exam 2 (Ch 5-8)</td>
<td>Practice Exam 2 (bring to class)</td>
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*Shedding light on atomic energy levels (segment of Hydrogen spectrum)*

- 3.02 eV
- 2.85 eV
- 2.55 eV
- 21.69 eV
Where we’ve been:
- Energy on the macroscopic scale
- Energy on the atomic scale

Where we’re going:
- Energy on the electronic scale

Mathematically like solar system, but much too small and delicate to directly see orbital radii and speeds – need another way to deduce
Hydrogen Energy Levels

\[
(K+U)_n = -\frac{13.6\text{eV}}{n^2}
\]

\[
(K+U)_2 = -\frac{13.6\text{eV}}{2^2}
\]

\[
U = -\frac{1}{4\pi\varepsilon_0} \frac{e^2}{r}
\]

Ground State

\[n = 1\]

\[-13.6 \text{ eV}\]

Excited States

\[n = 2\]

\[-3.40 \text{ eV}\]

\[n = 3\]

\[-0.85 \text{ eV}\]

\[n = 4\]

\[-0.54 \text{ eV}\]

\[n = 5\]

\[-1.51 \text{ eV}\]

\[n = \infty\]

\[-13.6 \text{ eV}\]
\[(K + U)_n = -\frac{13.6\text{eV}}{n^2}\]

Hydrogen Energy Levels: Excitation

Ground State

-3.40 eV

-1.51 eV

-0.85 eV

-0.54 eV

0

K+U

n = \infty

n = 5

n = 4

n = 3

n = 2

n = 1

Ground State

Excited States
Hydrogen Excitation: 1st in ground state

\[(K+U)_n = -\frac{13.6\text{eV}}{n^2}\]

- Ground State: \(n = 1\), \(-13.6\text{eV}\)
- Excited States:
  - \(n = 2\), \(-3.40\text{eV}\)
  - \(n = 3\), \(-1.51\text{eV}\)
  - \(n = 4\), \(-0.85\text{eV}\)
  - \(n = 5\), \(-0.54\text{eV}\)
- \(n = \infty\) marks the “occupied state”
Hydrogen Excitation: 2nd Adsorbs energy from Collision

\[(K+U)_n = -\frac{13.6\text{eV}}{n^2}\]

excites to 2nd state

Ground State

Excited States

n = 1

n = 2

n = 3

n = 4

n = 5

n = \infty
Hydrogen Excitation: 3rd Looses Energy by photon emission, de-excites to ground state

\[(K + U)_n = -\frac{13.6eV}{n^2}\]

\[
\begin{align*}
0 & \quad n = \infty \\
-0.54 \text{ eV} & \quad n = 5 \\
-0.85 \text{ eV} & \quad n = 4 \\
-1.51 \text{ eV} & \quad n = 3 \\
-3.40 \text{ eV} & \quad n = 2 \\
-13.6 \text{ eV} & \quad n = 1
\end{align*}
\]

Ground State

Photon Emission

\[E_{ph} = -\Delta E_H\]

\[E_{ph} = -\left(\frac{-13.6eV}{1^2} - \frac{-13.6eV}{2^2}\right)\]

\[E_{ph} = 10.2eV\]
Example Atoms in Gas-Discharge Tube
Frank-Hertz Experiment

Monitoring electron beam’s loss of energy to the atoms

Hydrogen Gas Discharge Tube

Energy of Hydrogen’s n=1 to 2 transition

10.2eV

Electron’s kinetic energy

High accelerating voltage
Medium accelerating voltage
Low accelerating voltage

Different exiting kinetic energies are reflected in different current readings

Distance along tube
Here are the quantized energy levels (K+U) for an atomic or molecular object, and the object is in the "ground state" (marked by a dot). An electron with kinetic energy 6 eV is fired at the object and excites the object to the −5 eV energy state. What is the remaining kinetic energy of this electron?

a) 9 eV  
b) 6 eV  
c) 4 eV  
d) 3 eV  
e) 2 eV
Absorption Spectrum

Your eye

Interstellar atomic dust cloud

Distant star

Colors / energies of light from the star that interact with cloud’s atoms scatter; it’s depleted from the star light you see.
A collection of some atoms objects is kept very cold, so that all the objects are in the ground state. Light consisting of photons with a range of energies from 1 to 7.5 eV passes through this collection of objects. What photon energies will be depleted from the light beam (“dark lines”)?

**Note:** assume the atoms don’t stay in excited states long enough to get further excited another step up from them.

a) 2 eV, 5 eV, 9 eV  
b) 3 eV, 4 eV  
c) 0.5 eV, 3 eV, 4 eV  
d) 4 eV, 7 eV  
e) 3 eV, 4 eV, 7 eV
## Temperature Effects on Absorption Spectrum

### T very low

- All atoms initially in ground state; only absorption lines for transitions from it

<table>
<thead>
<tr>
<th>Energy Level</th>
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<tbody>
<tr>
<td>-1 eV</td>
</tr>
<tr>
<td>-2 eV</td>
</tr>
<tr>
<td>-5 eV</td>
</tr>
<tr>
<td>-9 eV</td>
</tr>
</tbody>
</table>

### T very high

- Many states have some atoms; you see absorption lines between many states

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<tbody>
<tr>
<td>-1 eV</td>
</tr>
<tr>
<td>-2 eV</td>
</tr>
<tr>
<td>-5 eV</td>
</tr>
<tr>
<td>-9 eV</td>
</tr>
</tbody>
</table>

### T medium

- More energetic collision; lower-energy (redder) light excites transition
- Less energetic collision; higher (bluer) light excites transition

**Thermally broadened Spectral lines**
Quantitatively Relating Light’s Energy and Frequency
The Photo-electric Effect

“Ionizing” metal plate
Shine mono-chromatic (single color) light on metal

With low frequency light, no matter how bright, no electrons are freed, no current measured.

Turn up frequency; at and above some threshold frequency, f, electrons are freed, current measured.

Threshold frequency relates to metal plate’s “ionization energy” (work function) by \[ E = hf \]

Deduce: light falls like rain with packets of energy related to its frequency \[ E = hf \]
\[ h = 6.6 \times 10^{-34} \text{Js} = 4.1 \times 10^{-15} \text{eVs} \]
Example: He-Ne laser.

Gas discharge tube filled with He and Ne. They have a rich emission spectrum but the tube’s length, like the string of a piano is right to help light resonate at just one frequency, $4.36 \times 10^{14}$ Hz, a rich red. How much energy does one red photon of from the He-Ne have?

This is a 0.95 mW = 0.00095 J/s laser; that’s the rate at which the beam of photons carry away energy. How many photons are emitted per second?
Simple Harmonic Oscillator
Energy spectrum & Structure

Imagine a charged particle riding a mass on a spring

\[ f = \frac{1}{2\pi} \sqrt{\frac{k_s}{m}} \]

Radiates light with the same frequency as its own oscillation

\[ E_{\text{light}} = hf \]

Mass-on-spring must *lose* this much energy

\[ \Delta E_{\text{system}} = E_{\text{light}} = hf \]

\[ (K+U)_1 = U_{eq} + \frac{1}{2} k_s s_{\text{max.1}}^2 \]
\[ (K+U)_2 = U_{eq} + \frac{1}{2} k_s s_{\text{max.2}}^2 \]
\[ (K+U)_3 = U_{eq} + \frac{1}{2} k_s s_{\text{max.3}}^2 \]

Still oscillating at same \( f \) again radiates light of frequency \( f \).

Etc.
Simple Harmonic Oscillator
Energy spectrum & Structure

Imagine a charged particle riding a mass on a spring

\[ f = \frac{1}{2\pi} \sqrt{\frac{k_s}{m}} \]

We’ve deduced

\[ (K + U)_n = U_{eq} + \frac{1}{2} k_s s_{max}^2 = E_{min} + n\hbar \omega \]

where \( n = 1, 2, 3, \ldots \)

Takes real Quantum Mechanics to nail down \( E_{min} \):

\[ E_{min} = U_{eq} + \frac{1}{2} \hbar \omega \]

\[ (K + U)_n = U_{eq} + \hbar \omega \left(n + \frac{1}{2}\right) = U_{eq} + \hbar \omega \left(n + \frac{1}{2}\right) \]
Example: Macroscopic mass on spring

We certainly don’t notice that a mass on a spring has only specific allowed energies, it seems to be able to oscillate with any energy / amplitude (until it breaks). Given an 0.01 kg mass on our 3 N/m spring, initially displaced 0.1m, how much energy has it got, and how big is the step to the next energy level lower?

How about a H$_2$ molecule, what’s the energy step size for its vibrations? Roughly 10$^{-27}$ kg mass protons and 100 N/m spring constant.
Two atoms joined by a chemical bond can be modeled as two masses connected by a spring. In one such molecule, it takes 0.05 eV to raise the molecule from its vibrational ground state to the first excited vibrational energy state.

How much energy is required to raise the molecule from its first excited state to the second excited vibrational state?

1) 0.0125 eV
2) 0.025 eV
3) 0.05 eV
4) 0.10 eV
5) 0.20 eV
### Molecular Bonds

<table>
<thead>
<tr>
<th>Molecule A: 2 atoms of mass $M_A$</th>
<th>Which molecule has vibrational energy levels spaced closer together?</th>
</tr>
</thead>
</table>
| Molecule B: 2 atoms of mass $4M_A$ | 1) A  
| Stiffness of interatomic bond is approximately the same for both. | 2) B  
|                                                | 3) the spacing is the same |

Suppose the atoms in diatomic molecules C and D had approximately the same masses, but

Stiffness of bond in C is 3 times as large as stiffness of bond in D.

<table>
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</tr>
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</table>
| 1) C  
| 2) D  
| 3) the spacing is the same |
Pb: $k_s \approx 5 \text{ N/m}$  
Al: $k_s \approx 16 \text{ N/m}$  
Which vibrational energy level diagram represents Pb, and which is Al?  
1) A is Pb and B is Al  
2) A is Al and B is Pb  
3) A is both Pb and Al  
4) B is both Pb and Al
Molecular Bonds
(zoomed out)

High energies: Like hydrogen (closer and closer)

Low energies: Like harmonic oscillator (evenly spaced)
Spectra & Energy Step Sizes

Stiffer / stronger bonds, *bigger* steps between energy levels

Electron (eV's)

Vibrational

Energy (10^-2 eV's)

Rotational

Energy (10^-2 eV's)
Stiffer / stronger bonds, *bigger* steps between energy levels

<table>
<thead>
<tr>
<th>Type of State</th>
<th>Energy</th>
</tr>
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<tbody>
<tr>
<td>Hadronic (quark composites)</td>
<td>$10^8$eV</td>
</tr>
<tr>
<td>Nuclear (nucleon composites)</td>
<td>$10^6$eV</td>
</tr>
<tr>
<td>Electronic (atoms &amp; molecules)</td>
<td>1 eV</td>
</tr>
<tr>
<td>Vibrational (molecules)</td>
<td>$10^{-2}$eV</td>
</tr>
<tr>
<td>Rotational (molecules)</td>
<td>$10^{-4}$eV</td>
</tr>
</tbody>
</table>