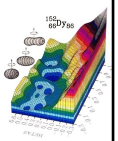
Physics 141.
Lecture 12.



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Physics 141.
Lecture 12.

- Course Information
- Chapter 8, Energy Quantization:
  - Quantization of energy.
  - Emission and absorption spectra.
  - Vibrational energy levels.
  - Rotational energy levels.
  - Example of quantization.
  - Incoherent and coherent emission of light.

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Physics 141.
Course Information.

- Homework:
  - Homework set 5 is due on Friday 10/11 at 12 pm.
  - No homework during the week of fall break.
  - Homework set 6 is due on Friday 10/25 at 12 pm.
- Laboratory:
  - Laboratory # 3 took place on Monday 10/7.
  - Laboratory # 3 office hours will be on Monday 10/21.
  - Laboratory # 3 report will be due on Wednesday 10/23 at noon.
- Exam # 2:
  - Thursday 10/17 at 8 am in Hoyt.
  - I will review the material covered on Exam # 2 on Thursday 10/10.
- Next week:
  - No recitations on Tuesday 10/15.
  - Regular office hours and recitations on Wednesday 10/16 to help you prepare for Exam # 2.
  - No office hours on Thursday 10/17

3

Chapter 8.
Energy quantization.

- Until the early 20th century, scientists assumed that the total energy of a system could have any arbitrary value (constraint only by the potential energy of the system).
  - The energy of a planet in a circular orbit around the sun will have an energy that depends on the radius of the orbit. By changing the radius, we can change the energy of the system.
  - The success of the planetary model led to applications of this model to the description of atoms where electrons carry out orbital motion around the nucleus.
  - This model predicts that the total energy of the electron is only constraint by the electrostatic potential energy.

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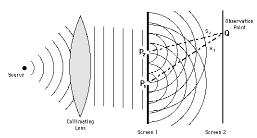
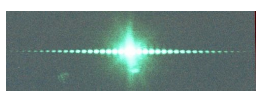
Quantization of light.

- Before 1905, light was assumed to be an electromagnetic wave, characterized by an amplitude and a wavelength.
- When the intensity of the light increases, the amplitude of the electromagnetic wave increases.
- Most phenomena could be understood in terms of the wave nature of light. Diffraction and interference provided compelling evidence that the wave picture of light was correct.





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Energy quantization.
Quantization of light.

- But …… the photoelectric effect (emission of electrons from metals) could not be understood in terms of the wave model of light.
- To explain the photoelectric effect, light must be described in terms of **"particle" properties**. When the intensity of a "particle" beam increases, the number of particles increases but the energy of each particle does not change.
- The particles of light are called **photons**. The energy of a photon is determined by its wavelength (the typical energy for a photon of visible light is around 2 - 3 eV).
- The energy of the photon is hc/λ, where h is Planck's constant (= 6.6×10^{-34} Js) and λ is the wavelength of the light.

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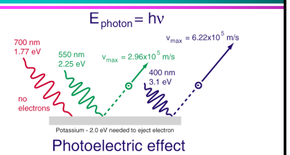
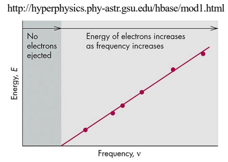
Quantization of light.
The photoelectric effect.



http://hyperphysics.phy-astr.gsu.edu/hbase/mod1.html

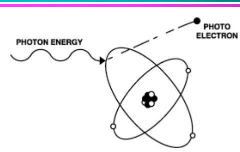


http://www.mhhe.com/physsci/astronomy/fix/student/chapter6/06f07.html

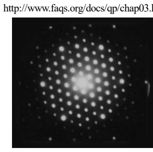
- Experiments showed that light can liberate electrons from a material (the photoelectrons).
- The following surprising observations were made:
  - No electrons are liberated if the wavelength of the light is larger than some critical value (independent of the intensity of the light).
  - The maximum energy of the electrons liberated does not depend on the intensity of the light. It only depends on the wavelength of the incident light.

Quantization of light.
The photoelectric effect.

- Einstein explained this effect by interpreting light as a collection of photons with discreet energies.
- Einstein proposed that the photon energy is only determined by the wavelength of the light ($E = hc/\lambda$).
- Changes in light intensity reflect changes in the number of photons, not the energy of the individual photon.
- The resulting **wave-particle duality** also predicted that "particles" can behave like waves. It was observed that for example electrons can behave like waves (electron diffraction). Note: more on this in Phy 143.

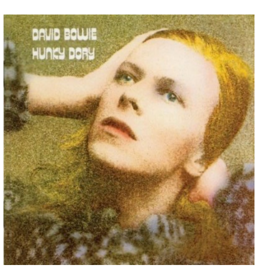


http://www.faqs.org/docs/qp/chap03.html



http://www.matter.org.uk/diffraction/electron/electron_diffraction.htm

3 Minute 40 Second Intermission
(42 seconds more than during lecture 11).



- Since paying attention for 1 hour and 15 minutes is hard when the topic is physics, let's take a 3 minute 40 second intermission.
- You can:
  - Stretch out.
  - Talk to your neighbors.
  - Ask me a quick question.
  - Enjoy the fantastic music.
  - Go asleep, as long as you wake up in 3 minutes and 40 seconds.

Quantization of light.
Different wavelengths, different energies.

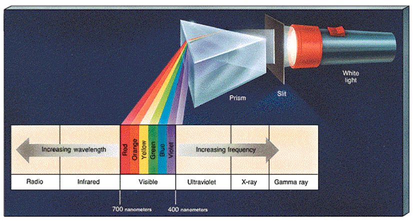


Figure: Chaisson and McMillan, *Astronomy today*

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Energy quantization.
Energy levels of hydrogen.

Emission pattern of Hydrogen.
"Astronomy! A Brief Edition," J. B. Kaler, Addison-Wesley, 1997.

- Light is emitted by heated hydrogen gas only at specific wavelengths.
- Excited hydrogen atoms can thus only emit specific amounts of energy.
- This implies that the energy states of hydrogen atoms are quantized.

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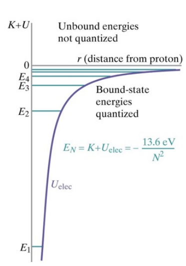
11

Energy quantization.
Energy levels of hydrogen.

- Experiments examining the details of atomic structure showed that the electrons can only occupy certain specific energy levels.
- The measurements show that the total energy of the electron, $K + U$, is equal to $-13.6/N^2$ eV where N is an integer ($N = 1, 2, \ldots$).
- The quantization of the energy levels is a result of quantum-mechanical effects (to be discussed in more detail in Physics 143).



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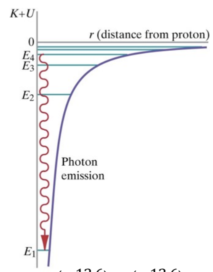
Quantization of light. Emission patterns.

- Light is emitted when an excited atom makes a transition to a lower energy level.
- Since the energy level of atoms are quantized, the light emitted will have discrete wavelengths (energies).
- The energy levels serve as a signature (fingerprint) for the atom, and the emission pattern can be used to identify the atom(s).



$$E_\gamma = \left(-\frac{13.6}{4^2}\right) - \left(-\frac{13.6}{1^2}\right) = 12.75 \text{ eV}$$

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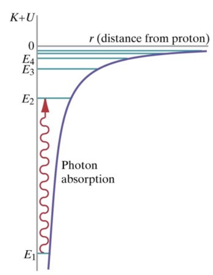
Quantization of light. Absorption patterns.

- When an atom is in its ground state, it can only absorb photons of specific frequencies.
- Only photons with an energy that exactly match possible transitions between energy levels in the atom are absorbed by the atom.
- The absorption spectrum can also be used as a signature of the atom.



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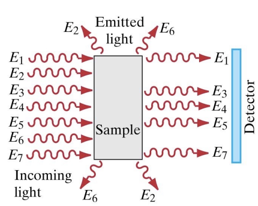
Quantization of light. Absorption patterns.

- The atoms that absorb the photons will decay back to the ground state.
- When these transitions occur, the emitted photons will have the same energies as the energies of the photons being absorbed.
- However, the reemitted photons are emitted in random directions, and only a few are emitted in the direction of the incoming photons.



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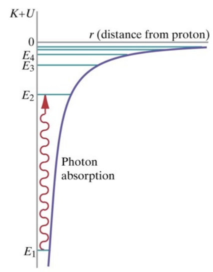
Quantization of light. Absorption patterns.

- At room temperature, almost all hydrogen atoms will be in their ground state *(E* = -13.6 eV).
- The first excited state in hydrogen is at *E* = -3.4 eV and a 10.2 eV photon is required to make the transition.
- Since visible light has energies around 2 - 3 eV, the hydrogen will appear to be transparent to visible light.
- Note: visible light can be absorbed when the atom is already in an excited state, but this is unlikely at room temperature.



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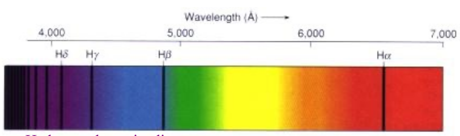
Emission in the laboratory allows ID via absorption in the universe.

Emission pattern of Hydrogen.
"Astronomy! A Brief Edition," J. B. Kaler, Addison-Wesley, 1997.



Hydrogen absorption lines.
"Astronomy! A Brief Edition," J. B. Kaler, Addison-Wesley, 1997.

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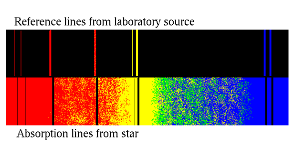
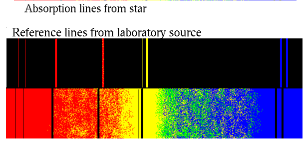
Absorption patterns. Make sure we consider the velocity of the emitter!



Star moving towards us.



Star moving away from us.

From: Davison E. Soper, Institute of Theoretical Science, University of Oregon, Eugene OR 97403 USA

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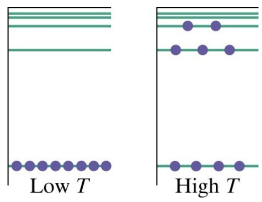
Absorption patterns. Temperature dependence.

- The absorption pattern depends on the population of states in the sample.
- Atoms with excited states populated are able to absorb lower-energy light (longer wavelength) since the energy spacing between atomic levels decreases with increasing energy.
- Since the population patterns depends on temperature, we expect to see a temperature dependence of the absorption spectrum.



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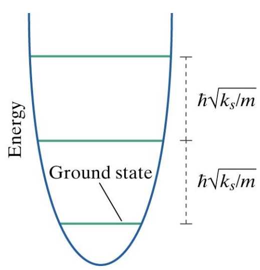
Other examples of quantization. The atomic model of matter.

- Although many properties of matter can be understood based on a simple "spring" model, others, such as thermal conduction, can not.
- In the classical "spring" model, the energy of the spring-mass system can have any value:

$$E = \frac{1}{2}k_s A^2$$

- In order to describe the thermal properties of matter we must incorporate the quantum nature of these oscillators in our model.



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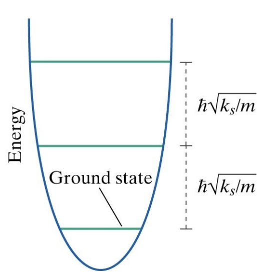
Other examples of quantization. The atomic model of matter.

- The effect of the quantum treatment of the oscillator is that the energy of the system is quantized.
- It turns out that in many cases a potential well consistent with the spring force is consistent with the observed atomic properties.
- The energy levels in this well are quantized and the spacing between the levels is

$$\Delta E = \frac{h}{2\pi}\sqrt{\frac{k_s}{m}} = \hbar\sqrt{\frac{k_s}{m}}$$

- One important consequence of this quantization is that atoms can only transfer energy to each other in discrete amounts.



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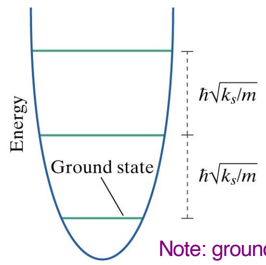
Position of the ground state.

- The ground state of the atom is not located at the bottom of the well.
- The energy of the ground state above the bottom of the well is half the level spacing:

$$E_0 = \frac{1}{2}\frac{h}{2\pi}\sqrt{\frac{k_s}{m}} = \frac{1}{2}\hbar\sqrt{\frac{k_s}{m}}$$

- This is a consequence of the uncertainly principle which will be discussed in Phy 143.



Note: ground state not at 0!

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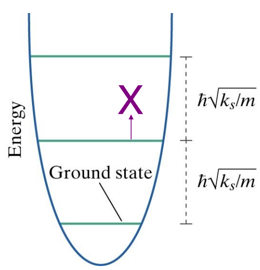
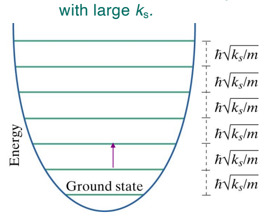
Other examples of quantization. The atomic model of matter: dependence on k_s.



Can be absorbed by atoms with small k_s, but not by atoms with large k_s.



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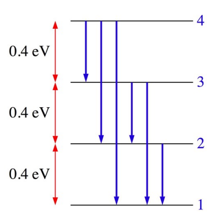
Example Problem.

- If you have a collection of quantum oscillators that occupy the lowest four energy levels, you expect to see the following emission pattern:
  - E_1 = 0.4 eV (2 to 1, 3 to 2, and 4 to 3).
  - E_2 = 0.8 eV (3 to 1, and 4 to 2).
  - E_3 = 1.2 eV (4 to 1).
- The intensity will be a strong function of the population pattern.
- The energy of the emitted photons allows us to probe the energy levels of the atom.



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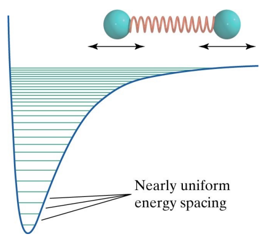
Other examples of quantization. Molecular vibrational energy.

- When we measure the vibrational energy levels for a two-atomic molecule we find that at low energies the vibrational model works fine (nearly uniform energy spacing).
- At higher energies, the potential well starts to deviate from a harmonic oscillator well, and the vibrational energy levels are no longer uniformly spaced.



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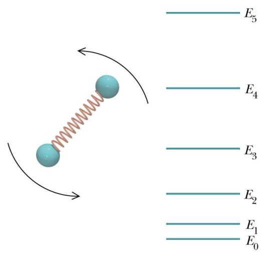
Other examples of quantization. Molecular rotational energy.

- Molecules can also carry rotational energy.
- The rotational energy of a molecule is also quantized, but the spacing between levels increases with increasing excitation energy.
- The rotational energy is found to be equal to

$$E_\ell = \frac{1}{2I}\ell(\ell+1)\hbar^2$$

where ℓ is an integer (0, 1, …) and I is the moment of inertia (depends on mass and shape).



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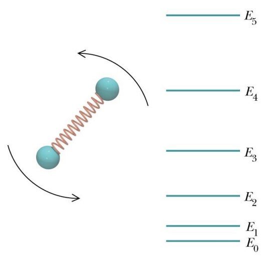
Other examples of quantization. Molecular rotational energy.

- When a molecule is in a rotational excited state, it will decay back to the ground state by gradually lowering its excitation energy.
- The transition energies expected to be seen are

$$\Delta E_{\ell\to\ell-1} = E_\ell - E_{\ell-1} =$$

$$= \frac{1}{2I}\{\ell(\ell+1) - (\ell-1)\ell\}\hbar^2 =$$

$$= \frac{\ell}{I}\hbar^2$$



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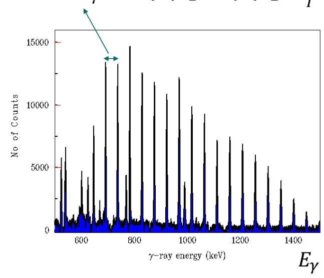
Nuclear energy levels.
The rotation of super-deformed nuclei.

$$\Delta E_\gamma = \Delta E_{\ell\to\ell-1} - \Delta E_{\ell\to\ell-2} = \frac{\ell}{I}\hbar^2 - \frac{\ell-1}{I}\hbar^2 = \frac{\hbar^2}{I}$$



The energy of the photons is consistent with the rotation of a super-deformed rigid object around its symmetry axis.

$$E_\gamma = E_{\ell\to\ell-1} = \frac{\ell}{I}\hbar^2$$

http://wnsl.physics.yale.edu/structure/research/highspin/sd.html

Different systems.
Different energies.

State	Energy level spacing (eV)
Hadronic	100,000,000
Nuclear	1,000,000
Atomic	1
Molecular (vibrational)	0.01
Molecular (rotational)	0.0001

Done for today!
Review of Exam # 2 on Thursday.

gammasphere