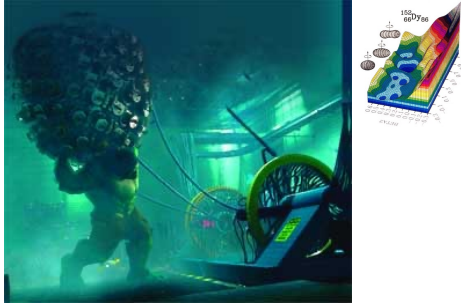


Physics 141.  
Lecture 12.



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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 10/13 at 12 pm.
  - No homework during the week of fall break.
  - Homework set 6 is due on Friday 11/3 at 12 pm.
- Laboratory:
  - Laboratory # 3 took place on Monday 10/9.
  - Laboratory # 3 office hours will be on Monday 10/23.
  - Laboratory # 3 report will be due on Friday 10/27 at noon.
- Next week:
  - No recitations.
  - Regular office hours on Wednesday, Thursday, and Friday to help you prepare for Exam # 2.
  - Review of the material covered on Exam # 2 on Thursday 10/19.

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## Chapter 8. Energy quantization.

- Until the early 20<sup>th</sup> 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 constrained by the electrostatic potential energy.

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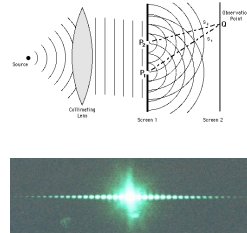
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## Quantization of light.

- 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  $hc/\lambda$ , where  $h$  is Planck's constant ( $= 6.6 \times 10^{-34}$  Js) and  $\lambda$  is the wavelength of the light.

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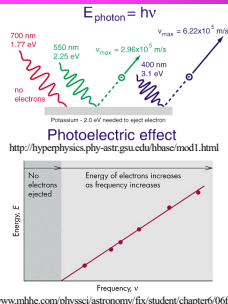
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## Quantization of light. The photoelectric effect.

- 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.



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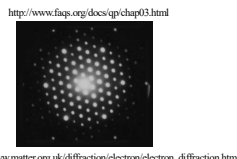
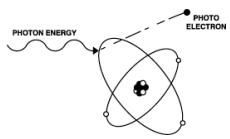
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## Quantization of light. The photoelectric effect.

- Einstein explained this effect by interpreting light as a collection of photons with discrete 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).



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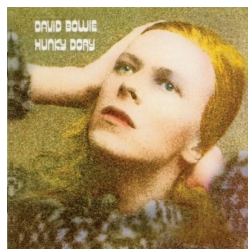
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## 3 Minute 40 Second Intermission (42 seconds more than during lecture 11).



- 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.



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## Quantization of light. Different wavelengths, different energies.

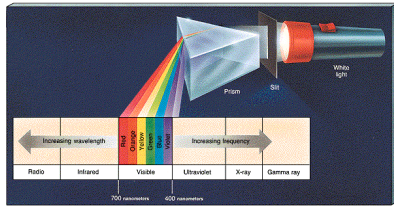


Figure: Chaisson and McMillan, *Astronomy today*

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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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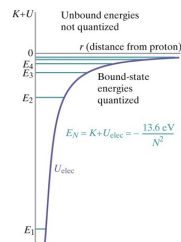
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## Energy quantization. Energy levels of hydrogen.

- 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 ( $N = 1, 2, \dots$ ).
- 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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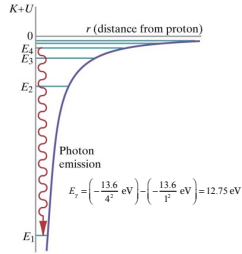
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## Quantization of light. Emission patterns.

- 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 (finger print) for the atom, and the emission pattern can be used to identify the atom(s).



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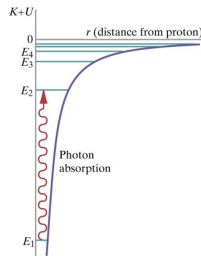
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## Quantization of light. Absorption patterns.

- 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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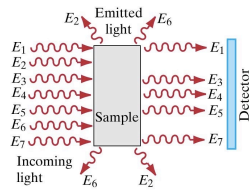
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## Quantization of light. Absorption patterns.

- 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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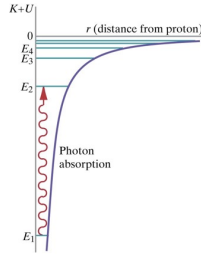
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## Quantization of light. Absorption patterns.

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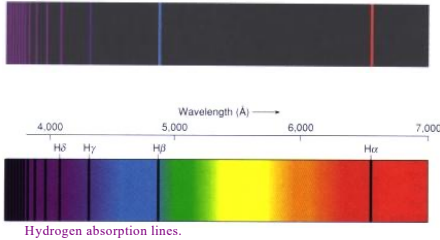
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## Emission in the laboratory allows ID via absorption in the universe.

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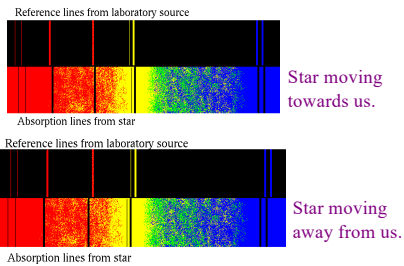
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## Absorption patterns. Make sure we consider the velocity of the emitter!



From: Davison E. Soper, Institute of Theoretical Science, University of Oregon, Eugene OR 97403 USA  
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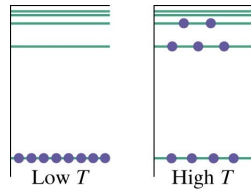
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## Absorption patterns. Temperature dependence.

- 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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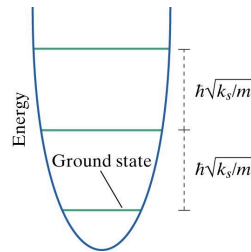
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## Other examples of quantization. The atomic model of matter.

- 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:
- $$E = (1/2)kx^2$$
- 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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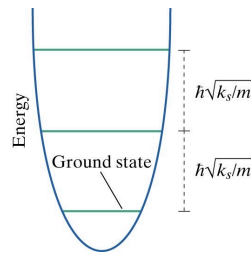
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## Other examples of quantization. The atomic model of matter.

- 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  $(h/2\pi)\sqrt{k_s/m}$ .
- One important consequence of this quantization is that atoms can only transfer energy to each other in discrete amounts.



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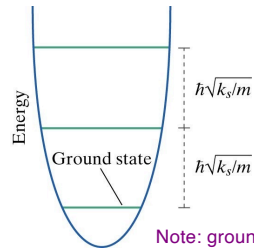
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## Position of the ground state.

- 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:

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

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



Note: ground state not at 0!

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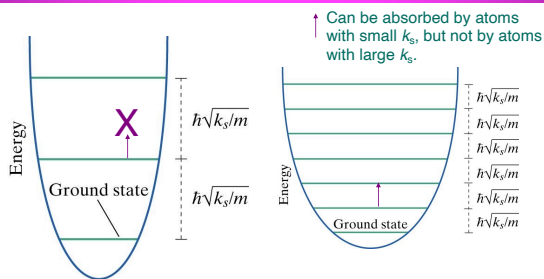
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## Other examples of quantization.

The atomic model of matter: dependence on  $k_s$ .



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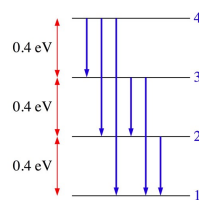
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## Example Problem.

- If you have a collection of quantum oscillators that occupy the lowest four energy levels, you expect to see the following emission pattern:

- $E_1 = 0.4 \text{ eV}$  (2 to 1, 3 to 2, and 4 to 3).
- $E_2 = 0.8 \text{ eV}$  (3 to 1, and 4 to 2).
- $E_3 = 1.2 \text{ eV}$  (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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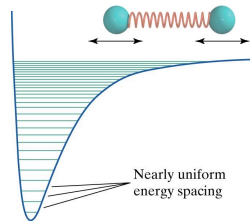
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### Other examples of quantization. Molecular vibrational energy.

- 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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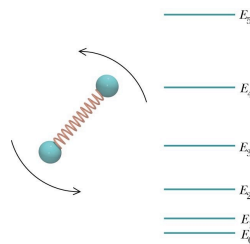
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### Other examples of quantization. Molecular rotational energy.

- 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  $\ell$  is an integer (0, 1, ... )  
and  $I$  is the moment of inertia  
(depends on mass and shape).



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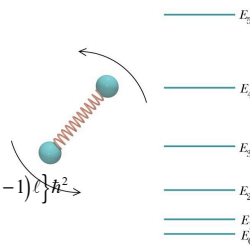
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### Other examples of quantization. Molecular rotational energy.

- 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

$$\begin{aligned} \Delta E_{\ell \rightarrow \ell-1} &= E_\ell - E_{\ell-1} \\ &= \frac{1}{2I} \{ \ell(\ell+1) - (\ell-1)\ell \} \hbar^2 \\ &= \frac{\ell}{I} \hbar^2 \end{aligned}$$



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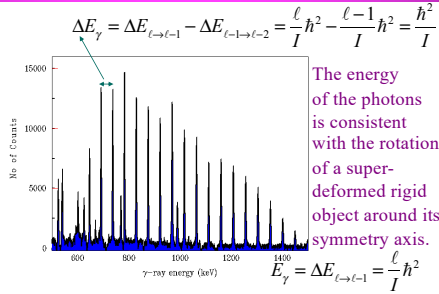
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## Nuclear energy levels. The rotation of super-deformed nuclei.



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

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Done for today!  
Have a great fall break!



*gammasphere*

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