# What I did on my Christmas vacation.

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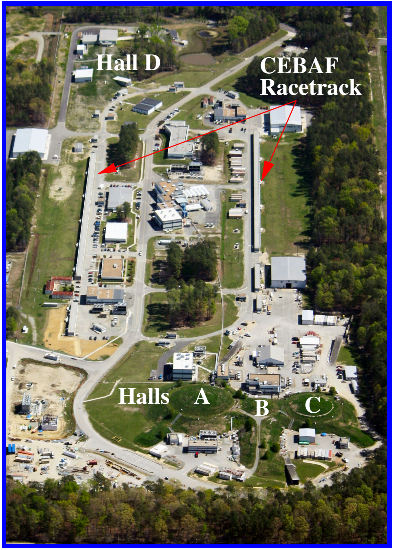

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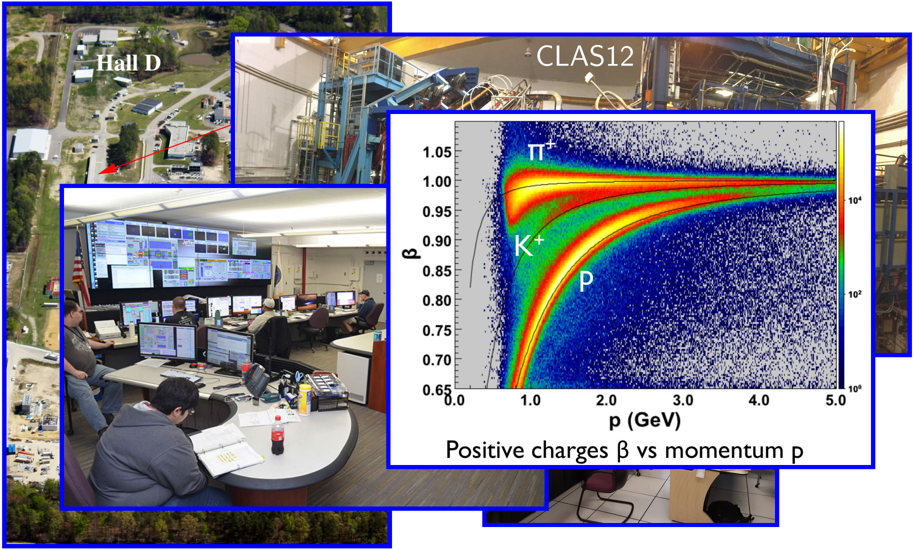

Positive charges β vs momentum p

# Welcome to Quantum Mechanics

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- "The most important fundamental laws and facts have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. ... Our future discoveries must be looked for in the sixth place of decimals."

  Albert A. Michelson (1894)

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- "I cannot seriously believe in the quantum theory..."

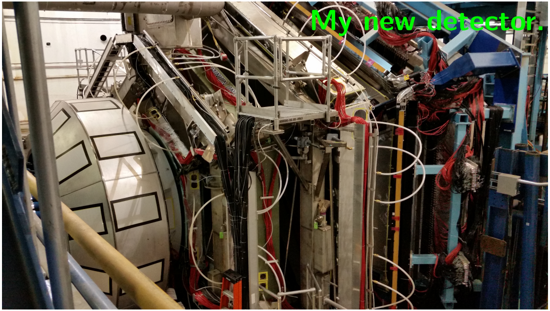
  Albert Einstein

- "The more success the quantum theory has the sillier it looks."

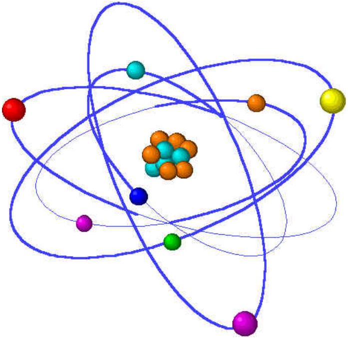
  Albert Einstein

# The Physics 309 Approach

1. Start with a detector and take some data.
2. Develop the quantum program.
3. Apply the quantum program.
4. What are the classical alternatives?



# The Spectral Lines Problem



← A toy atom.

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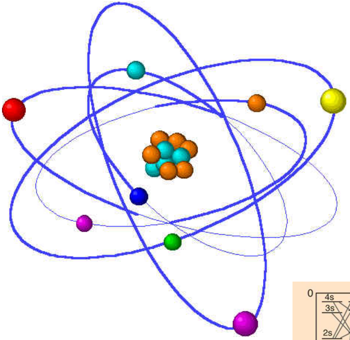

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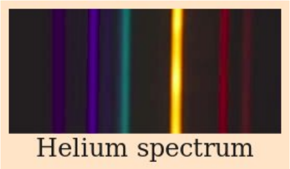

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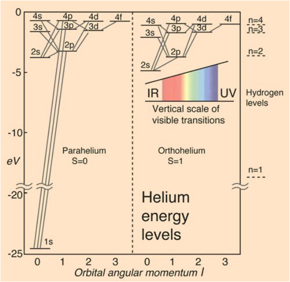
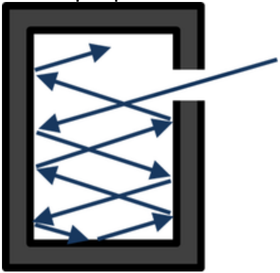


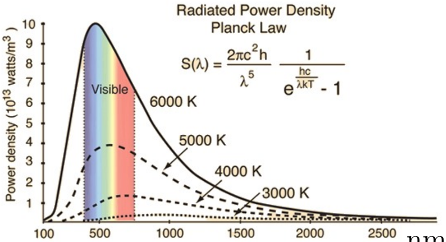
# Blackbody Radiation

A black body is an idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence. In thermal equilibrium (at a constant temperature) it emits electromagnetic radiation called black-body radiation with two notable properties.



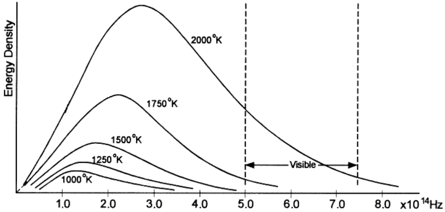
1. It is an ideal emitter: it emits as much or more energy at every frequency than any other body at the same temperature.
2. It is a diffuse emitter: the energy is radiated isotropically, independent of direction.

# Measuring The Blackbody Radiation



nm

Wavelength ($\lambda$)

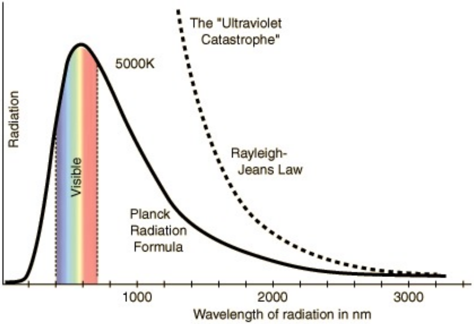


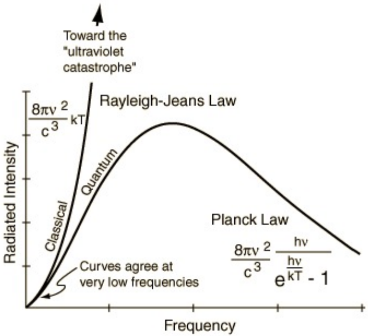
Frequency ($\nu$)

Measured by Lummer and Pringsheim (1899).

$$R_T(\nu)d\nu = \frac{\text{energy}}{\text{time-area}} \qquad \text{in the range } \nu \rightarrow \nu + d\nu$$

# The Ultraviolet Catastrophe



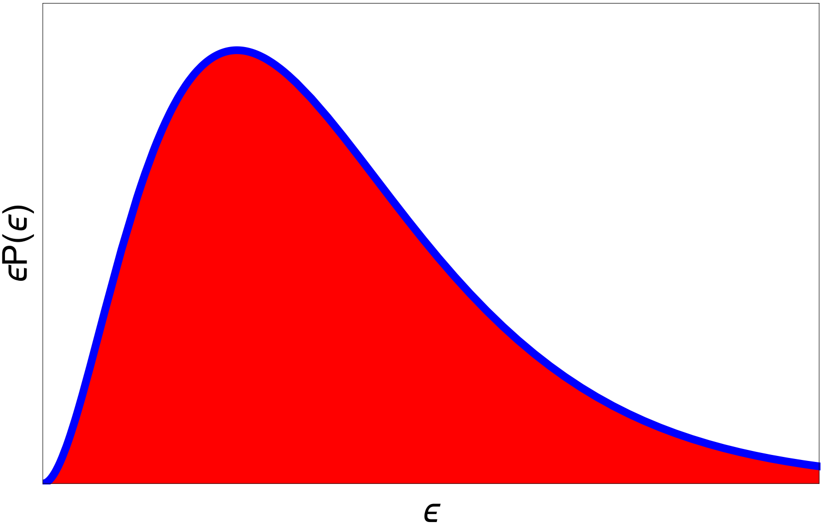


Rayleigh-Jeans Law

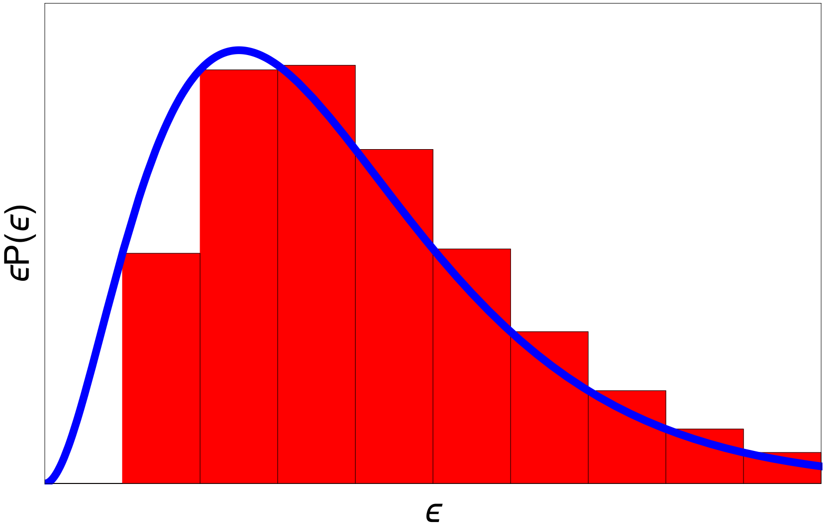
$$u(\nu)d\nu = \frac{8\pi}{c^3}k_B T\nu^2 d\nu \quad \text{in the range } \nu \rightarrow \nu + d\nu$$

$T$ - temperature. $k_B$ - Boltzmann constant.

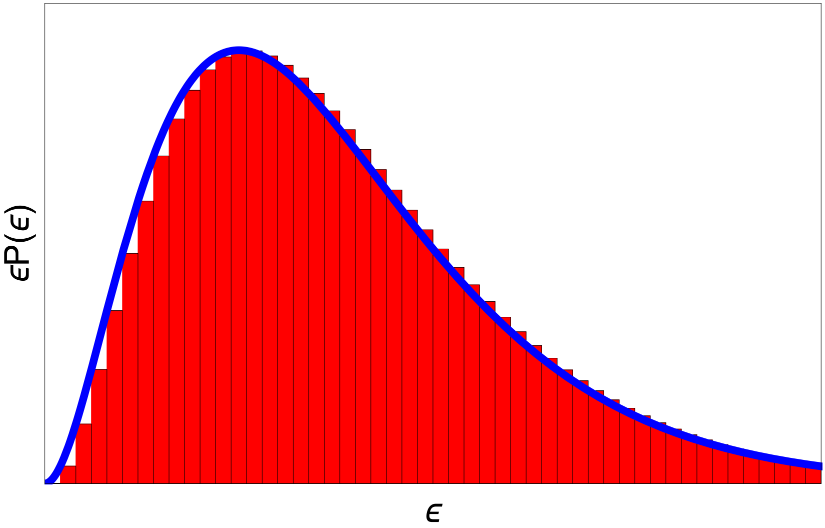
# Planck's Guess - the Boltzmann Distribution



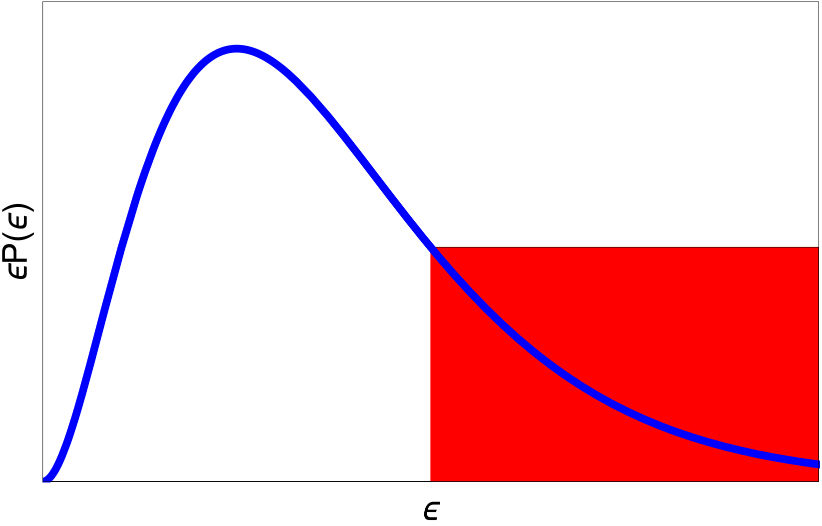
# Planck's Guess - Do a Riemannian Sum



# Planck's Guess - Do a Riemannian Sum (low $\nu$)



# Planck's Guess - Do a Riemannian Sum (high $\nu$)



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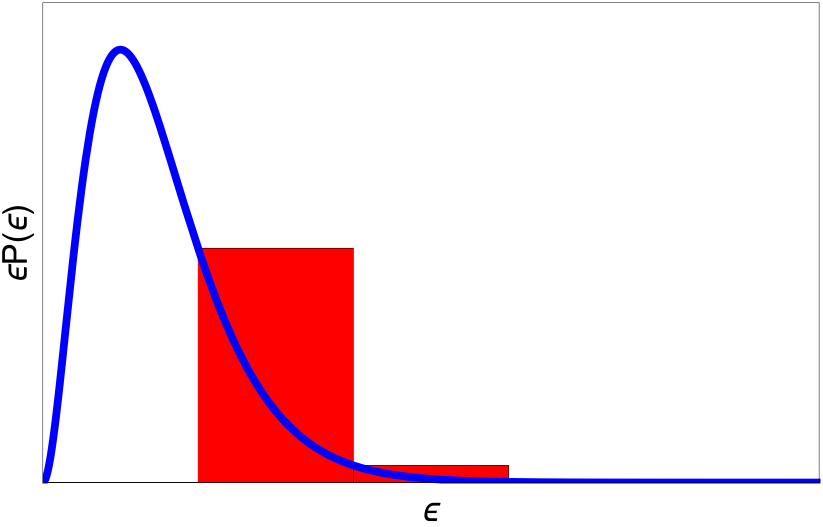

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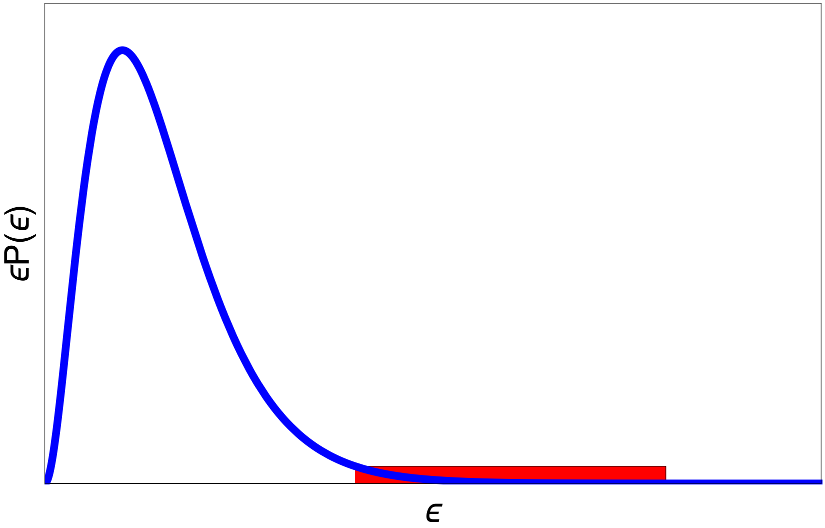
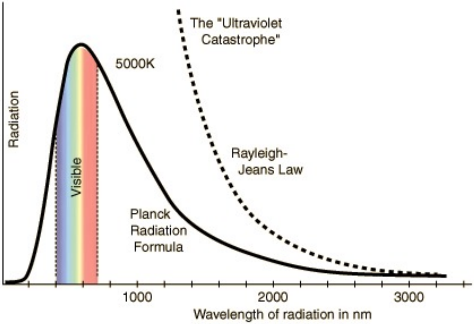
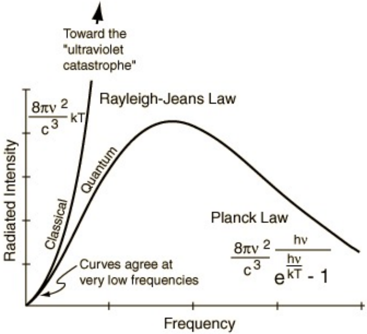


# The Ultraviolet Catastrophe





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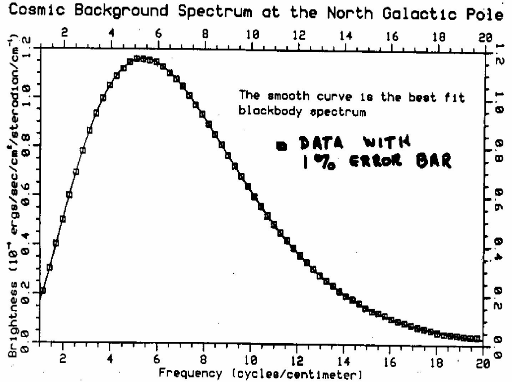
$T$ - temperature. $k_B$ - Boltzmann constant.

# The Blackbody Radiation



Scan of first showing of the COBE measurement of cosmic microwave background radiation at the American Astronomical Society meeting in January, 1990.

# The Blackbody Radiation

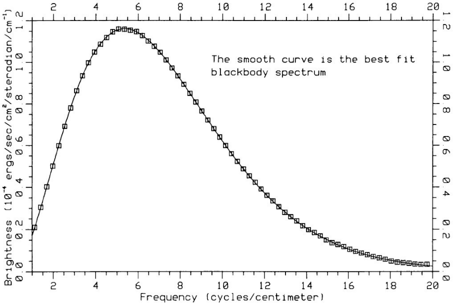


FIG. 2.—Preliminary spectrum of the cosmic microwave background from the FIRAS instrument at the north Galactic pole, compared to a blackbody. Boxes are measured points and show size of assumed 1% error band. The units for the vertical axis are $10^{-4}$ ergs $s^{-1}$ $cm^{-2}$ $sr^{-1}$ cm.

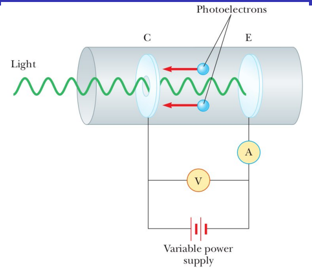
COBE measurement of the cosmic microwave background radiation from J.C Mather *et al.*, Astrophysical Journal **354**, L37-40 (1990).

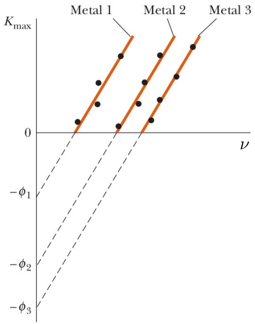
# The Photoelectric Effect

1. Shine a light on metal and eject electrons.
2. Classical physics predicts that any frequency/wavelength of light will work as long as the light is intense enough.
3. Measurements by Lennard and others show very different behavior including a linear dependence on frequency and a lower limit. No intensity dependence.
4. Einstein uses Planck's hypothesis to explain it with a simple equation invoking the quantum hypothesis

$$K_{max} = eV_{stop} = h\nu - \Phi$$

where $\Phi$ is the work function, $V_{stop}$ is the minimum voltage for zero current, $\nu$ is the frequency of the light, and $K_{max}$ is the maximum kinetic energy of the ejected electrons.





# Uncertainty

1. In classical mechanics there is no limitation on the accuracy of our ability to measure the position $\vec{r}(t)$ and velocity $\vec{v}(t)$ of a particle.
2. The only limitations are experimental ones which can be overcome (hopefully) with improvements in technology and technique.
3. In wave mechanics (and quantum mechanics) this is no longer true!
4. For the motion of a quantum particle in one dimension the Heisenberg Uncertainty Principle is a fundamental limit that cannot be overcome. It is

   $$\Delta x \Delta p_x \geq \frac{\hbar}{2}$$

   where $\hbar = h/2\pi$, $h$ is Planck's constant and the $\Delta$'s are the uncertainties.

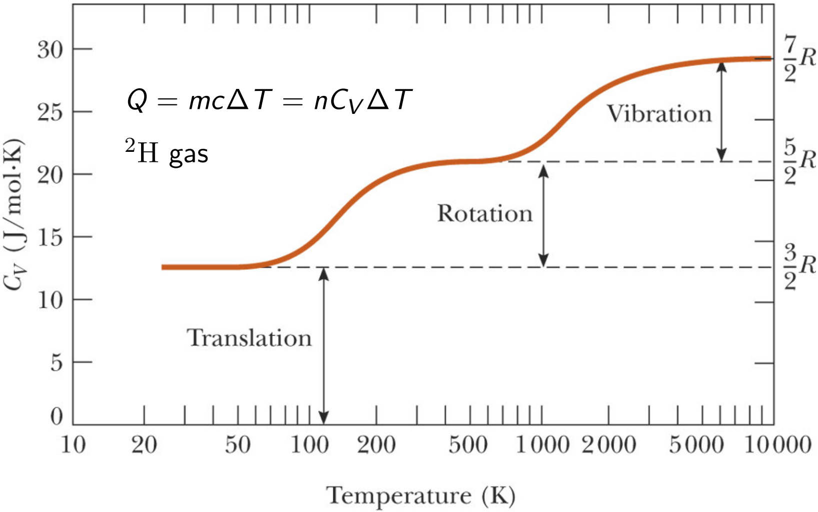
# A List of Mysteries (that Quanutm Mechanics Explained)

- Spectral lines
- Blackbody radiation
- Photoelectric effect
- Specific heat freeze-out
- Compton effect
- Davisson-Germer
- Radioactivity
- Atomic structure/nuclear physics

The current list:

`https://en.wikipedia.org/wiki/List_of_unsolved_problems_in_physics`

# The Specific Heat Freezeout Problem



$$Q = mc\Delta T = nC_V\Delta T$$

$^2$H gas

© 2006 Brooks/Cole - Thomson

# The Specific Heat

1. The Specific Heat

   $$Q = mc\Delta T = nC_V\Delta T \qquad \text{for gas in a fixed volume.}$$

2. The Kinetic Model of Ideal Gases
   1. The gas consists of a large number of small, mobile particles and their average separation is large.
   2. The particles obey Newton's Laws, but can be described statistically.
   3. The particles' collisions are elastic.
   4. The inter-particle forces are small until they collide.
   5. Gas is pure.
   6. Gas is in thermal equilibrium with the container walls.
3. $C_V = \frac{1}{2}N_{dof}R$ where $R$ is the gas constant.

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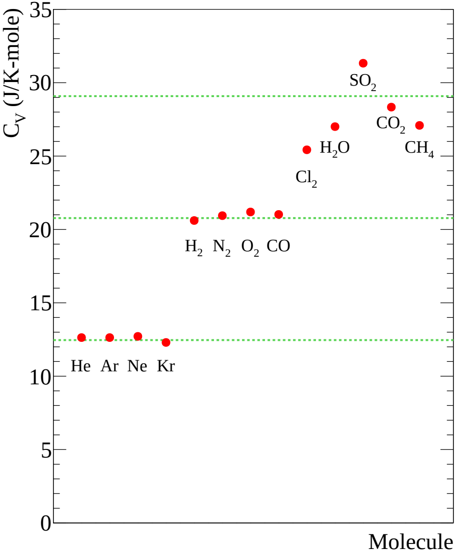
   Monatomic gas: $C_V = \frac{3}{2}R$. Diatomic gas: $C_V = \frac{8}{2}R = 4R$.

# Molar Specific Heat of Gases at Room Temperature



# Molar Specific Heat of Gases at Room Temperature

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where $R$ is the gas constant.

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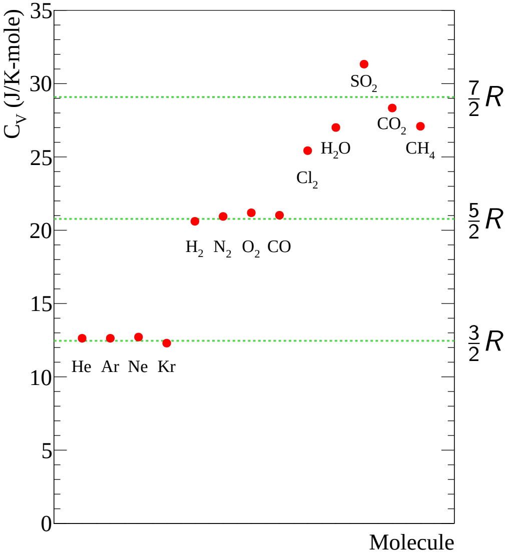
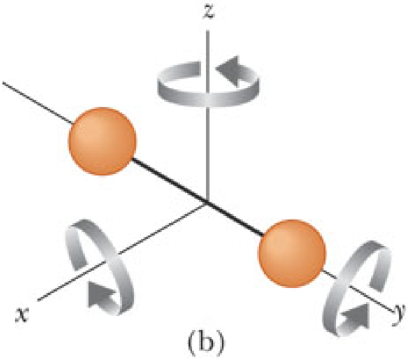
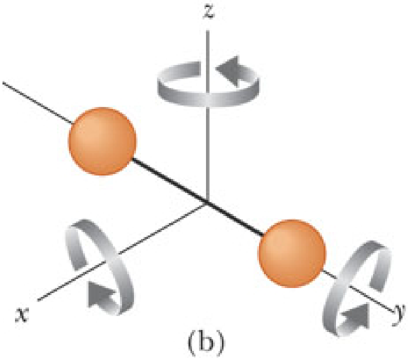


# Moment of Inertia Depends on Axis of Rotation



$$I = \sum m_i r_i^2 \rightarrow \int r^2 dm$$

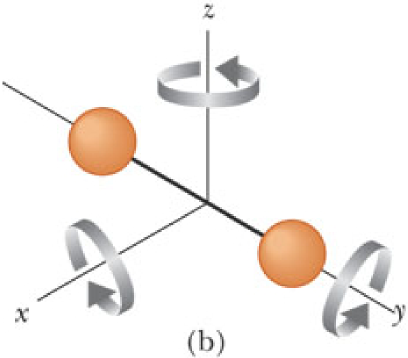
# Moment of Inertia Depends on Axis of Rotation



$$I = \sum m_i r_i^2 \rightarrow \int r^2 dm$$

$$I_x = I_z >> I_y$$

# Moment of Inertia Depends on Axis of Rotation



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$$E_{rot} = \frac{L^2}{2I}$$

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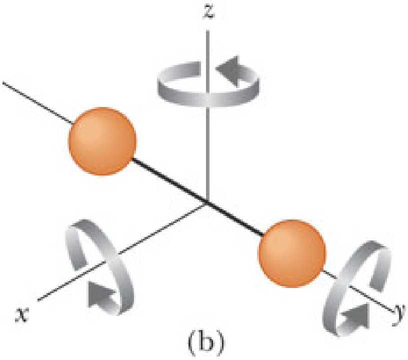


$$I = \sum m_i r_i^2 \rightarrow \int r^2 dm$$

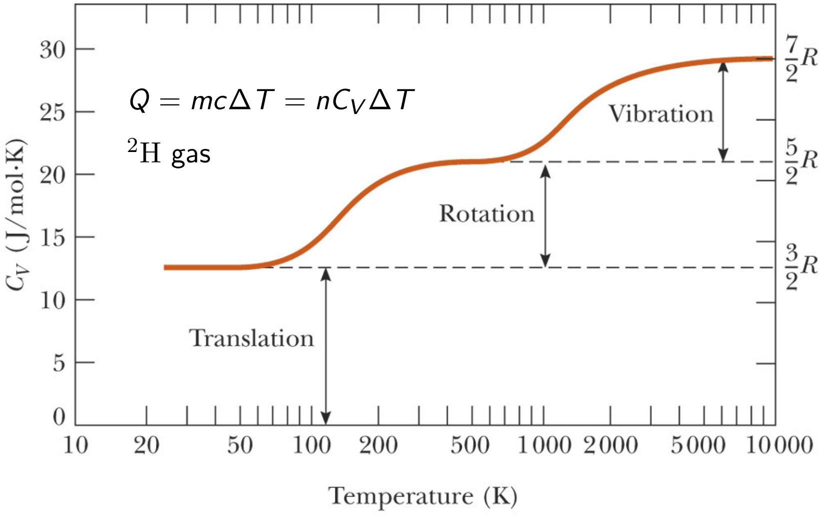
$$I_x = I_z >> I_y$$

$$E_{rot} = \frac{L^2}{2I}$$

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

$$l = 0, 1, 2, \ldots$$

# The Specific Heat Freeze-out of $H_2$



$$Q = mc\Delta T = nC_V\Delta T$$

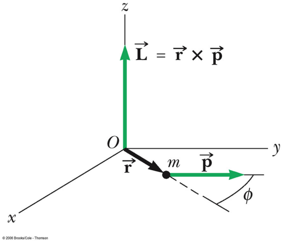
$^2H$ gas

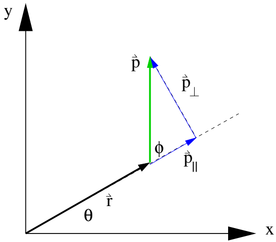
# Recall the Angular Momentum

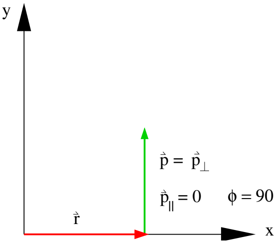
From Intro Physics and Classical Mechanics:

$$|\vec{L}| = L = \mu r^2 \dot{\theta} = \mu r(r\dot{\theta}) = \mu r v_T = r p_T = r p_\perp$$

$$\vec{L} = \vec{r} \times \vec{p}$$







# And the Moment of Inertia

From Intro Physics and Classical Mechanics:

$$I = \sum m_i r_i^2 \rightarrow \int r^2 dm$$

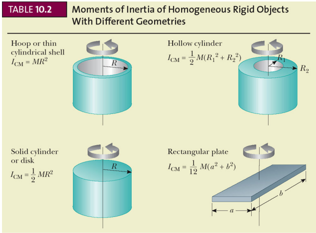


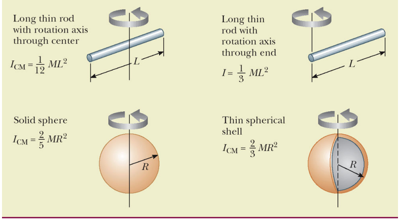
**TABLE 10.2** Moments of Inertia of Homogeneous Rigid Objects With Different Geometries

Hoop or thin cylindrical shell
$I_{CM} = MR^2$

Hollow cylinder
$I_{CM} = \frac{1}{2}M(R_1{}^2 + R_2{}^2)$

Solid cylinder or disk
$I_{CM} = \frac{1}{2}MR^2$

Rectangular plate
$I_{CM} = \frac{1}{12}M(a^2 + b^2)$



Long thin rod with rotation axis through center
$I_{CM} = \frac{1}{12}ML^2$

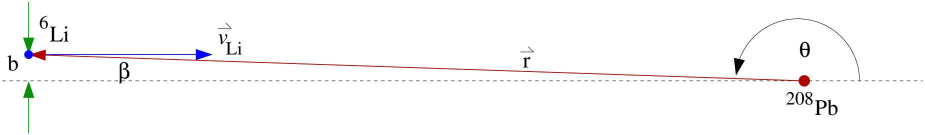
Long thin rod with rotation axis through end
$I = \frac{1}{3}ML^2$

Solid sphere
$I_{CM} = \frac{2}{5}MR^2$

Thin spherical shell
$I_{CM} = \frac{2}{3}MR^2$

# Angular Momentum from Classical Mechanics

Initial Rutherford scattering geometry



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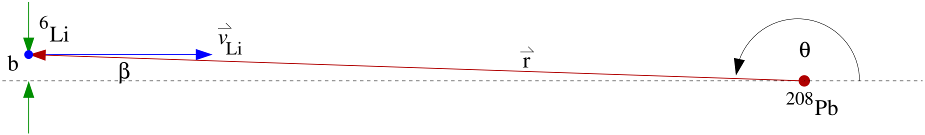
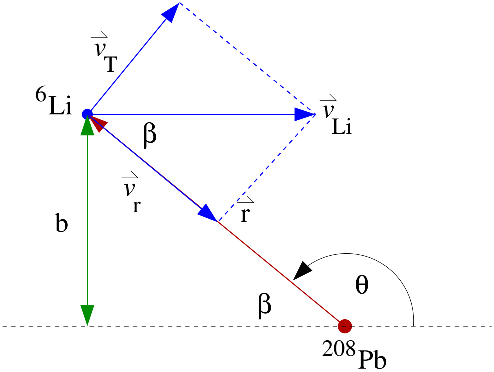


Re-scale it to see the angles better.

$$L = \mu r^2 \dot{\theta} = \mu r (r\dot{\theta}) = \mu r v_T$$



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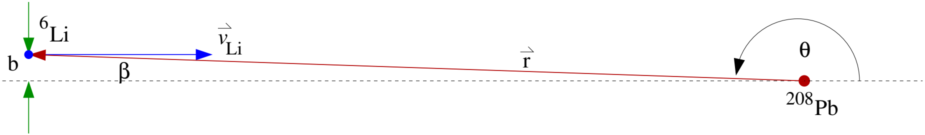
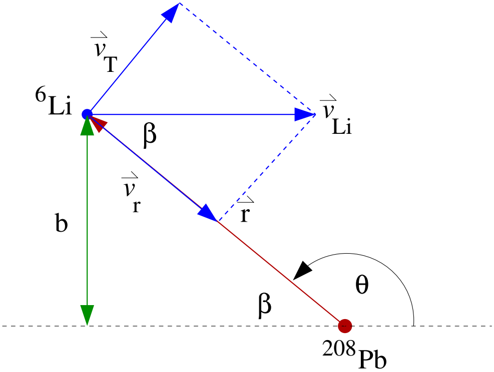


Re-scale it to see the angles better.

$$L = \mu r^2 \dot{\theta} = \mu r(r\dot{\theta}) = \mu r v_T$$
$$= \mu r v_{Li} \sin\beta$$



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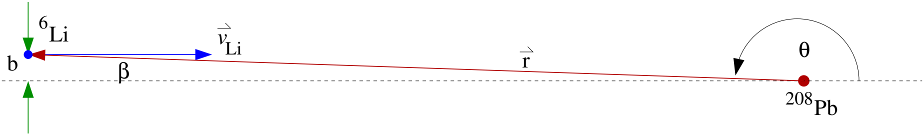

Re-scale it to see the angles better.

$$L = \mu r^2 \dot{\theta} = \mu r (r\dot{\theta}) = \mu r v_T$$
$$= \mu r v_{Li} \sin\beta = \mu v_{Li} b$$