PH100: Mechanics and Thermodynamics (3-1-0:4)

Lecture 1

Ajay Nath

Course Description and Objectives

This course provides engineering students with important foundational knowledge about mechanics, and thermodynamics and its application to common engineering systems. The course also includes weekly small-group problem-solving tutorial session.

On successful completion of this course, students should be able to:

1. demonstrate knowledge of the physical principles that describe mechanics, materials, heat transfer, and thermodynamics
2. apply physical principles to common physical systems
3. use the methods of algebra, vectors and calculus to make quantitative and qualitative predictions about the behavior of physical systems and
4. associate the correct unit with every physical quantity they use.

Syllabus

- **[A] Mechanics:**

- *Review of Newtonian Mechanics*- Vectors and their time derivatives, Inertial and non-inertial frames of reference, Centrifugal and Coriolis forces; Work-Energy Theorem; Conservation Principles, Collision problem in laboratory and centre of mass frame, Motion under Central Force and its universal features, Oscillatory Motion-Free, Damped and Driven.

- *Introduction to Quantum Mechanics*- Double-slit experiment, de Broglie's hypothesis. Uncertainty Principle, Wave-Function and Wave-Packets, Phase- and Group-velocities. Schrödinger Equation. Probabilities and Normalization. Expectation values. Eigenvalues and Eigenfunctions. Applications of Schrödinger Equation: Particle in a box, Finite Potential well, Harmonic oscillator, Hydrogen Atom problem.

[B] Thermodynamics:

Temperature and Zeroth Law of Thermodynamics, Work, Heat and First Law of Thermodynamics, Ideal Gas and Heat Capacities, Second Law of Thermodynamics, Carnot Cycle, Entropy, Thermodynamic variables and energies.

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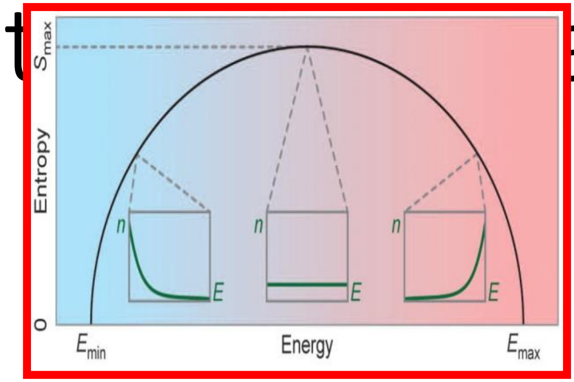
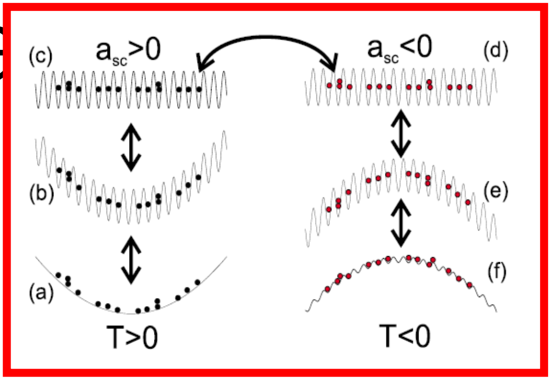
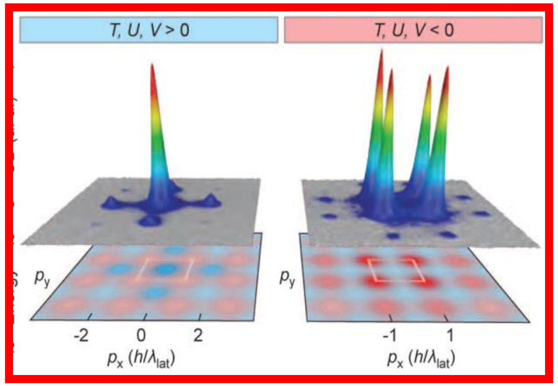


Science 339, 52 (2013)



Phys. Rev. Lett. 105, 220405 (2010)



Science 339, 52 (2013)

Negative Absolute Temperature for Motional Degrees of Freedom

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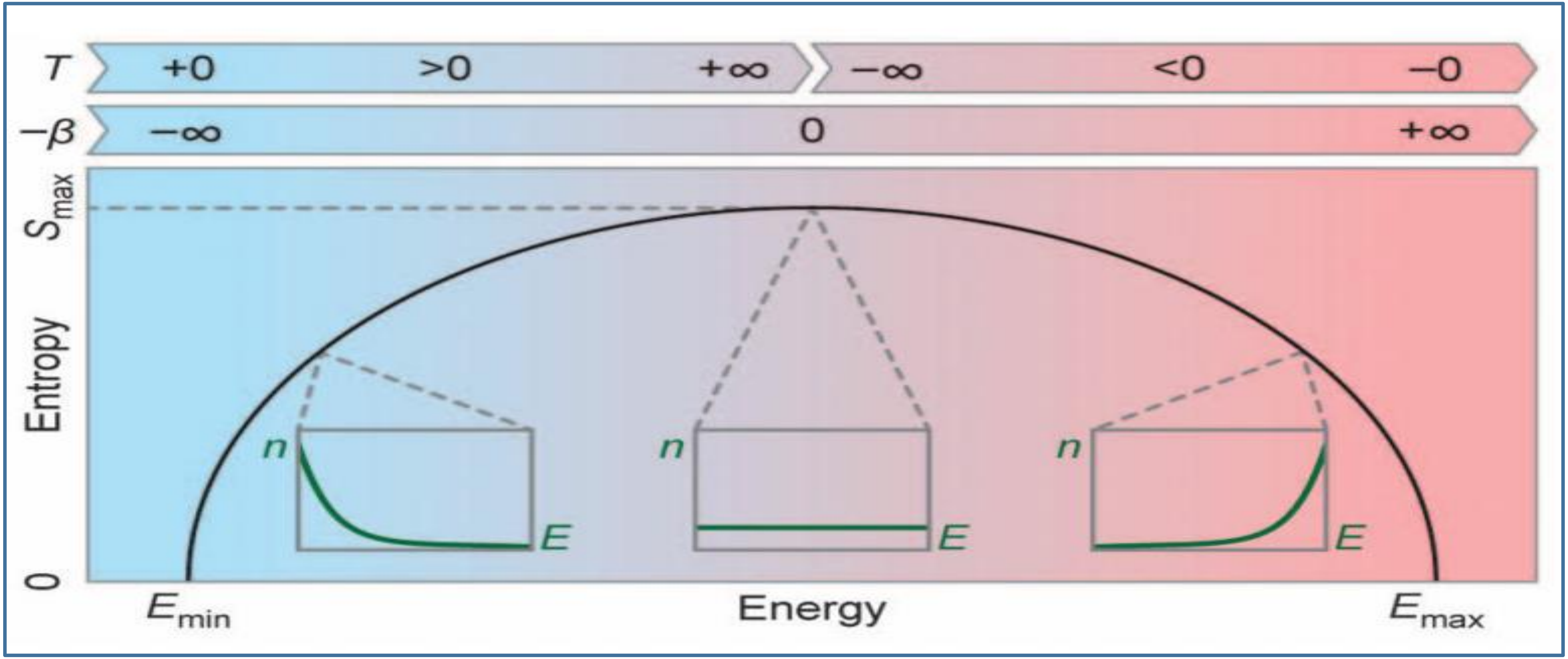
Absolute temperature is usually bound to be positive. Under special conditions, however, negative temperatures—in which high-energy states are more occupied than low-energy states—are also possible. Such states have been demonstrated in localized systems with finite, discrete spectra. Here, we prepared a negative temperature state for motional degrees of freedom. By tailoring the Bose-Hubbard Hamiltonian, we created an attractively interacting ensemble of ultracold bosons at negative temperature that is stable against collapse for arbitrary atom numbers. The quasimomentum distribution develops sharp peaks at the upper band edge, revealing thermal equilibrium and bosonic coherence over several lattice sites. Negative temperatures imply negative pressures and open up new parameter regimes for cold atoms, enabling fundamentally new many-body states.



$-\beta = -1/k_B T$

Books

An Introduction to Mechanics	D. Kleppner and R. Kolenkow, Second Edition
Concepts of Modern Physics	A. Beiser, Sixth Edition.
Heat and Thermodynamics	M. W. Zemansky and R. H. Dittman, Seventh Edition.

- The Feynman Lectures on Physics, Vol-I & III, Feynman, Leighton and Sands; Pearson Education.
- Introduction to Classical Mechanics, David Morin, Cambridge University Press, NY, 2007
- Berkeley Physics Course Vol 4: Quantum physics, Eyvind H. Wichmann, McGraw Hill, 1971.

- For the Love of Physics: From the End of the Rainbow to the Edge of Time - A Journey Through the Wonders of Physics, Walter Lewin, Warren Goldstein Taxmann Publications Private Limited
- Surely you're Joking Mr Feynman: Adventures of a Curious Character, Richard P Feynman RHUK (19 November 1992)

Tutorial

- The main purpose of the tutorial is to provide you with an opportunity to interact with a teacher.
- The teacher will assist you in clearing your doubts and answer your queries regarding the course topics.
- A problem sheet will be given to you for your practice. These problems also indicate the difficulty level of the examinations.
- Your are expected to attempt these problems before you come to tutorial class. Ask your doubts regarding these problems to your teacher during the tutorial class.
- The teacher may or may not solve all the problems in the tutorial class. In case you find a problem very difficult, do ask your teacher to help you.

Evaluation

End-semester:	45%
Mid-semester:	30%
Continuous Evaluation:	25% (includes two announced quizzes)

Vectors

- **Definition of vector:**

  A vector is defined by its invariance properties under certain operations --

- **Translation**
- **Rotation**
- **Inversion etc**

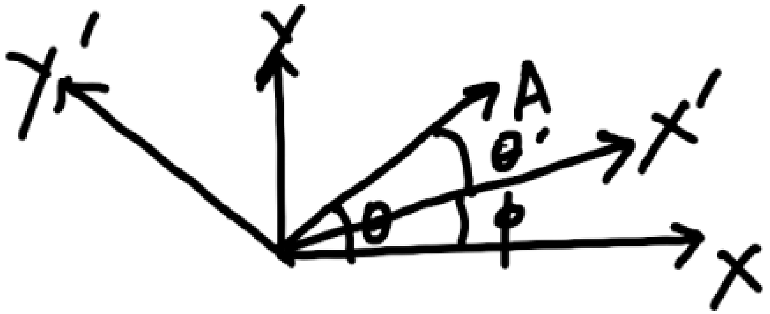
Invariance Under Rotation

$A_x = A\cos\theta$

$A_y = A\sin\theta$

$A_x' = A\cos\theta'$

$A_y' = A\sin\theta'$



$$A_x' = A\cos(\theta - \phi) = A\cos\theta\cos\phi + A\sin\theta\sin\phi$$

$$A_y' = A\sin(\theta - \phi) = A\sin\theta\cos\phi - A\cos\theta\sin\phi$$

Simplifying

$$A_x' = A_x\cos\phi + A_y\sin\phi$$

$$A_y' = -A_x\sin\phi + A_y\cos\phi$$

- **In a compact form**

$$\begin{pmatrix} A_x' \\ A_y' \end{pmatrix} = \begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix} \begin{pmatrix} A_x \\ A_y \end{pmatrix}$$

Transformation equations for the components of a vector can be written as,

$$\bar{A'} = R\bar{A}$$

GENERALISATION TO 3 DIMENSIONS

- Consider the Rotation Matrix in 3D,

$$R = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Rotation about *z*-axis by an angle θ

With the help of this we shall prove that $\vec{A} \times \vec{B}$ is a vector i.e. it is invariant under rotation.

- Since $\vec{A}$ is a vector its component transform as,

$$\begin{pmatrix} A'_x \\ A'_y \\ A'_z \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} A_x \\ A_y \\ A_z \end{pmatrix}$$

$A_x{}' = A_x\cos\theta + A_y\sin\theta$

$A_y{}' = - A_x\sin\theta + A_y\cos\theta$

$A_z{}' = A_z$

(because of rotation about ***z***-axis, the ***z***-component remains invariant.)

Similarly

$B_x' = B_x \cos\theta + B_y \sin\theta,$

$B_y' = - B_x \sin\theta + B_y \cos\theta$

$B_z' = B_z$

Now, consider the vector,

$$\bar{\mathbf{C}}' = \bar{\mathbf{A}}' \times \bar{\mathbf{B}}'$$

$$\bar{A}' \times \bar{B}' = (\bar{A}' \times \bar{B}')_x + (\bar{A}' \times \bar{B}')_y + (\bar{A}' \times \bar{B}')_z$$

Consider only x- component (for a moment)

$$\overrightarrow{(A \times B)}_X = (-\sin\theta A_x + \cos\theta A_y)B_Z' - (-\sin\theta B_x + \cos\theta B_y) A_Z'$$

Since $A_Z' = A_Z$

$B_Z' = B_Z$

$$\overrightarrow{(A \times B)}_X = \sin\theta(B_x A_z - A_x B_z) + \cos\theta(A_y B_z - B_y A_z)$$

$$\overrightarrow{(A' \times B')}_X = R_x \overrightarrow{(A \times B)}_X$$

Similarly we can prove it for the other components also.

$$\overrightarrow{(A' \times B')}_y = R_y \overrightarrow{(A \times B)}_y ; \overrightarrow{(A' \times B')}_z = R_z \overrightarrow{(A \times B)}_z$$

Hence, $\overrightarrow{(A \times B)}$ is invariant under rotation and transforms like a vector.

Vector Calculus

- Gradient: To know the direction along which a scalar function changes the fastest
- $\varphi(x, y, z)$ is scalar function in cartesian coordinates

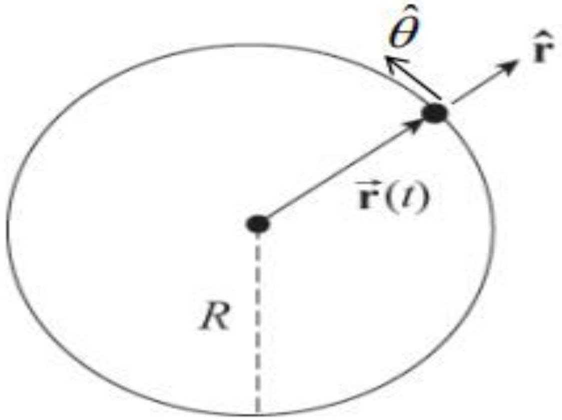
$$\bar{\nabla}\Phi = \hat{x}\frac{\partial \Phi}{\partial x} + \hat{y}\frac{\partial \Phi}{\partial y} + \hat{z}\frac{\partial \Phi}{\partial z}$$

Gradient operator

$$\bar{\nabla} = \hat{x}\frac{\partial}{\partial x} + \hat{y}\frac{\partial}{\partial y} + \hat{z}\frac{\partial}{\partial z}$$

Find $\bar{\nabla}\varphi$ for $\varphi(x, y, z) = r = \sqrt{x^2 + y^2 + z^2}$

Example-1: Uniform Circular Motion



$$\vec{\mathbf{r}}(t) = R\hat{\mathbf{r}}$$

$$\vec{v} = \dot{r}\hat{r} + r\dot{\theta}\hat{\theta}$$

Since $\dot{r} = \dfrac{dR}{dt} = 0$ and $\omega = \dfrac{d\theta}{dt} = \dot{\theta}$

$$\vec{\mathbf{v}}(t) = R\frac{d\theta}{dt}\hat{\boldsymbol{\theta}}(t) = R\,\omega\,\hat{\boldsymbol{\theta}}(t)$$

Since $\vec{v}$ is along $\hat{\theta}$ it must be perpendicular to the radius vector $\vec{r}$ and it can be shown easily

$$R^2 = \vec{\mathbf{r}} \cdot \vec{\mathbf{r}} \qquad \frac{d}{dt}R^2 = \frac{d}{dt}(\vec{\mathbf{r}} \cdot \vec{\mathbf{r}}) = 2\vec{\mathbf{r}} \cdot \vec{\mathbf{v}} = 0, \qquad \vec{\mathbf{r}} \perp \vec{\mathbf{v}}$$