

Physics GRE Summary

October 18, 2011

General Tips

- Pick moderate statements. Extreme statements are usually wrong.
- Use Taylor expansion to deal with extreme cases, e.g. $h\nu \ll kT$, $e^{h\nu/kT} \approx 1 + \frac{h\nu}{kT}$.
- When knowing L^2 value, be careful to calculate l from $\hbar^2 l(l+1)$, two solutions.
- Conservation of momentum (including angular momentum) should be checked before conservation of energy.
- Be careful about dimension of the problem, e.g. in 3D, radial wave, $P = \int |\psi|^2 d\vec{r} = \int |\psi|^2 4\pi r^2 dr$
- Read underlined words carefully.
- Calculate T^4 carefully.
- Don't think too hard, the questions are easy enough to be solved in 2 minutes.
- Use method of elimination.
- Dimensional analysis is always useful.
- Usually order of magnitude calculation is good enough.
- In general, $F = -\nabla(\text{potential energy})$, but in E&M notice V stands for potential, not potential energy, so $F = -\nabla(q \cdot \text{potential})$
- Usually it is convenient to set $h = \hbar = c = \dots = 1$, but if ans differs from choices, that's a signal we need to keep them.
- When you get stuck, take limits
- If some experimenter is involved in the question, it is usually a failed experiment.
- **Things to work on**

1 Classical Mechanics

- A worked example on velocity and acceleration in a curved path in a a plane: (the idea is to skillfully use $d(AB) = AdB + BdA$. This applies to change of momentum as well.)

$$\hat{r} = \hat{i} \cos \theta + \hat{j} \sin \theta, \quad \hat{\theta} = -\hat{i} \sin \theta + \hat{j} \cos \theta$$

$$\hat{v} = \frac{d(R\hat{r})}{dt} = \frac{dR}{dt} \hat{r} + R \frac{d\hat{r}}{dt} = \dot{R} \hat{r} + R\omega \hat{\theta}$$

Similarly,

$$\vec{a} = (\ddot{R} - R\omega^2) \hat{r} + (R\ddot{\theta} + 2\dot{R}\dot{\theta}) \hat{\theta}$$

- Firing rocket

$$(v_g - v)dM + d(MV) = 0$$

M is rocket mass, v is speed, v_g is relative speed of the waste fired out.

- Bernoulli's equation

$$P + \frac{1}{2}\rho v^2 + \rho gy = \text{const}$$

(conservation of energy)

- Torricelli's Theorem: The outlet speed is the free-fall speed. For a barrel with water depth d , an outlet at base has horizontal flow speed $v = \sqrt{2gd}$.
- Stoke's law: viscous drag is $6\pi\eta r_s v$.

- Poiseille's Law:

$$\Delta P = \frac{8\mu L Q}{\pi r^4}$$

where L is length of tube, Q is volume rate. This describes viscous incompressible flow through a constant circular cross-section.

- Kepler's laws.

- An orbiting body travels in an ellipse

$$r(\theta) = \frac{a(1 - e^2)}{1 + e \cos \theta}$$

- “A line joining a planet and the Sun sweeps out equal areas during equal intervals of time.”

$$\frac{d}{dt} \left(\frac{1}{2} r^2 \dot{\theta} \right) = 0$$

or

$$\frac{dA}{dt} = \frac{1}{2} r^2 \dot{\theta} = \text{constant}$$

- “The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit.”

$$P = \frac{A}{dA/dt} = 2\sqrt{\frac{\mu}{R}} R^{3/2} \quad P^2 \propto R^3$$

or

$$\frac{P^2}{a^3} = \frac{4\pi^2}{MG}$$

- Coriolis force:

$$\vec{F} = -2m(\vec{\omega} \times \vec{v})$$

- Diffusion: Fick's law. The diffusion flux is given by

$$\vec{J}_r = -D\nabla_n \phi$$

- Frequency of a pendulum of arbitrary shape:

$$\omega = \sqrt{\frac{mgL}{I}} \quad T = 2\pi\sqrt{\frac{I}{mgL}}$$

where L is the distance between the axis of rotation and the center of mass.

- Hamiltonian formulation:

$$\mathcal{H} = \sum_i p_i \dot{q}_i - \mathcal{L}, \quad \dot{p} = -\frac{\partial \mathcal{H}}{\partial q}, \quad \dot{q} = \frac{\partial \mathcal{H}}{\partial p}$$

- Circular orbits exist for almost all potentials. Stable non-circular orbits can occur for the simple harmonic potential and the inverse square law.
- Orbit questions:

$$V_{\text{eff}}(r) = V(r) + \frac{L^2}{2mr^2}$$

For a gravitational potential, $V(r) \propto \frac{1}{r}$. The total energy of an object

$$E = \frac{1}{2}mv^2 + V_{\text{eff}}$$

$E < V_{\text{min}}$ gives a spiral orbit, $E = V_{\text{min}}$ gives a circular orbit, $V_{\text{min}} < E < 0$ gives an ellipse, $E = 0$ is a parabolic orbit, and $E > 0$ has a hyperbolic orbit.

- If we want to approximate the equation of motion as a small oscillation about a point of equilibrium $V'(x_0) = 0$ we can Taylor expand to get

$$V(x) = V(x_0) + \frac{1}{2}V''(x_0)(x - x_0)^2$$

and then get the force

$$F = -\frac{dV}{dx} = -V''(x_0)(x - x_0)$$

so that we can approximate small oscillations has harmonic oscillations with $k = V''(x_0)$ and

$$\omega = \sqrt{\frac{V''(x_0)}{m}}.$$

2 Electromagnetism

- Resistance is defined in terms of resistivity as

$$R = \frac{\rho L}{A}$$

- Faraday's laws of electrolysis

- The mass liberated \propto charge passed through
- Mass of different elements liberated \propto atomic weight/valence

$$m = \frac{QA}{Fv}$$

where v is valence, A is atomic weight in kg/kmol, $F = 9.65 \times 10^7 \text{C/kmol}$ (Faraday's constant)

- Parallel plate capacitor $C = \epsilon_0 A/d$ or $\epsilon A/d$ for a dielectric. For a spherical capacitor,

$$C = \frac{4\pi\epsilon_0 ab}{a - b}$$

- In charging a capacitor,

$$q = q_0(1 - e^{-t/RC})$$

discharging

$$q = q_0 e^{-t/RC}$$

- Cyclotron/magnetic bending

$$r = \frac{mv}{qB}$$

- Torque experienced by a planar coil of N loops, with current I in each loop.

$$\tau = NIAB \sin \theta$$

where θ is the angle between B and line perpendicular to coil plane:

$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

- B -field of a long wire

$$B = \frac{\mu_0 I}{2\pi r}$$

Center of a ring wire

$$B = \frac{\mu_0 I}{2r}$$

Long solenoid

$$B = \mu_0 n I$$

where n is the turn density.

- Ampere's Law:

$$\oint \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 I_{\text{enc}}$$

- Conductors do not transmit EM wave, thus \vec{E} vector is reversed upon reflecting, B vector is increased by a factor of 2 (by solving propagation of EM wave).

- Magnetic fields in matter:

$$B = \mu H = \mu_0(H + M) = \mu_0(H + \chi_m H)$$

Diamagnetic $\leftrightarrow \chi_m$ very small and negative. Paramagnetic, $\leftrightarrow \chi_m$ small and positive, inversely proportional to the absolute temperature. Ferromagnetic $\leftrightarrow \chi_m$ positive, can be greater than 1. M is no longer proportional to H .

- For solenoid and toroid, $H = nI$, n is the number density.

- Self inductance:

$$\mathcal{E} = -L \frac{di}{dt}$$

L is in henries, $1H = 1V \cdot S/A = 1J/A^2 = 1 \text{ web}/A$

$$N\Phi = LI$$

is the flux linkage. Inductance of solenoid:

$$L = \frac{\mu N^2 A}{c}$$

- Induced e.m.f

$$|\mathcal{E}_s| = N \left| \frac{d\Phi_B}{dt} \right|$$

- Time constant for $R - L$ circuit $t = L/R$. For an $R - C$ constant $t = RC$. For an $L - C$ circuit, $\omega_0 = 1/\sqrt{LC}$.

- $X_L = 2\pi fL$ is the inductive reactance. $X_C = 1/2\pi fC$ is the capacitive reactance. The impedance is given by

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \quad \text{series}$$

$$\frac{1}{Z} = \left[\left(\frac{1}{R} \right)^2 + \left(\frac{1}{X_C} - \frac{1}{X_L} \right)^2 \right]^{1/2} \quad \text{parallel}$$

Current is maximized at resonance $X_L = \omega L = X_C = 1/\omega C$ (there will be a lot of questions on this)

- Larmor formula for radiation

$$P = \frac{\mu_0 q^2 a^2}{6\pi c} \propto q^2 a^2$$

where a is the acceleration. Energy per unit area decreases as distance increases (inverse square relation).

- Mean drift speed:

$$\vec{v} = \frac{\vec{J}}{ne}$$

where n is the number of atoms per volume, J is current density I/A .

- Impedance of capacitor

$$Z = \frac{1}{i\omega C}$$

Impedance of inductor

$$Z = i\omega L$$

- Magnetic field on axis of a circle of current

$$B = \frac{\mu_0 I}{2} \frac{r^2}{(r^2 + z^2)^{3/2}}$$

- Bremsstrahlung: electromagnetic radiation produced by the deceleration of a charged particle.
- For incident wave reflecting off a plane, just set up a boundary value problem.

$$E_1^\perp - E_2^\perp = \sigma \quad E_1^\parallel = E_2^\parallel$$

and remember the Poynting vector

$$\vec{S} \propto \vec{E} \times \vec{B}$$

points in the direction of propagation.

$$E_0 + E_0^{\text{reflected}} = E_0^{\text{transmitted}}$$

- Lenz's law: The idea is the system responds in a way to restore or at least attempt to restore to the original state.
- Impedance matching to maximize power transfer or to prevent terminal-end reflection.

$$Z_{\text{rad}} = Z_{\text{source}}^*$$

$$I(X_g) + I(X_L) = IR$$

Generator impedance:

$$R_g + jX_g$$

Local impedance:

$$R_L + jX_L$$

$$Z = R + j(\omega L + 1/\omega C)$$

- Propagation vector \vec{k}

$$\vec{E}(\vec{r}, t) = \vec{E}_0 e^{i(\vec{k} \cdot \vec{r} - \omega t)}$$

$$\vec{B}(\vec{r}, t) = \frac{1}{c} |\vec{E}(\vec{r}, t)|$$

$$(\hat{k} \times \hat{n}) = \frac{1}{c} \hat{k} \times \hat{E}$$

- No electric field inside a constant potential enclosure implies constant V inside.
- Hall effect

$$R_H = \frac{1}{(p - n)e}$$

can be used to test the nature of charge carrier. p for positive, n for negative.

- Lorentz force

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

- $\nabla \cdot (\nabla \times \vec{H}) = 0$, $\nabla \times (\nabla f) = 0$
- One usually has cycloid motion whenever the electric and magnetic fields are perpendicular.
- Faraday's law:

$$\mathcal{E} = \vec{E} \cdot d\vec{L} = -\frac{d\Phi}{dt}$$

- Visible spectrum in meters: Radio 10^3 (on the order of buildings); Microwave 10^{-2} ; Infrared 10^{-5} ; visible 700-900 nm (10^{-6}); UV 10^{-8} (molecules); X-ray 10^{-10} (atoms); gamma ray 10^{-12} (nuclei)
- Displacement field

$$\vec{D} = \epsilon_0 \vec{E} + \vec{P} = \epsilon_0 \vec{E} + \epsilon_0 \chi_e \vec{E} = \epsilon_0 (1 + \chi_e) \vec{E} = \epsilon \vec{E}$$

Dielectric constant

$$\epsilon_r = 1 + \chi_e = \frac{\epsilon}{\epsilon_0}$$

$$\sigma_b = \vec{P} \cdot \vec{n}$$

$$\rho_b = -\vec{\nabla} \cdot \vec{P}$$

These are the bound charge densities. Also note

$$\nabla \times \vec{D} = \nabla \times \vec{P}$$

is not necessarily zero.

- We have

$$\vec{B} = \begin{cases} \mu_0 n I \hat{z} & \text{inside a solenoid} \\ 0 & \text{outside a solenoid} \end{cases}$$

where n is density per length.

$$\vec{B} = \begin{cases} \frac{\mu_0 n I}{2\pi s} \hat{\phi} & \text{inside a toroid} \\ 0 & \text{outside} \end{cases}$$

- Force per unit length between two wires:

$$f = \frac{\mu_0}{2\pi} \frac{I_1 I_2}{d}$$

- $B = \frac{\mu_0 I}{4\pi s} (\sin \theta_2 - \sin \theta_1)$ looks like the magnetic field due to a segment of wire, where θ_i is the angle from the normal.

- Mutual inductance of two loops

$$M_{21} = \frac{\mu_0}{4\pi} \oint \oint \frac{d\vec{l}_1 \cdot d\vec{l}_2}{r_{ij}}$$

- Radiation pressure

$$P = \frac{I}{c} = \frac{\langle S \rangle}{c} \cos \theta$$

It's twice that for a perfect reflector.

- $\nabla \cdot \vec{D} = \rho_f$, $\nabla \times \vec{H} = \vec{J}_f + \frac{\partial \vec{D}}{\partial t}$, $\nabla \cdot \vec{B} = 0$, $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$.

- Boundary conditions:

$$\begin{aligned} \epsilon_1 \vec{E}_1^\perp - \epsilon_2 \vec{E}_2^\perp &= \sigma_f & \vec{B}_1^\perp - \vec{B}_2^\perp &= 0 \\ \vec{E}_1^\parallel - \vec{E}_2^\parallel &= 0, & \mu_1 \vec{B}_1^\parallel - \mu_2 \vec{B}_2^\parallel &= \vec{k}_f \times \hat{n} \end{aligned}$$

- Biot-Savart law:

$$\vec{B}(\vec{r}) = \frac{\mu_0 I}{4\pi} \int \frac{d\vec{l} \times \vec{r}}{|\vec{r}|^3}$$

- B -field at a center of a ring

$$\vec{B} = \frac{\mu_0 I}{2r}$$

- $H = \frac{1}{\mu_0} B - M$, $J_b = \nabla \times \vec{M}$, $\vec{k}_b = \vec{M} \times \hat{n}$

$$\vec{B} = \mu \vec{H}, \quad \mu = \mu_0(1 + \chi_m)$$

3 Optics and Wave Phenomena

- Speed of propagation for waves

- Transverse on string, $v = \sqrt{T/\rho}$
- Longitudinal in liquid, $v = \sqrt{B/\rho}$, B is bulk modulus
- Longitudinal in solid, $v = \sqrt{Y/\rho}$, Y is Young's modulus
- Longitudinal in gases, $v = \sqrt{\gamma P/\rho}$

- For open pipe, fundamental frequency is $v/2L$ where v is the speed of sound. For a closed pipe it is $(2n - 1)\lambda/4 = L$. The idea is $\lambda f = v$.

- Speed of sound in air is

$$v = \sqrt{\frac{\gamma kT}{m}} = \sqrt{\frac{\gamma RT}{M}} \propto \sqrt{T}$$

where m is the mass of a molecule, and M is the molar mass in kg/mole.

- Resonant frequency of a rectangular drum

$$f_{mn} = \frac{v}{2} \sqrt{\left(\frac{m}{L_x}\right)^2 + \left(\frac{n}{L_y}\right)^2}$$

- Doppler effect

$$f'' = \frac{v}{v + v_{\text{source}}} f$$

v is the velocity in the medium, v_{source} is the source velocity w.r.t. medium. In general,

$$\frac{f_{\text{listener}}}{v \pm v_{\text{lis}}} = \frac{f_{\text{source}}}{v \pm v_{\text{source}}}$$

The \pm can be determined by examining if the frequency received is higher or lower.

- Lens optics:

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

Sign convention, real image has positive sign.

- Lens maker's equation:

$$\frac{1}{f} \approx (n - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right)$$

If R_1 is positive, it's convex, negative, concave. If R_2 is positive, it's concave, if it's negative, it's convex.

- Young's double slit:

$$\begin{aligned} d \sin \theta &= m\lambda && \text{maxima} \\ yd &= mD\lambda && d \ll D, \theta \text{ small} \\ d \sin \theta &= (m + \frac{1}{2})\lambda && \text{minima} \end{aligned}$$

- If we have a slab of material with thickness t and refractive index n_2 , and the other medium is n_1 .

$$\begin{aligned} \frac{2n_2t}{n_1\lambda_1} &= m + \frac{1}{2} && \text{max} \\ \frac{2n_2t}{n_1\lambda_1} &= m + 1 && \text{min} \end{aligned}$$

- Conversely: if we have three layers of material, n_1 , n_t , and n_2 (top to bottom), then we have a couple of different situations that would like to a maximum in intensity:

$$\begin{aligned} d &= \frac{m\lambda}{2n_t} && n_1 > n_t > n_2, \quad n_1 < n_t < n_2 \\ d &= \frac{(m + \frac{1}{2})\lambda}{2n_t} && n_1 < n_t > n_2, \quad n_1 > n_t < n_2 \end{aligned}$$

I think it's fair to assume that the minima occur when you replace $m + \frac{1}{2}$ with m and vice-versa.

- Diffraction grating

$$d \sin \theta = m\lambda$$

If incident at angle θ_i

$$d(\sin \theta_m + \sin \theta_i) = m\lambda$$

The overall result is an interference pattern modulated by single slit diffraction envelope. Intensity of interference

$$I = I_0 \frac{\sin^2(N\phi/2)}{\sin^2(\phi/2)} \quad \phi = \frac{2\pi}{\lambda} d \sin \theta$$

Minima occurs at $N\phi/2 = \pi, \dots, n\pi$ where $n/N \notin \mathbb{Z}$. Maxima occurs at $\phi/2 = 0, \pi, 2\pi, \dots$. Single-slit envelope,

$$I = I_0 \frac{\sin^2(\phi'/2)}{(\phi'/2)^2} \quad \phi' = \frac{2\pi}{\lambda} w \sin \theta$$

where w is the width of the slit. Overall,

$$I = I_0 \frac{\sin^2(\phi'/2) \sin^2(N\phi/2)}{(\phi'/2)^2 \sin^2(\phi/2)}$$

- Bragg's law of reflection

$$m\lambda = 2d \sin \theta$$

Make sure that θ is a glancing angle, not angle of incidence (relative to the plane). This gives the angles for coherent and incoherent scattering from a crystal lattice.

- Index of refraction is defined as

$$n = \frac{c}{v}$$

Again,

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

- Brewster's angle is the angle of incidence at which light with a particular polarization is perfectly transmitted, no reflection.

$$\tan \theta = \frac{n_2}{n_1}$$

- Diffraction again (more background info). The light diffracted by a grating is found by summing the light diffracted from each of the elements, and is essentially a convolution of diffraction and interference pattern. Fresnel diffraction is near field, and fraunhofer diffraction is far field.

- Diffraction limited imaging

$$d = 1.22\lambda N$$

where N is the focal length/diameter. Angular resolution is

$$\sin \theta = 1.22 \frac{\lambda}{D}$$

where D is the lens aperture.

- Thin-film theory. Say the film has higher refractive index. Then there's a phase change for reflection off front surface, no phase change for reflection off back surface. Constructive interference thickness t : $2t = (n + 1/2)\lambda$. Destructive interference $2t = n\lambda$.

- The key idea for many questions is to scrutinize path difference (optical)

- Some telescopes have two convex lenses, the objective and the eyepiece. For the telescope to work the lenses have to be at a distance equal to the sum of their focal lengths, i.e. $d = f_{\text{objective}} + f_{\text{eye}}$:

$$M = \left| \frac{f_{\text{objective}}}{f_{\text{eye}}} \right|$$

Magnifying power = max angular magnification = image size with lens/image size without lens.

- Microscopy

$$\text{magnifying power} = \frac{\beta}{\alpha}$$

- In Michelson interferometer a change of distance $\lambda/2$ of the optical path between the mirrors generally results in a change of λ of optical path of light ray, thus potentially giving a cycle of bright→dark→bright fringes.

- Mirror with curvature $f \approx R/2$.

- Beats: the beat frequency is $f_1 - f_2$:

$$\sin(2\pi f_1 t) + \sin(2\pi f_2 t) = 2 \cos\left(2\pi \frac{f_1 - f_2}{2} t\right) \sin\left(2\pi \frac{f_1 + f_2}{2} t\right)$$

4 Thermodynamics and Statistical Mechanics

- PV diagram plots change in pressure wrt to volume for some process. The work done by the gas is the area **under the curve**.
- If the cyclic process moves clockwise around the loop, then W will be positive, and it represents a heat engine. If it moves counterclockwise, then W will be negative, and it represents a heat pump.
- The most basic definition of entropy is

$$dS \geq \frac{dQ}{T}$$

- Heat transfer

- Conduction: rate

$$H = \frac{\Delta Q}{\Delta t} = -kA \frac{T_2 - T_1}{L}, \quad \frac{dQ}{dt} = -kA \frac{dT}{dx}$$

where A is area, k is a constant.

- Convection (probably not in GRE),

$$H = \frac{\Delta Q}{\Delta T} = hA(T_s - T_\infty)$$

where T_s is the surface temperature, h =convective heat-transfer coefficient. There are both natural and forced convections.

- Radiation

$$\text{Power} = \epsilon \sigma AT^4$$

ϵ =emissivity, $\epsilon \in [0, 1]$. Net loss= $\epsilon \sigma A(T_{\text{emission}}^4 - T_{\text{absorption}}^4)$

- Wien's displacement law: The absolute temperature of a blackbody and the peak wavelength of its radiation are inversely proportional:

$$\lambda_{\text{max}} T = 2.898 \times 10^{-3} \text{ m}\cdot\text{K}$$

- Ideal gas law

$$PV = nRT = NkT$$

- Kinetic theory of gas

$$P = \frac{1}{3} \rho v_{\text{rms}}^2 \quad v_{\text{rms}} = \sqrt{\frac{3kT}{m}}, \quad \bar{v} = \sqrt{\frac{8kT}{\pi m}}, \quad v_{\text{most probable}} = v_m = \sqrt{\frac{2kT}{m}}$$

- Maxwell-Boltzmann distribution (less likely to be in GRE), number of molecules with energy between E and $E + dE$

$$N(E)dE = \frac{2N}{\sqrt{\pi}(kT)^{3/2}} \sqrt{E} e^{-E/kT} dE$$

$$f(v)d^3v = \left(\frac{m}{2\pi kT}\right)^{3/2} e^{-mv^2/2kT} d^3v$$

$$P(v) = \sqrt{\frac{2}{\pi}} \left(\frac{m}{kT}\right)^{3/2} v^2 e^{-mv^2/2kT}$$

(from which we can derive v_m)

- Mean free path of a gas molecule of radius b

$$l = \frac{1}{4\pi T b^2 (N/V)}$$

- Van der Waals equation of state

$$(P + an^2/V^2)(V - bn) = nRT$$

$$(P + aN^2/V^2)(V - Nb) = NkT$$

- Adiabatic process

$$PV^\gamma = \text{const}$$

For an ideal gas to expand adiabatically from $(P_1, V_1) \rightarrow (P_2, V_2)$, work done by the gas is

$$W = \frac{P_1V_1 - P_2V_2}{\gamma - 1}$$

derived from $W = \int_{V_1}^{V_2} PdV$.

- The greatest possible thermal efficiency of an engine operating between two heat reservoirs is that of a Carnot engine, one that operates in the Carnot cycle. Max efficiency is

$$y^* = 1 - \frac{T_{\text{cold}}}{T_{\text{hot}}}$$

For the case of the refrigerator

$$\kappa = \frac{Q_{\text{cold}}}{W} \quad \kappa_{\text{Carnot}} = \left(\frac{T_{\text{hot}}}{T_{\text{cold}}} - 1 \right)^{-1}$$

Carnot=adiabatic+isothermal, $dS = 0$. Otto=adiabatic+isobaric

$$y = 1 - \frac{T_d - T_a}{T_c - T_b}$$

- Dalton's Law

$$P = P_1 + P_2 = (n_1 + n_2) \frac{RT}{V}$$

- The critical isotherm is the line that just touches the critical liquid-vapor region

$$\left(\frac{dP}{dV} \right)_c = 0 \quad \left(\frac{d^2P}{dV^2} \right)_c = 0$$

with c the critical point. Equilibrium region is where pressure and chemical potential for the two states of matter equal, usually a pressure constant region in the $P - V$ diagram.

- In the Dulong-Petit law,

$$C_V = \frac{dE}{dT} = 3R$$

- Laws of thermodynamics

- 0th: If two thermodynamic systems are each in thermal equilibrium with a third, then they are in thermal equilibrium with each other.
- 1st: $\Delta U = Q - W$ (conservation of energy)
- 2nd: Entropy increases/heat flows from hot to cold/heat cannot be completely converted into work.
- 3rd: As $T \rightarrow 0$, $S \rightarrow \text{constant minimum}$.

- Change in entropy for a system where specific heat and temperature are constant;

$$\Delta S = Nk \ln \frac{V}{V_0}$$

- Change in energy for an ideal gas:

$$\Delta U = C_V \Delta T$$

- Work done by ideal gas:

$$W = \int P dV = \begin{cases} NkT \ln \frac{V_2}{V_1} & \text{Isothermal} \\ P \Delta V & \text{Ideal gas, constant Pressure} \end{cases}$$

- Partition function:

$$Z = \sum_i e^{-\beta E_i} = \int dE \Omega(E) e^{-\beta E} = \int dE e^{-\beta A(E)}$$

where $A(E)$ is the Helmholtz free energy and $\Omega(E)$ is the degeneracy.

$$P(E_i) = \frac{e^{-\beta E_i}}{Z}$$

$$S = k \ln \Omega = -k \sum_i P_i \ln P_i$$

- Equipartition Theorem: (1) Classical canonical and (2) quadratic dependence: each particle has energy $\frac{1}{2}kT$ for each quadratic canonical degree of freedom.
- Internal energy

$$dU = TdS - PdV$$

Enthalpy

$$H = U + PV \quad dH = TdS + VdP \quad \text{isobaric}$$

Helmholtz

$$F = U - TS, \quad dF = -SdT - PdV \quad \text{isothermal}$$

Gibbs free energy

$$G = U - TS + PV, \quad dG = -SdT + VdP$$

- Heat capacities:

$$C_V = \left(\frac{\partial U}{\partial T} \right)_V = T \left(\frac{\partial S}{\partial T} \right)_V$$

$$C_P = \left(\frac{\partial U}{\partial T} \right)_P + P \left(\frac{\partial V}{\partial T} \right)_P = T \left(\frac{\partial S}{\partial T} \right)_P = \left(\frac{\partial H}{\partial T} \right)_P$$

- Fun stuff:

$$\langle E \rangle = -\frac{\partial}{\partial \beta} \ln Z, \quad F = -kT \ln Z$$

$$S = k \ln Z + \langle E \rangle / T, \quad dS = \int \frac{dQ}{T}$$

Gibbs-Helmholtz equation.

$$U = F + TS = F - T \left(\frac{\partial F}{\partial T} \right)_V = -T^2 \left(\frac{\partial}{\partial T} \right)_V \left(\frac{F}{T} \right)$$

- Availability of system

$$A = U + P_0 V - T_0 S$$

In natural change, A cannot increase.

- Diatomic gas

$$U = \frac{5}{2}kT$$

- Maxwell Relations

$$\begin{aligned} \left(\frac{\partial T}{\partial V}\right)_S &= -\left(\frac{\partial P}{\partial S}\right)_V = \frac{\partial^2 U}{\partial S \partial V} \\ \left(\frac{\partial T}{\partial P}\right)_S &= \left(\frac{\partial V}{\partial S}\right)_P = \frac{\partial^2 H}{\partial S \partial P} \\ \left(\frac{\partial S}{\partial V}\right)_T &= \left(\frac{\partial P}{\partial T}\right)_V = -\frac{\partial^2 A}{\partial T \partial V} \\ -\left(\frac{\partial S}{\partial P}\right)_T &= \left(\frac{\partial V}{\partial T}\right)_P = \frac{\partial^2 G}{\partial T \partial P} \end{aligned}$$

- For ideal gas in adiabatic process, $W = \Delta U = \frac{3}{2}Nk\Delta T$
- Clockwise enclosed area in a $P - V$ diagram is the work done by the gas in a cycle.
- Chemical potential

$$\mu(T, V, N) = \left(\frac{\partial F}{\partial N}\right)_{T, V}$$

At equilibrium μ is uniform, F achieves minimum.

- $P_{\text{boson}} \propto T^{5/2}$, $P_{\text{classical}} \propto T$, $P_{\text{fermion}} \propto T_F$ (very big). $T_{\text{classical}} \gg T_{\text{boson}}$
- A thermodynamic system in maximal probability state is stable.
- Both Debye and Einstein assume $3N$ independent Harmonic oscillators for lattice. Einstein took a constant frequency

5 Quantum Mechanics

- Uncertainty principle

$$\Delta x \Delta p \geq \frac{\hbar}{2}, \quad \Delta E \Delta t \geq \frac{\hbar}{2}$$

- Schrodinger equation

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \Psi + V\Psi$$

- Commutator relation:

$$[AB, C] = ABC - CAB = ABC - ACB + ACB - CAB = A[B, C] + [A, C]B$$

- De Broglie

$$\lambda = \frac{h}{p} = \frac{hc}{E} = \frac{h}{\sqrt{2mkT}}$$

(The last equality is thermal)

- A one-dimensional problem has no degenerate states.
- Heisenberg's uncertainty principle generalized:

$$\Delta A \Delta B \geq \frac{1}{2} |\langle [A, B] \rangle|$$

- Infinite square well

$$\psi_n = \sqrt{\frac{2}{a}} \sin \frac{n\pi x}{a}, \quad E_n = \frac{n^2 \pi^2 \hbar^2}{2ma^2}, \quad n \geq 1$$

Delta-function well $V = -\alpha\delta(x)$. Only one bound state, many scattering states.

$$\psi(x) = \sqrt{\frac{m\alpha}{\hbar}} e^{-m\alpha|x|/\hbar^2}, \quad E = -\frac{m\alpha^2}{2\hbar^2}$$

Shallow, narrow well, there is always at least one bound state.

- Selection rule

$$\Delta l = \pm 1, \quad \Delta m_l = \pm 1 \text{ or } 0, \quad \Delta j = \pm 1 \text{ or } 0$$

Electric dipole radiation $\Leftrightarrow \Delta l = 0$. Magnetic dipole or electric quadrupole transitions are “forbidden” but do occur occasionally.

- Stimulated and spontaneous emission rate $\propto |p|^2$ where

$$p \equiv q \langle \psi_b | z | \psi_a \rangle$$

The lifetime of an excited state is $\tau = (\sum A_i)^{-1}$ where A_i are spontaneous emission rates.

- Time-independent first order perturbation

$$E_n^1 = E_n^0 + \langle \psi_n^0 | H' | \psi_n^0 \rangle, \quad \psi_n^1 = \psi_n^0 + \sum_{m \neq n} \frac{\langle \psi_m^0 | H' | \psi_n^0 \rangle}{E_n^0 - E_m^0} \psi_m^0$$

- Quantum approximation of rotational energy

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

- Fermi energy

$$E_F = kT_F \simeq \frac{1}{2}mv^2$$

- Differential cross-section

$$\frac{d\sigma}{d\Omega} = \frac{\text{scattered flux/unit of solid angle}}{\text{incident flux/unit of surface}}$$

- Intrinsic magnetic moment

$$\vec{\mu} = \gamma \vec{S}, \quad \gamma = \frac{eg}{2m}$$

where g is the Lande g -factor. If m points up, $\vec{\mu}$ points down.

- Total cross section

$$\sigma = \int D(\theta) d\Omega, \quad D(\theta) = \frac{d\sigma}{d\Omega}$$

- Stark effect is the electrical analog to the Zeeman effect.

- Born-Oppenheimer approximation: the assumption that the electronic motion and the nuclear motion in molecules can be separated, i.e.

$$\psi_{\text{molecule}} = \psi_e \psi_{\text{nuclei}}$$

- In Stern-Gerlach experiment, a beam of neutral silver atoms are sent through an inhomogeneous magnetic field. Classically, nothing happens as the atoms are neutral with Larmor precession, the beam would be deflected into a smear. But it actually deflects into $2s + 1$ beams, thus corroborating with the fact electrons are at spin $\frac{1}{2}$

- Know the basic spherical harmonics

$$Y_0^0 = \sqrt{\frac{1}{4\pi}}, \quad Y_1^{\pm 1} = \mp \sqrt{\frac{3}{8\pi}} \sin \theta e^{\pm i\phi}, \quad Y_1^0 = \sqrt{\frac{3}{4\pi}} \cos \theta$$

- Probability density current

$$\vec{J} = \frac{\hbar}{2mi}(\psi^* \nabla \psi - \psi \nabla \psi^*) = \Re \left(\psi^* \frac{\hbar}{im} \nabla \psi \right)$$

- Laser operates by going from lower state to high state (population inversion), then falls back on a metastable state in between (not all the way down due to selection rule).

- Neat identities:

$$\langle \mathcal{O} \rangle = \int \Psi^* \mathcal{O} \Psi dx, \quad [f(x), p] = i\hbar \frac{\partial f}{\partial x}, \quad p = -i\hbar \nabla$$

- Ehrenfest's Theorem: expectation values obey classical laws.

$$m \frac{d^2 \langle x \rangle}{dt^2} = \frac{d \langle p \rangle}{dt} = \left\langle -\frac{\partial V}{\partial x} \right\rangle$$

- If $V(x)$ is even, $\psi(x)$ can always be taken to be even or odd.

- More identities:

$$\langle H \rangle = \sum_{n=1}^{\infty} |c_n|^2 E_n, \quad \delta(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{ikx} dk$$

- Tunneling shows exponential decay.

- The ground state of even potential is even and has no nodes.

- In stationary states, all expectation values are independent of t .

- Harmonic oscillators:

$$H = \hbar\omega(a_- a_+ - \frac{1}{2}) = \hbar\omega(a_+ a_- + \frac{1}{2}), \quad a_{\pm} = \frac{1}{\sqrt{2\hbar m\omega}}(m\omega x \mp ip)$$

$$[a_-, a_+] = 1, \quad N \equiv a_+ a_-, \quad N \psi_n = n \psi_n$$

$$a_+ \psi_n = \sqrt{n+1} \psi_{n+1}, \quad a_- \psi_n = \sqrt{n} \psi_{n-1}$$

$$\psi_n = \frac{1}{\sqrt{n!}} (a_+)^n \psi_0, \quad x = \sqrt{\frac{\hbar}{2m\omega}}(a_+ + a_-), \quad p = i\sqrt{\frac{\hbar m\omega}{2}}(a_+ - a_-)$$

- Fourier transforms:

$$\Phi(p, t) = \frac{1}{\sqrt{2\pi\hbar}} \int_{-\infty}^{\infty} e^{-px/\hbar} \Psi(x, t) dx$$

$$\Psi(x, t) = \frac{1}{\sqrt{2\pi\hbar}} \int_{-\infty}^{\infty} e^{ipx/\hbar} \Phi(p, t) dp$$

- Operators changing in time:

$$\frac{d\langle Q \rangle}{dt} = \frac{i}{\hbar} \langle [H, Q] \rangle + \left\langle \frac{\partial Q}{\partial t} \right\rangle$$

- Virial theorem, in stationary state

$$2\langle T \rangle = \left\langle x \frac{dV}{dx} \right\rangle$$

- Hydrogen atom revisited:

$$\begin{aligned}
E_n &\propto \text{reduced mass} \\
&\propto Z^2 \\
&\propto 1/n^2 \\
&= - \left[\frac{m}{2\hbar^2} \left(\frac{e^2}{2\pi\epsilon_0} \right)^2 \right] \frac{1}{n^2} = \frac{E_1}{n^2} \\
E_n(Z) &= Z^2 E_n \\
a(Z) &= \frac{a}{Z} \\
R(Z) &= Z^2 R
\end{aligned}$$

Bohr radius $a = 4\pi\epsilon_0\hbar^2/m_e^2 = 0.528 \times 10^{-10}$ meters.

$$\psi_{100}(r, \theta, \phi) = \frac{1}{\sqrt{\pi a^3}} e^{-r/a}$$

- Angular momentum

$$[L_i, L_j] = i\hbar L_k \epsilon_{ijk}$$

where $\epsilon_{ijk} = 1$ for even permutations, -1 for odd permutations, zero otherwise.

$$\begin{aligned}
L_{\pm} &= L_x \pm iL_y, & [L^2, L_i] &= 0 \\
L^2 f_l^m &= \hbar^2 l(l+1), & L_z f_l^m &= \hbar m f_l^m \\
L_{\pm} f_l^m &= \hbar \sqrt{(l \mp m)(l \pm m + 1)} f_l^{m \pm 1} = \hbar \sqrt{l(l+1) - m(m \pm 1)} f_l^{m \pm 1} \\
[L_z, x] &= i\hbar y, & [L_z, p_x] &= i\hbar p_y, & [L_z, y] &= -i\hbar x, & [L_z, p_y] &= -i\hbar p_x \\
L_z &= \frac{\hbar}{i} \frac{\partial}{\partial \phi}
\end{aligned}$$

- Spin,

$$\begin{aligned}
S^2 &= \frac{3}{4} \hbar^2 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\
\sigma_x &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, & \sigma_y &= \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, & \sigma_z &= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \\
\vec{S} &= \frac{\hbar}{2} \vec{\sigma} \\
\chi_+^{(x)} &= \begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{pmatrix}, & \chi_-^{(x)} &= \begin{pmatrix} 1/\sqrt{2} \\ -1/\sqrt{2} \end{pmatrix} \\
\langle S_x^2 \rangle &= \langle S_y^2 \rangle = \langle S_z^2 \rangle = \frac{\hbar^2}{4}
\end{aligned}$$

- Clebsch-Gordan coefficients

$$\begin{aligned}
|sm\rangle &= \sum_{m_1+m_2=m} C_{m_1 m_2 m}^{s_1 s_2 s} |s_1 m_1\rangle |s_2 m_2\rangle \\
|s_1 m_1\rangle |s_2 m_2\rangle &= \sum_s C_{m_1 m_2 m}^{s_1 s_2 s} |sm\rangle
\end{aligned}$$

- Continuity equation

$$\nabla \cdot \vec{J} = -\frac{\partial}{\partial t} |\psi|^2$$

$$\int_S \vec{J} \cdot d\vec{a} = -\frac{d}{dt} \int_V |\psi|^2 d^3\vec{r}$$

- Representation of angular momentum.

$${}^{2s+1}\mathcal{L}_J$$

where s = spin, \mathcal{L} = orbital, J = total. Hund's rule: (1) State with highest spin will have lowest energy given Pauli principle satisfied; (2) For given spin and anti-symmetrization highest \mathcal{L} have lowest energy; (3) Lowest level has $J = |L - S|$, if more than half-filled $J = L + S$.

- Fermi gas

$$k_F = (3\rho\pi^2)^{1/3}, \quad \rho = Nq/V, \quad v_F = \sqrt{2E_F/m}$$

Degeneracy pressure

$$P \propto \rho^{5/3} m_e^{-1} m_p^{-5/3}$$

- Particle distributions

$$n(\epsilon) = \begin{cases} e^{-\beta(\epsilon-\mu)} & \text{Maxwell-Boltzmann} \\ (e^{\beta(\epsilon-\mu)} + 1)^{-1} & \text{Fermi-Dirac} \\ (e^{\beta(\epsilon-\mu)} - 1)^{-1} & \text{Bose-Einstein} \end{cases}$$

Blackbody density

$$\rho(\omega) = \frac{\hbar\omega^3}{\pi^2 c^3 (e^{\hbar\omega/kT} - 1)}$$

- Fine structure → spin-orbit coupling. Relativistic correction $\alpha = 1/137.056$. Then Lamb shift is from the electric field, then Hyperfine structure due to magnetic interaction between electrons and protons, then spin-spin coupling (21 cm line)
- Fine structure breaks degeneracy in l but still have j
- Fermi's golden rule is a way to calculate the transition rate (probability of transition per unit time) from one energy eigenstate of a quantum system into a continuum of energy eigenstates, due to a perturbation.
- Full shell and close to a full shell configuration are more difficult to ionize.
- Larmor precession:

$$\vec{\Gamma} = \vec{\mu} \times \vec{B} = \gamma \vec{J} \times \vec{B}$$

and we get $\omega = \gamma B$, where Γ is the torque, μ is the magnetic moment, and J is total angular momentum.

6 Atomic Physics

- $\Delta E = hf = \hbar\omega = hc/\lambda$. $hc = 12.4 \text{ keV}\cdot\text{\AA} = 1240 \text{ eV}\cdot\text{nm}$, de Broglie wavelength $\lambda = h/p$.
- Emission due to transition from level n to level m

$$\frac{1}{\lambda} = R \left(\frac{1}{m^2} - \frac{1}{n^2} \right)$$

$m = 1$ Lyman series, $m = 2$ Balmer series.

$$R = 1.097 \times 10^7 \text{ m}^{-1}, \quad E_n = -\frac{13.6 \text{ eV}}{n^2}$$

- Hydrogen model extended, Z =number of protons, quantities scale as

$$E \sim Z^2, \quad \lambda \sim \frac{1}{Z^2}$$

Reduced-mass correction to emission formula is

$$\frac{1}{\lambda} = \frac{RZ^2}{1 + m/M} \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

where m is the mass of electron, M is the mass of the proton, $m/M = 1/1836$.

- Bohr postulate $L = mvr = n\hbar$
- Zeeman effect: splitting of a spectral line into several components in the presence of a static magnetic field.
- k series refers to the innermost shell (K, L, M, N) so transition to innermost shell.

$$E = -13.6(Z - 1)^2 \left(1 - \frac{1}{n_i^2} \right) \text{ eV}$$

where the $(Z - 1)^2$ is a shielding approximation.

- Frank-Hertz Experiment: Electrons of a certain energy range can be scattered inelastically, and the energy lost by electrons is discrete.
- Spectroscopic notation is a standard way to write down the angular momentum quantum number of a state,

$$^{2s+1}L_j$$

where s is the total spin quantum number, $2s + 1$ is the number of spin states, L refers to the orbital angular momentum quantum number ℓ but is written as S, P, D, F, \dots for $\ell = 0, 1, 2, 3, \dots$ and j is the total angular momentum quantum number. So for hydrogen we could have things like

$$^2P_{\frac{3}{2}}, ^2P_{\frac{1}{2}}$$

(since $s = 1/2$ and $\ell = 1$, spin up versus spin down).

7 Special Relativity

- Energy:

$$E^2 = (pc)^2 + (mc^2)^2$$

For massless particles, $E = pc = h\nu$

- Relativistic Doppler Effect

$$\lambda = \sqrt{\frac{1 \pm \beta}{1 \mp \beta}} \lambda_0$$

$\beta = v/c$. Sign is determined by whether source is moving away or closer.

- Space-time interval

$$\Delta s^2 = c^2 \Delta t^2 - \Delta x^2 - \Delta y^2 - \Delta z^2$$

- Lorentz transformation

$$\begin{pmatrix} ct' \\ x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix}$$

- Relativistic addition of velocities

$$u'_x = \frac{u_x + v}{1 + u_x v/c^2}, \quad u'_y = \frac{u_y}{\gamma(1 + u_x v/c^2)}, \quad u'_z = \frac{u_z}{\gamma(1 + u_x v/c^2)}, \quad \gamma \equiv \frac{1}{\sqrt{1 - \beta^2}}$$

- Lorentz-Transformation of EM, parallel and perpendicular to direction of motion.

$$\begin{aligned} \vec{E}'_{\parallel} &= \vec{E}_{\parallel}, & \vec{E}'_{\perp} &= \gamma(\vec{E}_{\perp} + \vec{v} \times \vec{B}_{\perp}) \\ \vec{B}'_{\parallel} &= \vec{B}_{\parallel}, & \vec{B}'_{\perp} &= \gamma(\vec{B}_{\perp} - \vec{v} \times \vec{E}_{\perp}/c^2) \end{aligned}$$

- Relativistic energy/momentum

$$E = \gamma m c^2, \quad p = \gamma m v$$

- In every closed system, the total relativistic energy and momentum are conserved.
- Spacelike separation means two events can happen at the same time, which requires

$$\Delta s^2 = c^2 \Delta t^2 - \Delta x^2 < 0$$

- Transverse Doppler shift:

$$f = \frac{f'}{\sqrt{1 - \beta^2}} \text{ or } f = f' \sqrt{1 - \beta^2}$$

- Four-vectors can be useful. We can define

$$\mathbf{P} = \left(\frac{E}{c}, \mathbf{p} \right)$$

and the dot product

$$\mathbf{P}^2 = \frac{E^2}{c^2} - p^2 = m^2 c^2$$

to get

$$E^2 = m^2 c^4 + p^2 c^2.$$

Remember, this mass is invariant, so we can equate the \mathbf{P} vector at different times.

8 Laboratory Methods

- If measurements are independent (or intervals in a Poisson process are independent) both expected value and variance increase linearly with time, so longer time can improve uncertainty, which is usually defined as

$$\frac{\sigma}{R} \propto \frac{1}{\sqrt{t}}$$

- In Poisson distribution, $\sigma = \sqrt{x}$.
- Error analysis, estimating uncertainties. If you are sure the value is closer to 26 than to 25 or 27, then record best estimate 26 ± 0.5 .
- Propagation of uncertainties for sum of random and independent variables

$$\delta x = \sqrt{\sum_i (\delta x_i)^2}$$

If multiplication or divisions are involved, use fractional uncertainty:

$$\frac{\delta q}{|q|} = \sqrt{\sum_i \left(\frac{\delta x_i}{x_i} \right)^2}$$

- Experimental uncertainties can be revealed by repeating the measurements are called random errors; those that cannot be revealed in this way are called systematic errors.
- If the the uncertainties are different for different measurements, we have

$$\bar{x} = \frac{\sum(x_i/\sigma_i^2)}{\sum_i(1/\sigma_i^2)} \quad \sigma_{\bar{x}}^2 = \frac{1}{\sum_i(1/\sigma_i^2)}$$

9 Specialized Topics

- Photoelectric effect.

$$E_{\text{photon}} = \phi + K_{\text{max}}$$

(or the sum of the work function and the kinetic energy).

- Compton scattering:

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos \theta)$$

where m_e is the mass of the atom: $h/m_e c$ is the Compton wavelength of the electron, and λ' is the new wavelength.

- X-ray Bragg reflection

$$n\lambda = 2d \sin \theta$$

(compare to **diffraction grating** $n\lambda = d \sin \theta$)

- $1.602 \times 10^{-19} \text{J} = e(1 \text{ V}) = 1 \text{ eV}$.

- In solid-state physics, effective mass is

$$m^* = \frac{\hbar^2}{d^2 E / dk^2}$$

- Electronic filters: high pass means $\omega \rightarrow \infty$, $V_{\text{in}} = V_{\text{out}}$. Usually look at $I = V_{\text{in}}/Z$, $Z = R + i(X_L - X_C)$, $X_L = \omega L$, $X_C = 1/\omega C$.

- Band spectra is a term that refers to using EM waves to probe molecules.

- Solid state:

$$\text{primitive cell} = \frac{\text{unit cell}}{\# \text{ of lattice points in a Bravais lattice}}$$

Simple cubic \rightarrow 1 point, body-centered \rightarrow 2 points, face-centered \rightarrow 4 points.

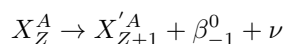
- Resistivity of undoped semiconductor varies as $1/T$.

- Nuclear physics: binding energy is a form of potential energy, convention is to take it as positive. It's the energy needed to separate into different constituents. It is usually subtracted for other energy to tally total energy.

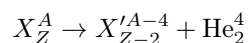
- Pair production refers to the creation of an elementary particle and its antiparticle. Usually need high energy (at least the total mass).

- At low energies, photoelectric-effect dominates Compton scattering.

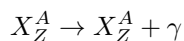
- Radioactivity: Beta decay



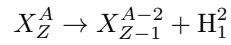
Alpha:



Gamma



Deuteron decay (not natural)



Radioactivity usually follows Poisson distribution.

- Coaxial cable terminated at an end with characteristic impedance in order to avoid reflection of signals from the terminated end of cable.
- Human eyes can only see things in motion up to ~ 25 Hz.
- In magnetic field, e are more likely to be emitted in a direction opposite to the spin direction of the decaying atom.
- Op-amp (operational amplifiers): if you only have two days to prepare for the GRE, this is not worth the effort, maximum one question on this. Read “The Art of Electronics” to check this out.
- The specific heat of a superconductor jumps to a lower value at the critical temperature (resistivity jumps too)
- Elementary particles: review the quarks, leptons, force carriers, generations, hadrons.
 - Family number conserved
 - Lepton number conserved
 - Strangeness is conserved (except for weak interactions)
 - Baryon number is conserved
- Internal conversion is a radioactive decay where an excited nucleus interacts with an electron in one of the lower electron shells, causing the electron to be emitted from the atom. It is not beta decay.