# Medical Physics

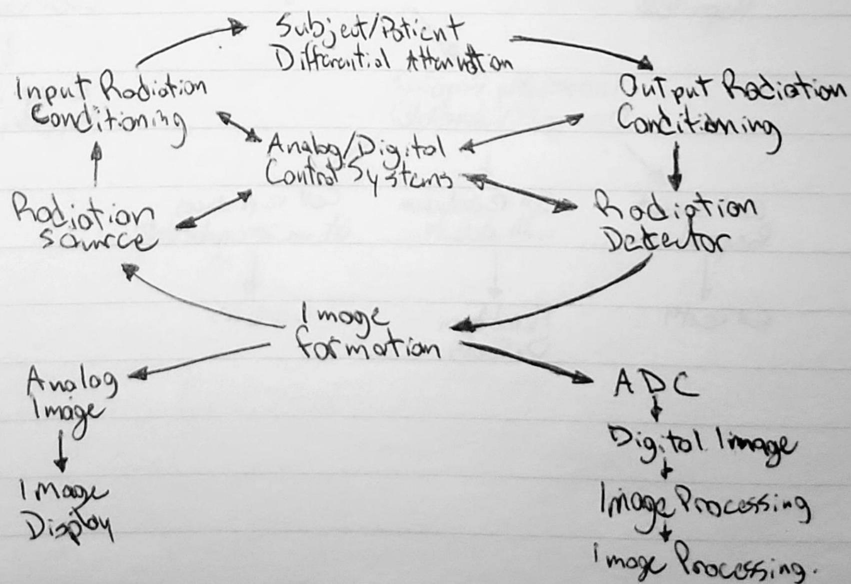
## Course Topics.

- Atoms, Radiation, and matter
- X-ray production, and imaging
- Nuclear Imaging, and medicine
- NMR and MRI
- Ultrasound.

## Medical Imaging

- Medical imaging requires some form of radiation capable of penetrating tissues.
- The radiation must also interact with body in such a way that there is a contrast.
- Image quality has trade-offs
  - Patient safety, Spatial Resolution, temporal resolution, and noise properties.

## Systematic Approach to Medical Imaging

- 

## Contrast.

- Radiation needs to interact with the body's tissue is some differential manner to produce contrast.
- X-ray/CT - differences in electron density ($e/cm^3 = \rho e/g$)
- Ultrasound - difference in acoustic impedance ($Z = \rho c$)
- External Contrast agents can enhance natural contrast levels.

## Radiation

- Radiation is the propagation of energy through space and matter
- Can be thought of as corpuscular (partial), acoustic (mechanical), electromagnetic.

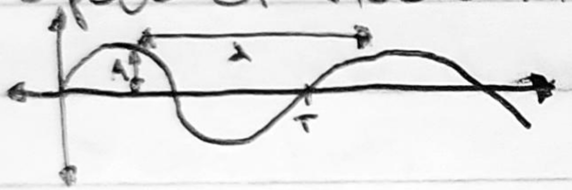
## Systematic Approach to Radiation Effects

- Cell Irradiated
  - ↓ DNA Damage
    - → Damage Repaired
    - → Unrepairable Damage (Cell Death) → Enough Cells Die for temporary or permanent tissue death
    - → Incorrectly Repaired Damage (Vulnerable)
      - → Cell doesn't Reproduce → Cell Death
      - → Cell reproduces with defects → Hereditary Defects
      - → Cell reproduces at an irregular rate → Cancer.

## What is Energy?

- Energy is a concept.
- This is like space or force.
- A very important concept is that energy is conserved.

## Characterizing Waves

- Amplitude (A) - Magnitude of the Wave
- Wavelength ($\lambda$) - Distance between identical points on adjacent cycles
- Period ($T$) - The time required to complete one wavelength
- frequency ($\nu$) - Number of periods per second.
- Speed of Radiation $= c = \lambda\nu$
- 

# Electromagnetic Radiation.

## Electric Charge

- There is an electric force acting on a point charge when in the presence of a second charge.
- Like charges ~~attract~~ repel, opposite charges attract.
- $+\rightarrow \leftarrow -$ , $\leftarrow + \quad + \rightarrow$

## Electrostatics

- Interactions between stationary charges react under Coulombs law: $\vec{F}_E = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2}$, where $q$ is the charges (C), $r$ is the distance between them (m), and $\frac{1}{4\pi\epsilon_0}$ is a constant.
- $\frac{1}{4\pi\epsilon_0}$ is also known as the 'K' value.
- $\epsilon_0$ is equal to $\approx 8.8542\times10^{-12}\ \frac{\text{Farads}}{\text{meter}}$ (Permittivity of freespace)
- $K$ is equal to $\approx 8.99\times10^{9}\ \frac{N\cdot m^2}{C^2}$

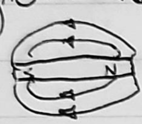
## The Electric Field

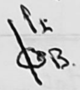
- Electric Field is defined as the electric force per unit charge.
- Electric Field lines originate on positive charges and terminate on negative ones.
- $\vec{E} = \frac{Kq}{r^2}$ or $\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}$

## Natural Potentials.

- Cell membranes in general maintain a small voltage across the membrane in its normal ~~or~~ or resting state.
- The potential difference is $-70$ millivolts.
- membrane $= 3\times10^{-9}$ m, so an electron would feel a force of $2.56\times10^{-11}$ N.

## Magnetostatics

- Magnetic fields are produced by electric currents.
- 


## Faradays Law

- Magnetic field lines make closed loops.
- A varying magnetic field makes an electric field.
- $E = NA\frac{\Delta B}{\Delta t}$

## Ampere's Law

- The magnetic field in space around an electric current is proportional to the electric current which serves as its source, just as the electric field in space is proportional to the charge which serves as its source.

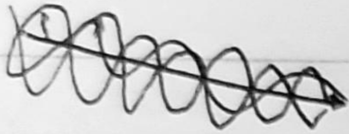
## Magnetostatics.

- Lorentz Force Law $=$ $\vec{F} = q\vec{v}\vec{B}$
- B is in $\frac{N\cdot s}{C\cdot m}$

## Hertz Confirmation

- Hertz was the first person to detect electro magnetic waves.

## EM Waves

- The E and B fields are perpendicular to each other.
- 
- Speed of EM Waves in a vaccum
  - $c = \lambda \nu$ , c is speed, $\lambda$ is wavelength, $\nu$ is frequency.

## Summary

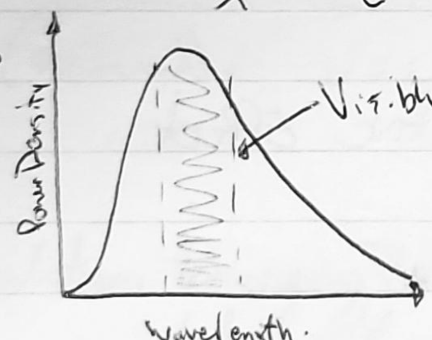
- Stationary charges make electric fields.
- Faraday observed the relation of E and B.
- Accelerated charges produced electromagnetic fields and waves
- 

003 - Atomic.

## EM Waves and Photons

- Light is a wave consisting of E and B fields.
- Light is also a photons
- Wave particle duality.

## Black Body Radiation

- When a body is heated, the particles produce vibrations and oscillations that give off heat and EM ~~waves~~ radiation.
- The spectral emittance $S_\lambda$ is the energy flux (energy per second per area)
- $S(\lambda) = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$
- 

- The human body gives of infrared EM waves.
- A black body is a perfectly absorbing and emitting surface.
- Its spectral emittance depends only on temperature
  - $S = \sigma T^4$, where $\sigma$ is $5.6703 \times 10^{-8} \frac{\text{watts}}{m^2 K^4}$

## Max Planck

- In an oscillator of frequency $\nu$, the only allowed values of energy are $E = 0, h\nu, 2h\nu, 3h\nu \ldots$, all other values are forbidden.
- Plancks constant $h$ was determined through the spectral emission equation.
- Plancks constant, $h = 6.63 \times 10^{-34}$ J·sec.

## Einstein

- All EM radiation consists of particle-like packets of energy, each with an energy of $h\nu$
- These are called photons

## Photons Explain the Photoelectric Effect

- If light is shined on a piece of metal, electrons are ejected from the metal.
- The number of electric depends on frequency of the wave not the intensity of the light.
- Thus energy of a photon is dependent ~~on~~ on the ~~wavelength not the~~ frequency not the number of photons.
- $K = h\nu - \phi$, $\phi$ is the work function, the amount of energy the photon needs to eject an electron from an atom.

Spectral Lines

- Spectral lines are characteristic of each element. Can be used to detect the presence of that element.
- Any spectral emission line can show up as an absorption line

Spectral Lines of Hydrogen

- $\lambda = 911.76 \frac{4n^2}{n^2-4}$, for $n = 2,3,4,5$ etc.
- In terms of frequency this becomes,
  - $\nu = cR_H \left(\frac{1}{2^2} - \frac{1}{n^2}\right)$, where $R_H = \frac{1}{911.76}$ Å (Rydberg constant)
- Generally, $\nu = cR_H \left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right)$, when $n_1 > n_2$

Forces on Charged Particles

- To manipulated a charged particle with an electric or magnetic, the particle experiences a force
  $\vec{F} = q\vec{E} + q\vec{v}B$. $q$ = Coloumbs, $E = \frac{\text{Volts}}{m}$, $B$ = Tesla.

- $E$ = Constant, $B = 0$
  - $\rightarrow ma = qE$
- Starting from rest
  - $\rightarrow v = at = \frac{qEt}{m}$
- Travelling a distance
  - $\rightarrow x = \frac{1}{2}at^2 = \frac{1}{2}\frac{qE}{m}t^2$
- Kinetic Energy
  - $\rightarrow \frac{1}{2}mv^2 = \frac{1}{2}\frac{q^2}{m}E^2t^2 = xqE$

- Kinetic Energy
  - $\Rightarrow K = \cancel{x}qE = q\Delta V$, where $\Delta V$ is the potential
- The electron volt is a unit of measurement which is the energy that is aquired when accelerating through a potential of 1 volt.
- $1 eV = 1.602 \times 10^{-19} J = e$.

## Charged Particle in a Magnetic Field

- Uniform Magnetic Field.
  - $\Rightarrow B = \text{constant}, E = 0$
  - $\Rightarrow ma = qvB$

## Centripetal Acceleration

- Uniform Circular Acceleration
- $a = \frac{v^2}{r} \Rightarrow f = ma = \frac{mv^2}{r} = qvB$

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

- Frequency of the circular motion
  - $\Rightarrow \nu = \frac{v}{2\pi r} = \frac{qB}{2\pi m}$

## Examples of Magnetic Fields

- Cyclotron
  - This is a device that accelerates charged particles at high speed to cause collisions.

## Discovery of the Electron.

- Electrons were allowed to flow freely from the cathode to the anode and through the rest of the vaccumm
- When the electric field was introduced the glow of the electrons began to bend proving ~~they~~ their charged existence.

## Charge of Electrons.

- In Millikan's Experiment, oil droplets preferentially form around atoms or molecules that have lost or gained one or more electrons.
- If one drop falls through the air, it can be observed to reach terminal velocity.
- $F_f = 6\pi\eta R v$ , where $\eta$ is the viscosity of air
- $mg = 6\pi\eta R v$ with weight.
- The mass of the droplet is known from its radius and density

  → $\frac{4}{3}\pi R^3 = \frac{m}{\rho}$
- Induce an electric field and then we can see

  → $q = \frac{mg}{E}\frac{v_2 + v_1}{v_1}$

## Partial Summary

- EM has wave-particle dualities.
- The atomic spectra of gaseous elements seems to be quantifiable but only hydrogen has a simple equation.

004 Atomic.

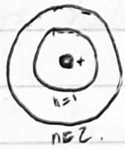
## Early Atomic Theory

- Maxwells equations show that light is a wave.
- The source of charge must be within the atoms
- Early model of the atom was the "plum-pudding" model where small $e^-$ swimm is positively charged mass.

## Rutherfords Experiment.

- Rutherford sent beams of alpha particles at a sheet of gold foil, and the particles deflected in such a way that he could conclude

## Bohrs Model of the Hydrogen Atom

- Niels Bohr proposed that the orbits and energies of the hydrogen atoms, are quatized.
- 


## Bohr's Rules

- ① When an electron is in one of the quantized orbits, it does not emit radiation. It is in a stationary state.
- The electron can make jumps between energy levels/stationary states, During this it does emit radiation.
- ② The classical laws of mechanics apply here to the orbital motion.
- ③ When it makes a transition $\Delta E = E_i - E_f$ is released as a pho $\nu = \Delta E/h$.
- ④ The permitted orbits are characterized quatized values of the orbital angular moment $L = n\frac{h}{2\pi} = n\hbar$

## Size of Bohr's Atom.

- Bohr used the coloumb force to calculate the size of an atom
- $f = \frac{ke^2}{r^2} \rightarrow \frac{m_e v^2}{r} = \frac{ke^2}{r^2} \rightarrow \dots \rightarrow r_n = \frac{4\pi\epsilon_0}{e^2} \frac{n^2\hbar^2}{m_e}$
- Radius of the smallest orbit ($n=1$) $0.529 \times 10^{-10}$ m

## Energy of Bohr's Atom

- Bohr used conservation of energy to find the energy at the quantum number, n.
- $E_n = \frac{1}{2}m_e v^2 - \frac{e^2}{4\pi\epsilon_0 r} \rightarrow \frac{1}{2}\frac{m_e n^2\hbar^2}{m_e^2}\left(\frac{e^2 m_e}{4\pi\epsilon_0 n^2\hbar^2}\right) - \frac{e^2}{4\pi\epsilon_0}\left(\frac{e^2 m_e}{4\pi\epsilon_0 n^2\hbar^2}\right) \rightarrow$

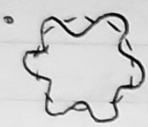
- $E_n = -\frac{e^4}{2(4\pi\epsilon_0)^2}\frac{m_e}{\hbar^2}\frac{1}{n^2}$.

- In the ground state $E_n = -13.6$ eV, but for other levels $E_n = \frac{-13.6}{n^2}$
- It takes 13.6 eV to remove an electron from its orbit then.
- This movement of the electron creates radiation.
- $\nu = \frac{\Delta E}{h} \rightarrow \frac{E_i - E_f}{h} \rightarrow \frac{e^4}{4\pi(4\pi\epsilon_0)^2}\frac{m_e}{\hbar^3}\left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right)$
- Comparing this to Rydberg's formula, we see
- $r = \frac{e^4 m_e}{4\pi(4\pi\epsilon_0)^2\hbar^3 c}$

## de Broglie Wavelength

- We know $E = h\nu$, and $p = \frac{h}{\lambda}$, where $p$ is momentum.
- These equations should hold up for all particles.
- $\lambda = \frac{h}{p} = \frac{h}{mv}$.

## The Electron Orbit Semi-Classically

- 

  The length of the circumference of an orbit is an integral ~~wav~~ number wavelengths.

  $2\pi r = n\lambda$

## The Atom Semi Classically

- Electrons of negative charge orbit the positively charged nucleus
- The nucleus contains most of the atoms mass (protons neutrons).
- The electron orbits are quantized.
- Electrons orbit like a standing wave.

## Particle-Wave Duality

- Wave Function $= \Psi(x,t) = A\cos(2\pi(\frac{x}{\lambda} - t\nu))$

## Schrödingers Equation Solution

- $E_n = (n + \frac{1}{2})h\nu$
- $E_n = \frac{n^2 h^2}{8mL^2}$

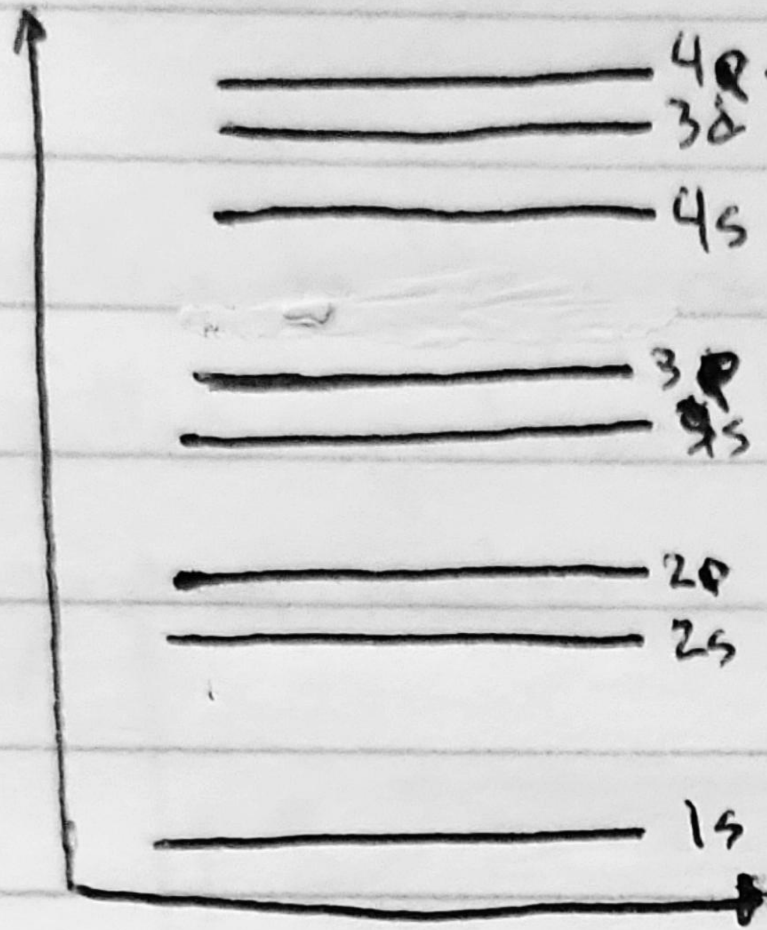
- The last equation only accounted for the atoms trapped with 1 quantum number, $n$
- Though there are 4 different quantum numbers $n, l, m_l, m_s$
- Every unique set of quantum numbers describes an ~~atom~~ electron in the atom.

Quantum Numbers.

- $N \to n$
  - n is the principle quantum number
  - Like the hydrogen bohr atom it sets the total energy for various quatized electron orbits. (electron shell)
  - n, sometimes have letter names: K, L, M, N, O, P
  - $n \to \infty$
- $L \to l$
  - This describes the angular momentum of the electron
  - The first l values have letter names: s, p, d, f, g, h, i, j
  - Sober Physicists Dont Find Giraffes Hiding In Jars.
  - $l = 0 \to$ ~~nel~~
- $m_l$ - this is the magnetic quantum number.
  - In a magnetic field the orientation of the electron orbit is quantized.
  - $m_l = -l$ or $+l$, for a total of $2l+1$ values.
- $m_s$ - this is the electron spin quantum number.
  - There are only 2 possible spin states.
  - $m_s = +1$ or $-1$

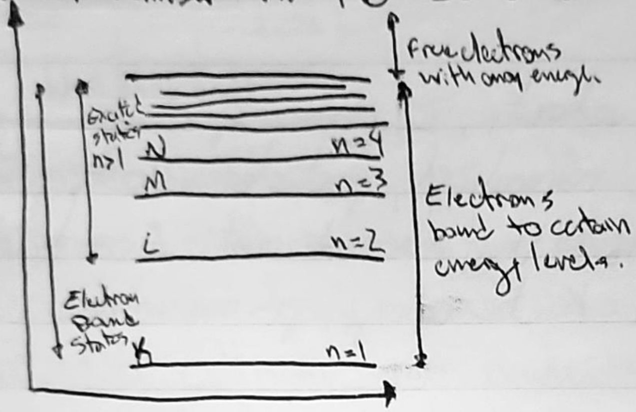
| n | l | $m_l$ | name |
|---|---|---|---|
| 1 | 0 | 0 | 1s |
| 2 | 0 | 0 | 2s |
| 2 | 1 | -1, 0, +1 | 2p |
| 3 | 0 | 0 | 3s |
| 3 | 1 | -1, 0, +1 | 3p |
| 3 | 2 | -2, -1, 0, +1, +2 | 3d. |

# The Order of the Energy Levels



OOS X Rays.

X Ray Generation.

- When building atoms electron by electron, the electron orbitals filled up from lowest energy up. using the principle quantum number n. The zero energy level is when $n=\infty$
- 

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- The highest energy photon one can get is -13.6 eV which is the K shell electron (Hydrogen)
- For other elements → $E_{n} = Z^2 \frac{-13.6}{n^2}$

- A ~~rays~~ way to knock out low-level electrons is needed to produce x-rays.
- A current I is sent through a wire to a cathode where electrons are released through a potential, V, where they hit an anode. The electrons collide with metal and knock out electrons
- If you want a 10KeV xray, you need a minimum of 10 KeV to knock out an electron from an orbital.

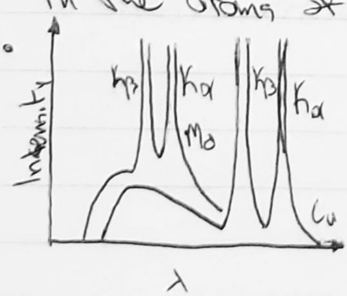
# Einstein's Relativistic Corrections

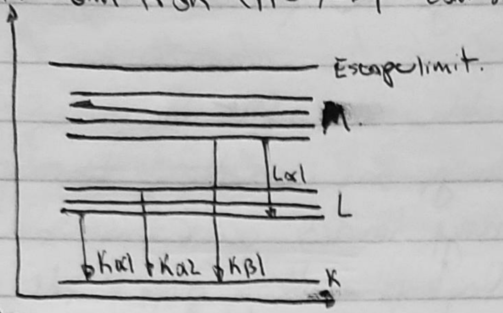
- $m(v) = \frac{m_0}{\sqrt{1-\frac{v}{c}}} = \frac{m_0}{\sqrt{1-\beta^2}} = \gamma m_0$
- $E = mc^2$
- $E_K = E - E_0 = (\gamma - 1)E_0$
- $E^2 = E_0^2 + p^2c^2$
- v is the particle velocity, c is the speed of light in a vaccum, $\beta$ is the normalized particle velocity, m(v) is the mass at velocity v, $m_0$ is the mass at rest, E is total energy, $E_0$ = rest energy, $E_K$ = Kinetic energy, p = momentum.

# Interactions of Electrons with Matter

- Electrons traverse through matter and as they do, they go through coulomb interactions and collisions.
- This causes lose in kinetic energy, or a change in direction.

# X-Ray Generation

- High Energy electrons hit and knock out anode electrons out of the low lying orbitals in the anode atoms. Electrons from higher orbitals drop down to lower energy levels. Extra energy is released as x-rays. Characteristic x-rays are from electron transitions between inner orbitals in the atoms of the anode material
- 

- XRay names are given according to the final energy state of the electron. Sub names in greek letters are given for which orbital it came from ($n=4 \rightarrow 1$ can be denoted as $K_\gamma$)
- 

- "Bremsstrahlung" radiation is the low background radiation.
- Electrons slow down as they enter the anode material, through interactions with the atoms.
- Inelastic collisions with nuclei heats the anode material
- Colomb attractions, decelerate the electrons, who then emit radiation.
- Below a certain energy, any radiation emitted by the slowing electrons is absorbed by the anode material, and heats it.
- Little energy is lost when dealing with the medium of air.

Interactions of Photons with Matter

- The photon interactions may be with a tightly bound electron, with an essentially free orbital electron, or the field of the nucleus
  - Tightly bound orbital electron - binding energy is larger than the energy of the photon.
  - Freely bound orbital electron - binding energy is much less than the energy of the photon.
- During the interaction the photon might scatter elastically or inelastically
  - Elastic - Photon does not loose energy
  - Inelastic - Photon ~~does not~~ looses some energy.

# Rayleigh Scattering.

- Also called coherent scattering, the photon interacts with bound orbital electron.
- The event is elastic in the sense that the photon loses essentially none of its energy and is scattered through only a small angle. Since no energy transfers occur from the photon to charged particles, Rayleigh scattering plays no role in the energy transfer.

# Compton Scattering.

- The Compton effect represents a photon interaction with an essentially "free and stationary" orbital electron. The incident photon energy, $h\nu$, is much larger than the binding energy of the orbital electron. The photon loses part of its energy in the recoil and is scattered as a new photon with new energy $h\nu'$
- $h\nu = h\nu' + KE$
- $h\nu' = \dfrac{h\nu}{1 + \frac{h\nu}{mc^2}(1-\cos\theta)}$ } Photons new frequency
- $\delta\lambda = \dfrac{h}{m_e c}(1-\cos\theta)$ } change in photon $\lambda$
- $E_{tr} = h\nu \dfrac{\alpha(1-\cos\theta)}{1+\alpha(1-\cos\theta)}$ } KE of the knocked out $e^-$
- $\alpha = \dfrac{h\nu}{m_e c^2}$ and "tr" is transferred energy.

Photoelectric Effect

- The photon interacts with a tightly bound orbital electron of an attenuator and disappears, while the orbital electron is ejected from the atom as a photo-electron with KE given as a function of the binding energy.
- $E_{Tr} = h\nu - E_b$

Pair Production

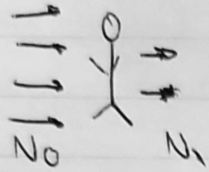
- In pair production the photon disappears and an electron-positron pair with a combined KE equal to $h\nu - 2m_ec^2$ is produced in the nuclear coulomb field
- Since Mass is produced out of photon energy in the form of an electron-position pair, pair production has an energy threshold of $2m_ec^2 = 1.02$ MeV.
- When pair production occurs in the field of an orbital electron, the effect is referred to as triplet production, and three particles (electron-positron pair and the orbital) share the available energy. The threshold for this effect is $4m_ec^2$.
- The probability for pair production is zero for photon energies below the threshold energy and increases rapidly with photon energy above the threshold.

Photoelectric or Compton

- Which occurs depends on the photon energy and binding energy. If $h\nu >> E_b$, then Compton. If $h\nu \sim E_b$ then photoelectric is more likely.

# X Ray Attenuation

- In many cases depending on the Z and $h\nu$, the X Ray wont make is out of the patient.
- The intensity of a single narrow beam is
  $N = N_0 e^{-\mu x}$, $\mu$ is the linear coefficient, $N_0$ is the original amount of photons

- 

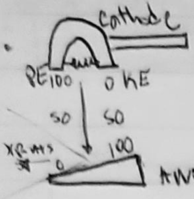

- The half-value layer is defined as that thickness of the attenuator that attenuates the photon beam intensity to 50% of the original value.
- $x_{\frac{1}{2}} = HVL = \frac{\ln 2}{\mu}$
- Linear Coefficient.
  - Has units of $cm^{-1}$
  - Mass attenuation coefficient $\mu_m = \frac{\mu}{\rho}$ units of $\frac{cm^2}{g}$
- For use in measure the amount of energy absorbed by tissue, there are 2 additional coefficients
  - $E = E_0 e^{-\mu_{tr} x}$
- Energy Transfer Coefficient.
  - $\mu_{tr} = \frac{\mu E_{tr}}{h\nu}$
- 2 Ways to Characterize Attenuation
  - ① # of photons that make it through the material ($N = N_0 e^{-\mu x}$)
  - ② Amount of Energy transfered into the particles ($E_{tr} = E_0 (1 - e^{-\frac{\mu_{tr}}{\rho} \rho x})$)

# Ionizing Radiation

- Radiation has 2 main categories
  1. Ionizing - can ionize matter direct or indirectly.
     1. - Directly Ionizing Radiation - electrons, protons, α particles, and heavy ions.
     2. - Indirect Ionizing Radiation - photons (x rays, γ rays) and neutrons.
  2. Nonionizing - cannot ionize matter.

006 X Rays.

# X Ray Generation.




- High Energy Electrons
- Low Energy Electrons

- Electron transitions from the L, M, or higher shell to the K shell emit characteristic K x-rays.

# Photoelectric Effect

- The absorption of a photon knocks out a K shell electron
- Probability of PE occurring $\propto \frac{Z^3}{(h\nu)^3}$

- If you want to stop x-rays, use a high Z material
- Large differences in transmission between adjacent tissues occur at lower energies, which enhances contrast.

# Rayleigh Scattering

- No absorption of photon energy but the photon changes direction slightly
- Probability $\propto \frac{Z}{(h\nu)^2}$
- RS is not a big problem for X-ray imaging.

# Compton Scattering.

- Probability $\propto Z$ and decreases with energy.
- Compton Scattering in the forward direction can seriously affect the image quality.

## Pair Production

- Pair Production will not happen with diagnostic x-rays but will happen with nuclear medicine.

## Things to Consider

- ① Its the x-rays that make it through the patient that make the image
② The x-rays that dont make it through contribute to radiation dose of the patient.
③ How x-rays dont make it through effects the quality of the image.

## X-Ray Attenuation

- The mass attenuation coefficient $\mu_m = \frac{\mu}{\rho}$ for compounds

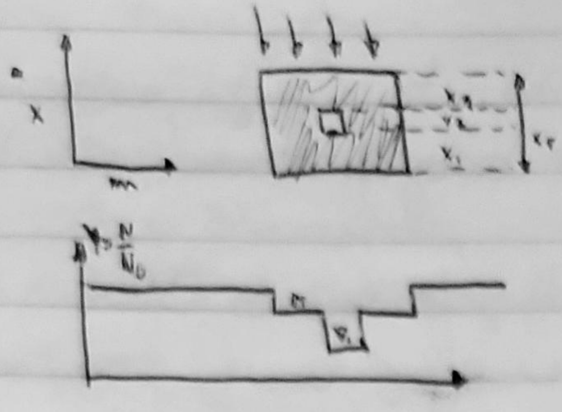
can be estimated by the average of the constituent element

$$\left(\frac{\mu}{\rho}\right)_{compound} = \sum_{i=1}^{N} m_i \left(\frac{\mu}{\rho}\right)_i$$ where $m_i$ is the mass fraction component

## X-Ray Contrast

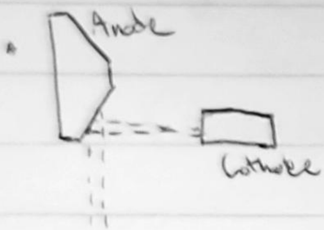
- Contrast is the difference between the light and dark part of an image
- $C_{AB} = \frac{N_A - N_B}{N_A}$
- Let the Yield be $Y = \frac{N}{N_0} = e^{-\frac{\mu}{\rho}\rho x}$
- $C_{AB} = \frac{Y_A - Y_B}{Y_A} \rightarrow 1 - \frac{Y_B}{Y_A}$.

# X-Ray Contrast: Simple Limits




- Contrast is known to be $1-e^{-(\frac{\mu}{\rho})_T \rho_T (x_1+x_3-x_4) - (\frac{\mu}{\rho})_B \rho_B x_2}$
- To maximize contrast only $\left(\frac{\mu}{\rho}\right)_T$ and $\left(\frac{\mu}{\rho}\right)_B$
- The only way to alter the parameters is through their dependence on the energy of the X-Ray. In most case the only control we have is from the energy.

# X-Ray Spot Size

- 


# X-Ray Focusing Cup.

- Focusing cup slot width determines the focal spot width

# X-Ray Focal Spot and Focal Length

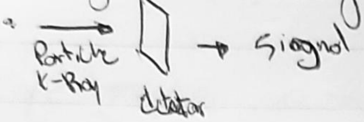
- Magnification = $M = \dfrac{\text{Source to Image Distance}}{\text{Source to Object Distance}}$
- Blurring = Width of blurring = $(M-1)\times(\text{focal spot size})$

# X-Ray Blurring Due to Compton Scattering

- Photoelectric Effect is preferrable to Compton scattering for the low-Z atoms in biological tissue, since there are few secondary X-Rays.
- When the contrast is small, it becomes difficult to tell the difference from the regions causing compton scattering, thus results in blurred images.
- To quantify this reduction due to scattering we refer to the primary to scattered photons; $S/P$ ie. # of compton scattered photons vs # of primary photons.
- Contrast is reduced by a factor of $\dfrac{1}{1+\left(\frac{S}{P}\right)}$

007 - X Rays.

## X Ray Radiography

- Projection imaging is the acquisition of a 2D image of a 3D anatomy.
- Projection radiography is a transmission imaging procedure.
- 


## X Ray Dettectors

- QDE - Quantum Detection Efficiency - the probability of detecting the incident radiation at a given photon energy.
- CE - Conversion Effect - the transfer of an absorbed X Ray energy into an amplified signal that is used to create an image.
- DQE - Detection Quantum Efficiency - the efficiency of info capture
  - $DQE = \dfrac{(\text{Signal to noise of the final image})^2}{(\text{True signal to noise of the incident radiation})^2}$
- DQE $\neq$ QDE

## X-Ray Film

- Considered the analog technique.
- The film relies on scintillators to increase efficiency of detecting the X-Rays by changing one x-ray to many lower energy UV and visible light photons
- Conversion factor $f_c$ = # of UV photons created for every x-ray
- The more efficient the detector, the fewer x-rays needed.

Scintillator Screens

- Scintillator screens increase the chances of detection
- The trade off is thickness & the film can similar

Modular Transfer Function.

- Describes resolution properties of an imaging system
- Can be measured with test strips
- Wider the MTF, the better the resolution

Conversion Efficiency

- Total CE of a screen-film combination refers to the ability of the screens to convert the energy deposited by the absorbed x-rays in to film darkening or optical density
- CE depends on:
  - Intrinsic CE of phosphor
  - Efficiency of light propagation
  - Efficiency of the film emulsion in absorbing emitting light.
- CE ↓, Spatial resolution ↑

QDE

- How efficient the screen detects x-ray photons that are incident upon it.
- Absorbed x-rays deposit energy and some energy is converted to light photons

# Noise

- Local variations in film darkness, not representing variations of attenuation in patient.
- Visual perception of noise is reduced (better image) when the # of detected x ray photons increase.

# Optical Density

- Increased x-ray exposure → developed film becomes darker.
- Transmittance is the fraction of incident light → $T = \frac{I}{I_0}$
-
- $OD = -\log T = -\log \frac{1}{T} = \log \frac{I_0}{I} = T = 10^{-OD}$
- Some films need longer exposure times to achieve a greater OD.

# Digital X-Ray Detectors.

- UV light is detected by CCD (charge coupled devices) which convert light intensity to electrical voltage which is then recorded into a computer.
- Pixel size contributes to a loss of signal

# X Ray Dose & Beam Hardening

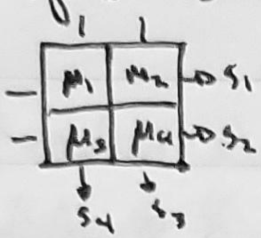
- X Ray lose is either scattered or absorbed
  - Can deposit thermal energy in tissue
  - Ionize chemical bonds.
- Radiation is measured in 2 ways
  - the amount of ionize due to radiation - exposure (rose)
  - the amount of energy deposited to radiation - absorbed dose.

# 008 - X-RAYS FLUOROSCOPY & MAMMOGRAPHY.

- Fluoroscopy - real time x-ray viewing of the patients.
- Mammography - The use of x-ray imaging
- Notifiers of Breast Cancer.
  - Irregular shaped masses
  - Cluster of micro-calcifications
  - Distortions of ~~breast~~ ~~ab~~ anatomical structures.
- Problems In Mammography.
  - Breast tissue is fat and glandular tissue. and its hard to differentiate from cancerous tissue.
  - If micro-calcification correlates with cancer that means extreme resolution is required.
- Some Components of ~~XRa~~ Mammography machines.
  - Special X-Ray Tubes
  - Breast compression Devices
  - Optimized Screen/film ~~Det~~ Detector systems.

009.- X-RAYS COMPUTERIZED TECHNOLOGY.

- CT image create cross-sectional images of the body.
- The projection of rays from the machine is either parallel beams. or fan beams.
- The images are put together by arrays and having the computer solve them




- The computer them sets up a matrix of ~~[illegible]~~ pixels in which they are mapped.
- CT images use filtered back projection which builds up a CT image by reversing the acquisition.
- Slice Sensitivity Profile - how thick a section is imaged and to what extent details within the section contribute to the signal.

001 ~~Nuclear~~ Nuclear Physics Concepts.

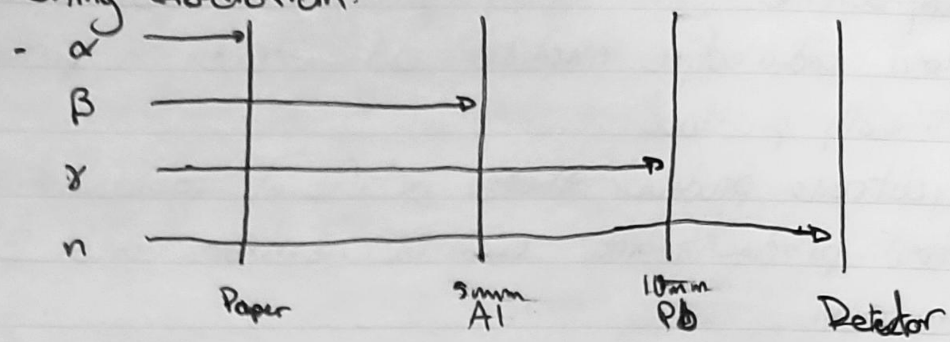
- X-Rays fail to detect ~~organ~~ bodily function/chemistry.
- This is where MRI's come into play
- They function off the quantum spin of elements and gamma radiation.
- Mass Defect - The difference in mass of an isotope and its mass number.
- Binding Energy - Energy that holds a nucleus together.
- Alpha Decay - Spontaneous Emission of $\alpha$ particle
  - $^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}X + {}^{4}_{2}He^{+2}$ + energy.
- Beta-Minus Decay - Spontaneous emission of a $\beta^-$ particle
  - $^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \bar{v}$ + energy.
- Beta-Plus Decay - Spontaneous emission of a $\beta^+$ particle
  - $^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + v$ + energy.
- Electron Capture Decay - The nucleus captures an electron from its orbit and combines with a proton ~~and~~ to make a neutron
  - $^{A}_{Z}X + e^- \rightarrow {}^{A}_{Z-1}Y + v$ + energy.
- Isomeric Transition - the daughter element of one of the reaction above is formed in an excited state
  - $^{Am}_{Z}X \rightarrow {}^{A}_{Z}X$ + energy.
- The left over mass is converted into that is what ~~?~~ in the KE of the particle & the creation of photons.
- Activity - # of radioactive atoms undergoing nuclear decay per unit time. $(-\frac{\Delta N}{\Delta t})$ (units = Bq).

O12 Nuclear Isotopes & radionuclide in biology and medicine.

- Decay Scheme - the decay process of a specific radionuclide.
- Most radioactive nuclides administered in patients are artificially produced.
- Cyclotrons produce these artificial radionuclides.
- Most products are rich in neutrons and $\beta^-$ particle emission.
- Radiopharmaceuticals
  - Important Factors in choosing on ~~the~~ radionuclides
  - Low Radiation Dose
  - High Target/Non-target Activity
  - Safety/Convenience/Cost effectiveness
  - Compartmental Localization and leakage - ingest by a means not intended
  - Cell Sequestration - ability of the spleen to recognize RBC.
  - Passive Diffusion - Disruption of the blood-brain barrier
  - Active Transport - Movement of ions/molecules by diffusion.
  - Chemotaxis - Movement of an organism is response to a chemical stimulus
  - Receptor Binding

013 Nuclear Radiation and Biology.

- Blocking Radiation.




- Fluence - Number of photons passing per area
  - $\Phi = \frac{\text{Photons}}{\text{Area}}$
- Flux - Number of photons passing per area per time.
  - $\Phi = \frac{\text{Photons}}{\text{Area} \cdot \text{time}}$
- Energy Fluence - Energy per area.
  - $\Psi = \frac{\text{Photons}}{\text{Area}} \cdot \frac{\text{Energy}}{\text{Photon}} = \Phi E_p$
- Kerma - Kinetic Energy Released in MAtter

Energy absorbed per Kg. →
- Absorbed Dose - $D = \frac{E}{m}$ units of Gy.

Radiation cause Biological Damage. →
- Equivalent Dose - $H = D W_R$. units of Sv.

includes a tissue weighting factor. →
- Effective Dose - $E = H_T W_T$ " " "
- Radiation Dosimetry - radiation dose quantities that cause biological damage are focused on.
- Deterministic Effects - Cell death.
  - Nausea, Vomiting etc.
- Stochastic Effects - Damage to chromosomes
  - Cancerous tumors etc.

014 Nuclear Radiation and Biology.

- Radiation Factors
  - Quality, Quantity, Dose Rate, Exposure Conditions.
- Biological Factors
  - Molecules Effects, cellular vs multicellular effects, Plant vs. Animal vs. Human.
- Stochastic Effects increase in probability with dose.
- Deterministic Effects increase in severity with dose.
- Radiation Interaction with tissue
  - Direct - Critical targets (DNA, RNA) directly ionized.
  - Indirect - Reacts with medium on create free radicals that interact with the critical targets.
- Linear Energy Transfer - LET - the amount of energy transferred per unit length ($\frac{eV}{cm}$).
- Factors Affecting Cellular Radio sensitivity.
  - Conditional Factors - physical/chemical factors that exist previous to irradiation
    - Dose Rate, LET, fractionation, Presence of $O_2$.
  - Inherent Factors - Biological characteristics of the cell.
    - Mitotic Rate.
    - Degree of Differentiation
    - Cell cycle phase.

# 16 - Nuclear.

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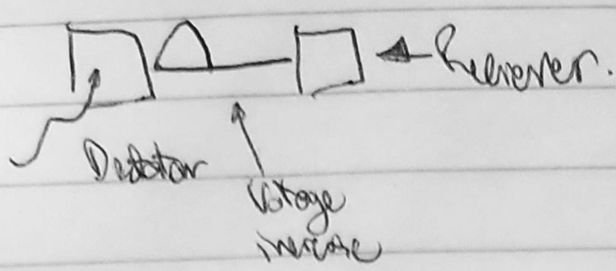
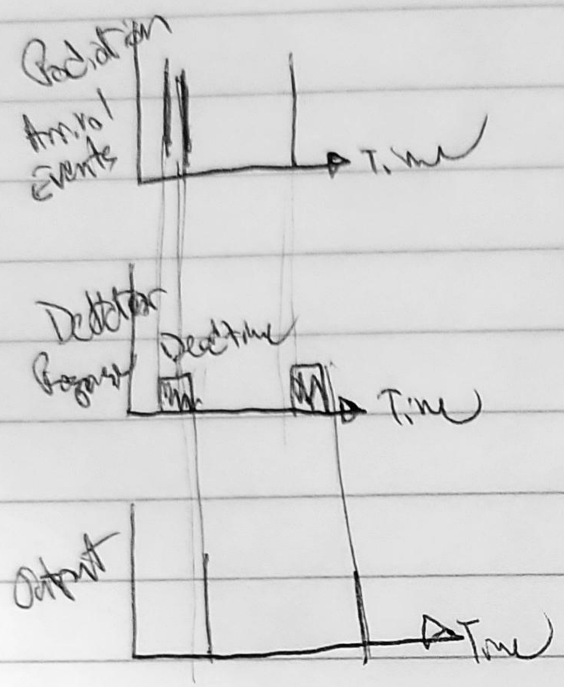
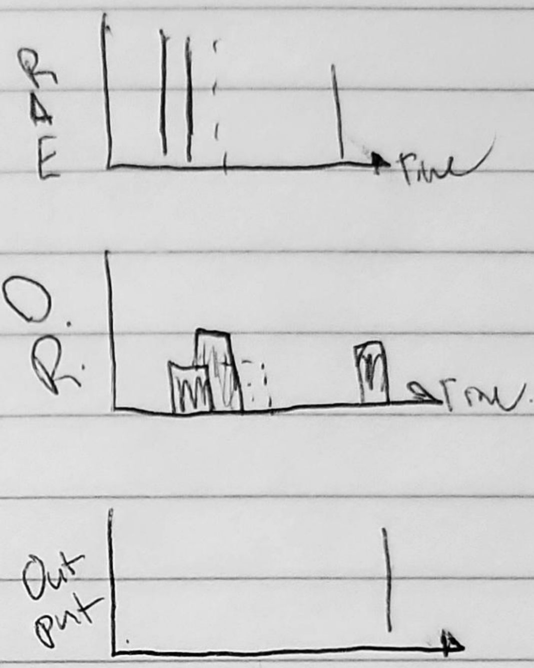



Non paralyzed



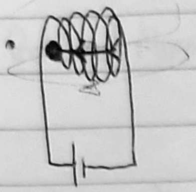

Paralyzed.

• Efficiency = $\dfrac{\text{Detected Radiation}}{\text{Emitted}}$

• Efficiency = $\dfrac{\text{reach detector}}{\text{emitters}} \cdot \dfrac{\text{detect}}{\text{reach detector}}$ or

018 - NMR.

- Magnetic Fields cannot penetrate ~~sp~~ super conductors.

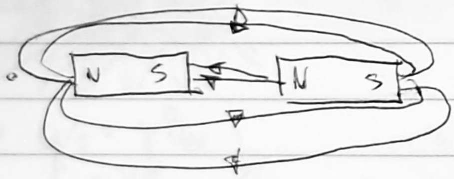
Slide 6: 

- $B = \frac{\mu_0 I}{2\pi r}$ $\mu_0 = 4\pi \times 10^{-7} \frac{T \cdot m}{A}$ Str8 wire

$B = \frac{\mu_0 I}{2R}$. ~~circle~~ loop.

$B = \frac{\mu_0 I N}{L} = \mu_0 I n$.

Flux $= \Phi = -\frac{N \Delta B A}{\Delta t}$



- $F = qvB\sin\theta$. $B = \text{Tesla} = \frac{N \cdot s}{C \cdot m}$

- RHR.

- $B = \frac{\mu_0 I}{2\pi r}$
$= \frac{(4\pi \times 10^{-7})}{2\pi}\left(\frac{0.8}{0.0525}\right)$
$= 2.5 \times 10^{-4}$ T.

$B = \frac{\mu_0 I}{2\pi r}$
$r = \frac{\mu_0 I}{2\pi B} \Rightarrow \frac{(4\pi \times 10^{-7})(7)}{2\pi(5\times10^{-5})}$.
$r = 0.0288$ m.

$B = \mu_0 I \frac{N}{L}$
$\frac{BL}{N\mu_0} = I$
$\frac{(5\times10^{-4})(.032)}{(430)(,32)} = I$
$0.0293\text{A} = I$

$F_{net} = ma$

$qvB = ma$

$\frac{qvB}{m} = a$

$\frac{(1.602 \times 10^{-19})(9.5)(1.2)}{1.67 \times 10^{-27}} = a$

$1.09 \times 10^{9} \ \frac{m}{s} = a$

$F_{net} = \frac{mv^2}{r}$

$qvB = \frac{mv^2}{r}$

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

$r = \frac{mv}{qB} = \frac{(9.11 \times 10^{-31})(6.27 \times 10^{5})}{(1.602 \times 10^{-19})(.55)}$

$= 6.482 \times 10^{-6}$ m

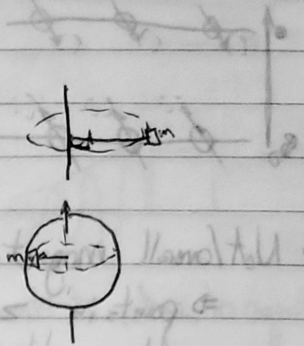
- Electric Dipole moment.

  $\vec{\mu}_{electric} = q\vec{d}$

- Magnetic Dipole moment

  $\vec{\mu}_{magnetic} = IA\hat{n}$

# NMR.



- $KE = \frac{1}{2}mv^2$
- Rotational Mass $\Rightarrow KE = \frac{1}{2} I \omega^2$

$$= \frac{1}{2}\left(\sum m r^2\right)\omega^2$$

Rotational acceleration $\Rightarrow \tau = I\alpha$

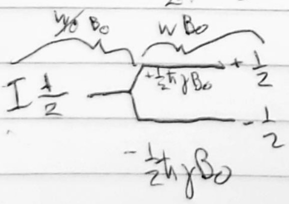
- Rotational momentum $\Rightarrow L = I\omega$

| | | |
|---|---|---|
| $p = mv$ | $L = I\omega$ | $F = \frac{d\vec{p}}{dt}$ |
| $F = ma$ | $\tau = I\alpha$ | |
| $KE = \frac{1}{2}mv^2$ | $KE = \frac{1}{2}I\omega^2$ | $\tau = \frac{d\vec{L}}{dt}$ |

- $\omega_0 = \gamma B_0$
- $f = \frac{\gamma B_0}{2\pi}$

Larmor Equation

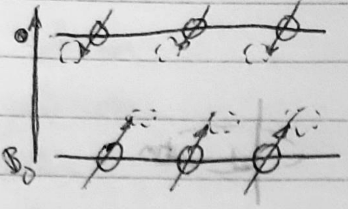
$\nu$ = frequency.




$\Delta E = \hbar\gamma B_0 = \hbar\nu_{EM}$ $\quad \nu_{EM} = \gamma B_0 = \omega_0$

NO IONIZING RADIATION IN MRI.

$$\frac{N_{EXCITED}}{N_{Ground}} = e^{-\frac{\Delta E}{k_B T}}$$



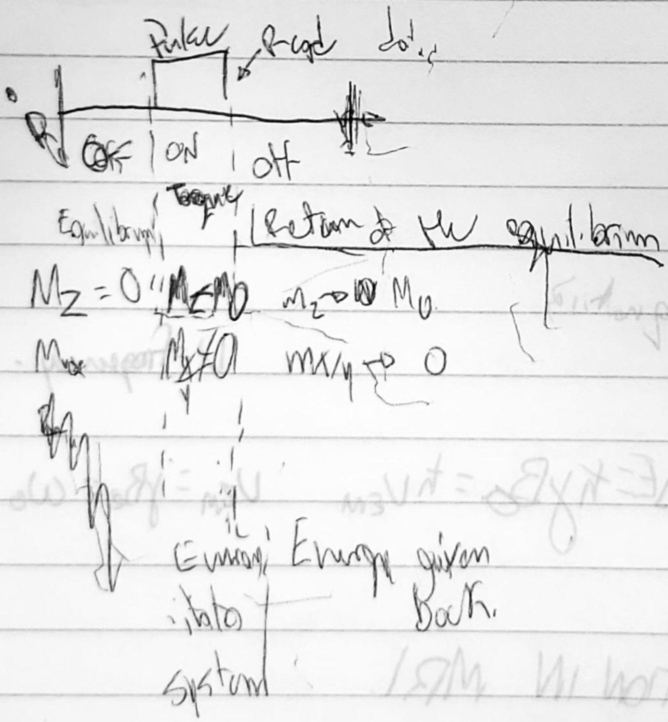

- Net/overall magnetization, $M_0$.
  - ⇒ points in z-direction
  - ⇒ At equilibrium

- $\omega_0$ Standard Model
  - $\omega_i$

- $(\omega_i - \psi\omega_i) \cdot \frac{1}{10^6}$

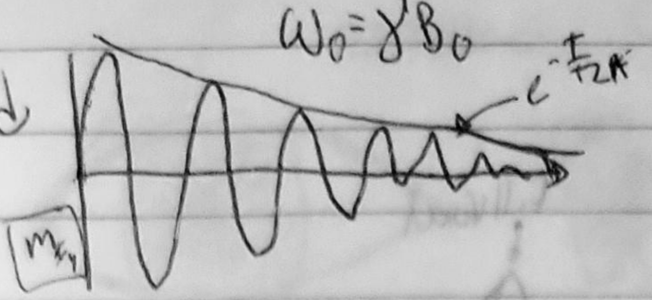
- $\frac{\gamma}{2\pi} = 42.56$ 42,560,000

  42,560,a




- $\theta = \gamma \cdot B_1 \cdot T$.

• Voltage induced in $B_1$ wire after pulse




Free induction decay.

Freely inducing decay because it wants to return to equilibrium.

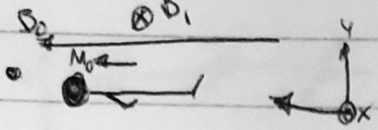
• We only magnetization in the xy direction.

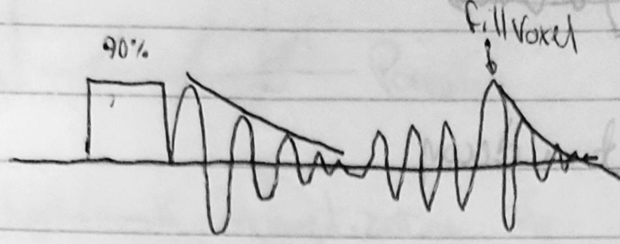
• Return to equilibrium but how?
- Primarily by collisions (Transfer of KE)

T2
• $M_{xy}(t) = M_{xy}(t=0)e^{-\left(\frac{t}{T2}\right)}$

• T2 - Microenvironments of chemical
$T2^*$ - Microenvironments of imperfect machines ($B_0$).

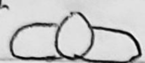
T1
• $M_z(t) = M_0\left(1 - e^{-\frac{t}{T1}}\right)$




- Larmor frequency $= \omega_0 = \gamma B_0$

- low magfield ⟷ high magfield
  Low Precession Freq. ⟷ high Precession Freq.



$-\Delta x \longleftarrow x=0 \longrightarrow +\Delta x$

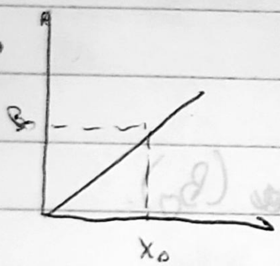
$B_0-\Delta B \longleftarrow B_0 \longrightarrow B_0+\Delta B$

$\omega_0-\Delta\omega \longleftarrow \omega_0 \longrightarrow \omega_0+\Delta\omega$

$\omega_0+\Delta\omega = \gamma B_0 + \gamma G \Delta x$

$\omega_{max} = \gamma B_0 + \gamma$ [redacted] $G \Delta x$

$\omega_{min} = \gamma B_0 - \gamma G \Delta x$




$$\frac{\text{Rise}}{\text{Run}} = \frac{(B_0+\Delta B)-(B-\Delta B)}{\Delta x-(-\Delta x)} = \frac{2\Delta B}{2\Delta x} = \frac{\Delta B}{\Delta x}$$

- Bandwidth $= \omega_{max} - \omega_{min} = \Delta\omega$

- $2\gamma G \Delta x = \Delta\omega$

$(2\Delta x)\gamma G = \Delta\omega$

$(FOV)\gamma G = \Delta\omega$

$(FOV)\gamma G =$ Bandwidth