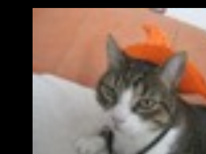


Ask Mish

Understanding PET, CT and MRI

A short and funny trip through Quantum Physics

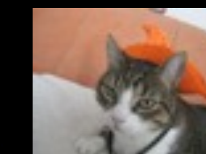
Ask Mish

Quantum Physics Phenomenons used in Medicine

Quantum Physics

Ask Mish

- studies fundamental particles
- these particles are also waves as opposite to classical physics where a particle is just a particle and wave is wave
- e.g. electron around nucleus moves like a wave creating a 'cloud' called orbital as opposite to "classical" particles moving on trajectories e.g Earth around sun
- quantum from Lat. (how much) refers to minimum amount; first used by Helmholtz



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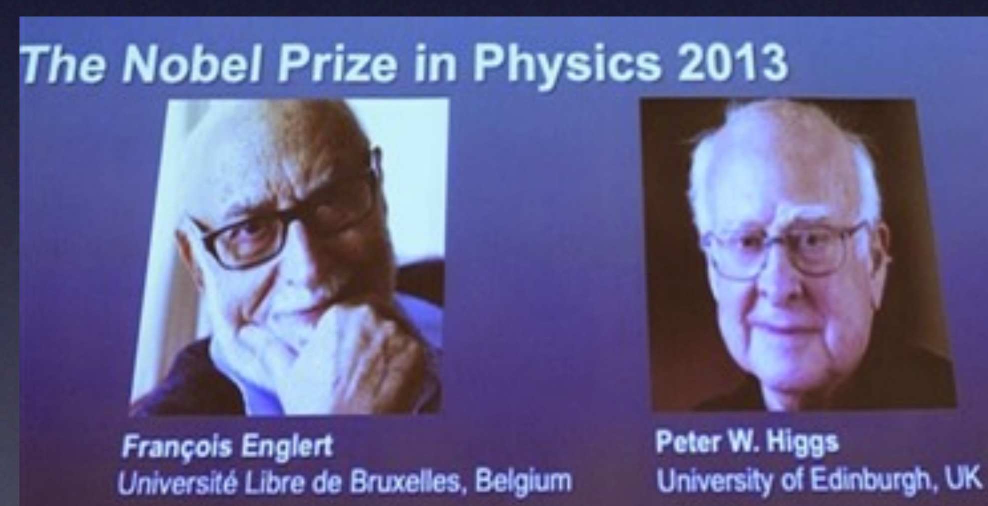
History: few milestones in quantum physics

- Democritus (460-370 B.C.) disciple of Greek philosopher Leucippus first described ATOM = cannot be cut (Gr. a + tomein) as the fundamental part of matter.
- 1983 - W and Z bosons
- 1995 - tau neutrino
- 2000 - top quark
- 2012 - Higgs boson



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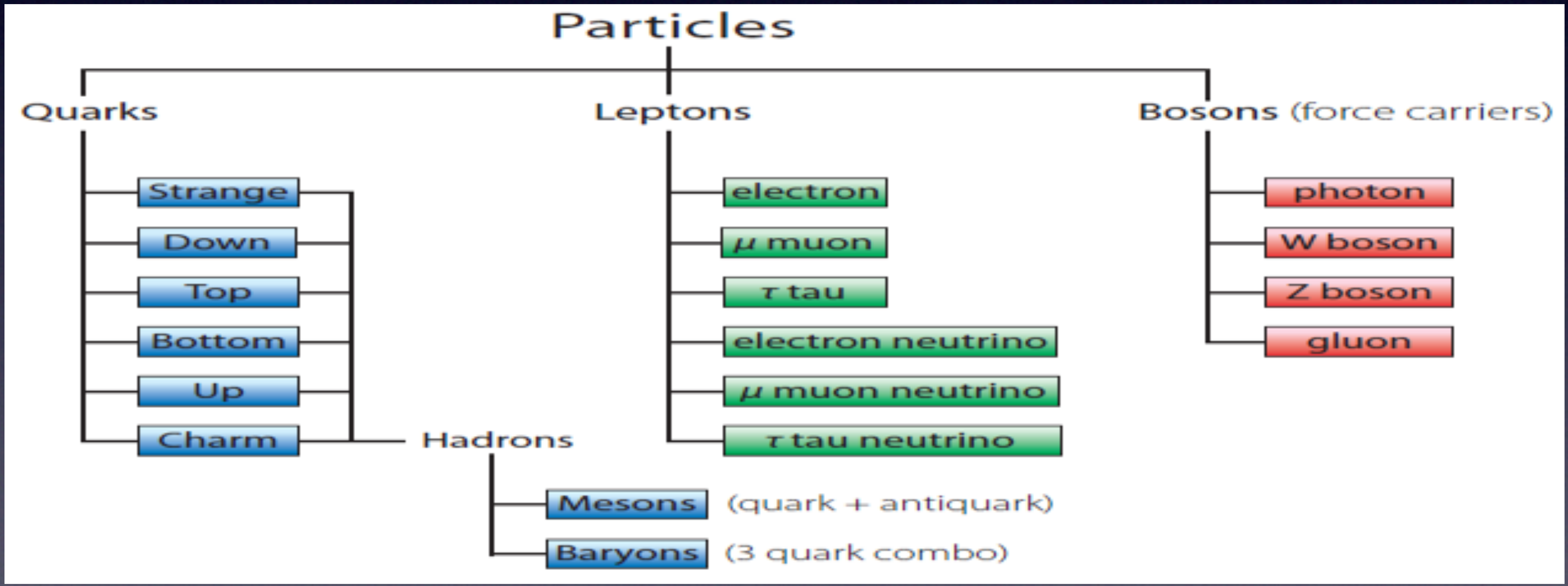
The Standard Model

- formulated in1970
- describes FUNDAMENTAL PARTICLES and their INTERACTIONS



Fundamental Particles- 2 types : F&B

• FERMIONS	• BOSONS
• 2 Fermions cannot be in the same • time and place =Exclusion Principle	• 2 Bosons can be in the same time and • place = not Exclusion Principle.
• create MASS : atoms, walls, people	• FORCE (Energy) carriers only
• spin 1/2	• Spin 1
• 2types: Quarks, Leptons	• photons, gluons, W,Z, H.

Fermions: Quarks & Leptons

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• QUARKS bind together 2 (Mesons), • 3(Baryons) 2,3= Hadrons (Thick)	• LEPTONS do not bind, • 1 only • = Thin
• 6 types: up/down, charm/strange, • top/bottom	• 6 types: electron, muon, tau • and neutrino for each
• charged: +2/3 up,charm, top	• charged: -1 electron, muon, tau
• charged: -1/3 down, strange, bottom	• not charged: neutrino, all 3 types

Origin of fundamental particles names

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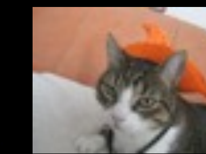
- Fermions : E.Fermi (1901-1954) of Italy and P.M.A.Dirac (1902-1984) of England describe the statistical rule which fermions obey

- Bosons : S. Bose (1894-1974) of India and A.Einstein (1879-1955) of Germany describe the statistical rule which bosons obey

- Quark : a drunk seagull from "Finnegan's Wake" by J.Joyce ordering 3 quarts of beer

- Leptons : from leptos (Gr.) meaning thin

The Standard Model:Fundamental Particles



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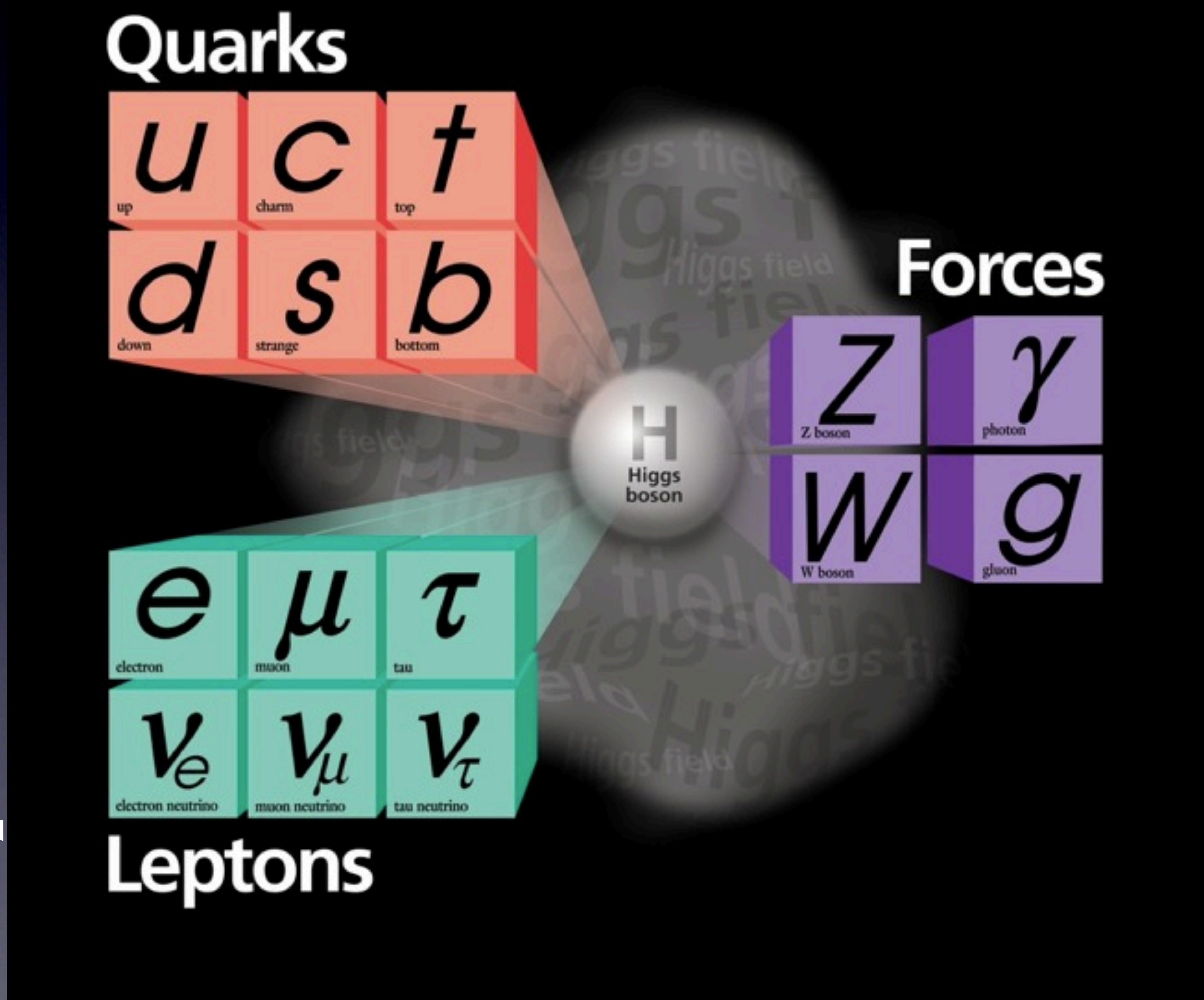
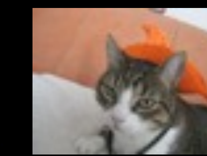
create MASS



FORCE carriers

Fundamental Particles : their names and location

Left column:found on Earth   Columns 2 and 3: not found naturally on Earth



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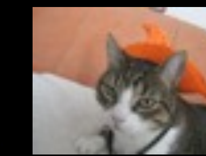
Quarks	up	charm	top	photons
	down	strange	bottom	gluons
Leptons	electron	muon	tau	W and Z bosons
	electron neutrino	muon neutrino	tau neutrino	Higgs boson

Bosons (right column)

Quarks & Leptons =mass creators



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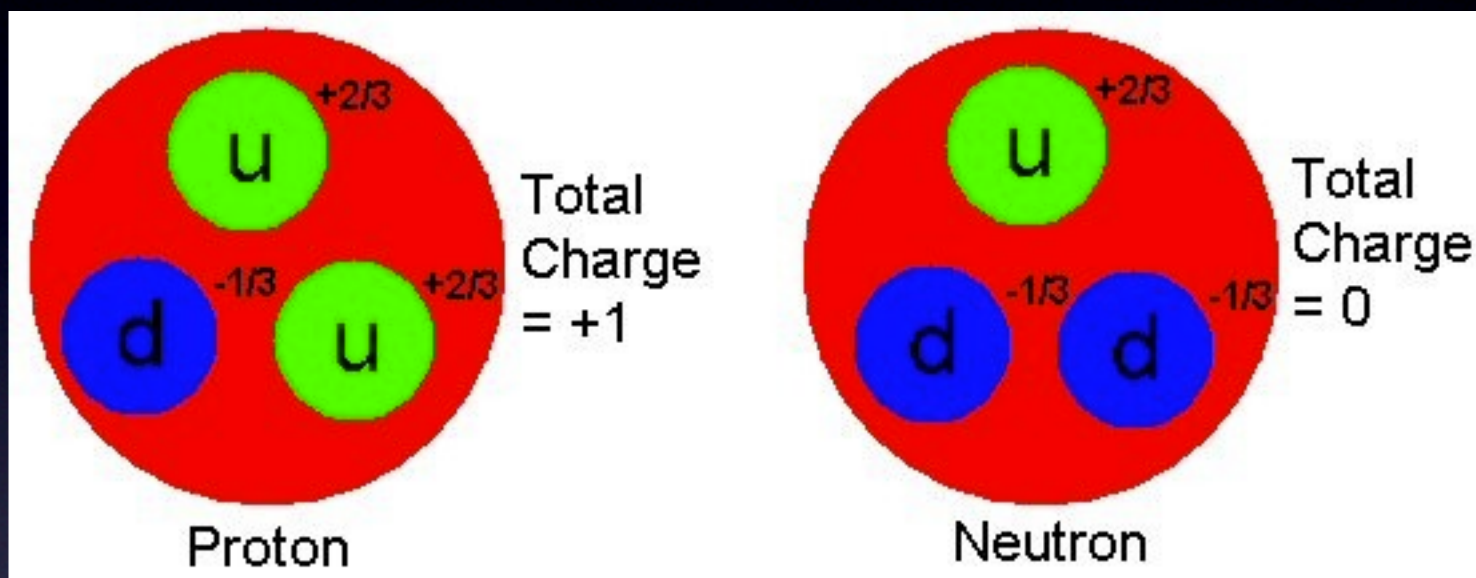
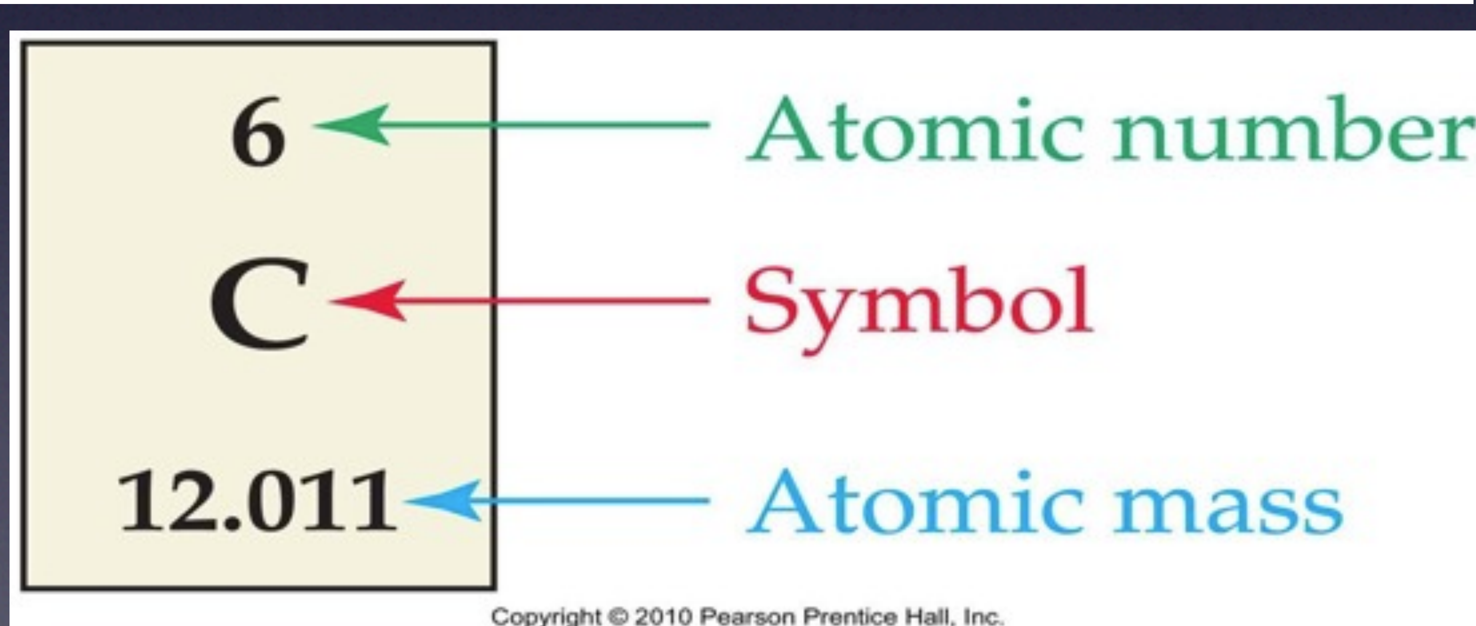
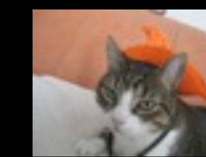




- 2 Q up+ 1 Q down= PROTON mass1, electric charge +1
- 1 Q up + 2 Q down= NEUTRON mass1,electric charge 0
- Q c/s t/b=not on Earth
- Total protons = atomic number Z
- Total protons + neutrons = nucleons A
- ELECTRON , mass 0, electric charge -1
- muon, tau greater mass, not found on Earth

Bosons= Force carriers



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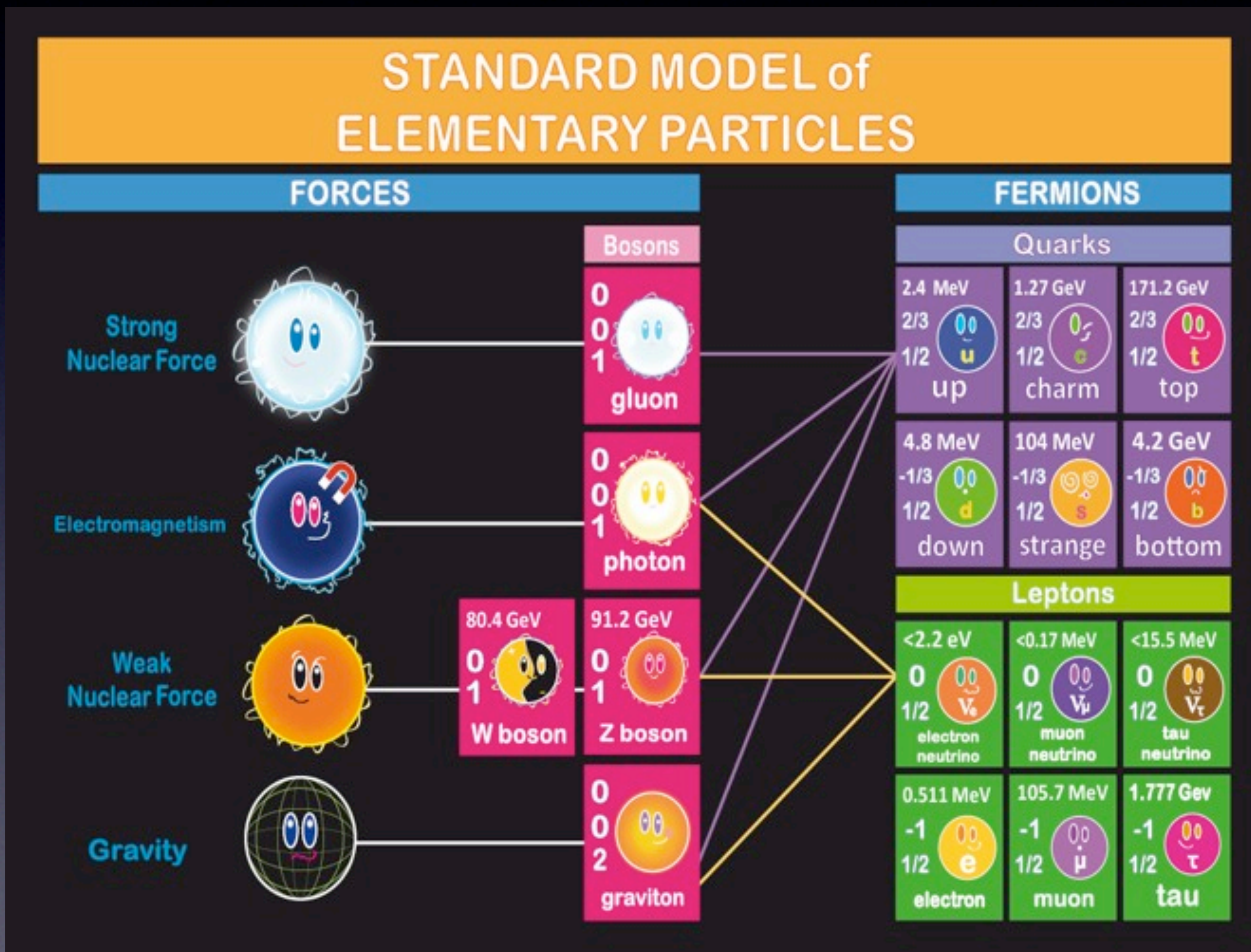
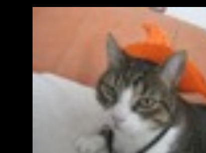


- Gluons carry Strong Nuclear Force, no mass/charge
- Photons carry Electromagnetic Force, no mass/charge
- W and Z boson intermediates Weak Nuclear Force huge mass, W:+1/-1, Z has no charge.
- Higgs boson intermediates the force that make the differentiation of fundamental particles in F&L, huge mass, spin 0



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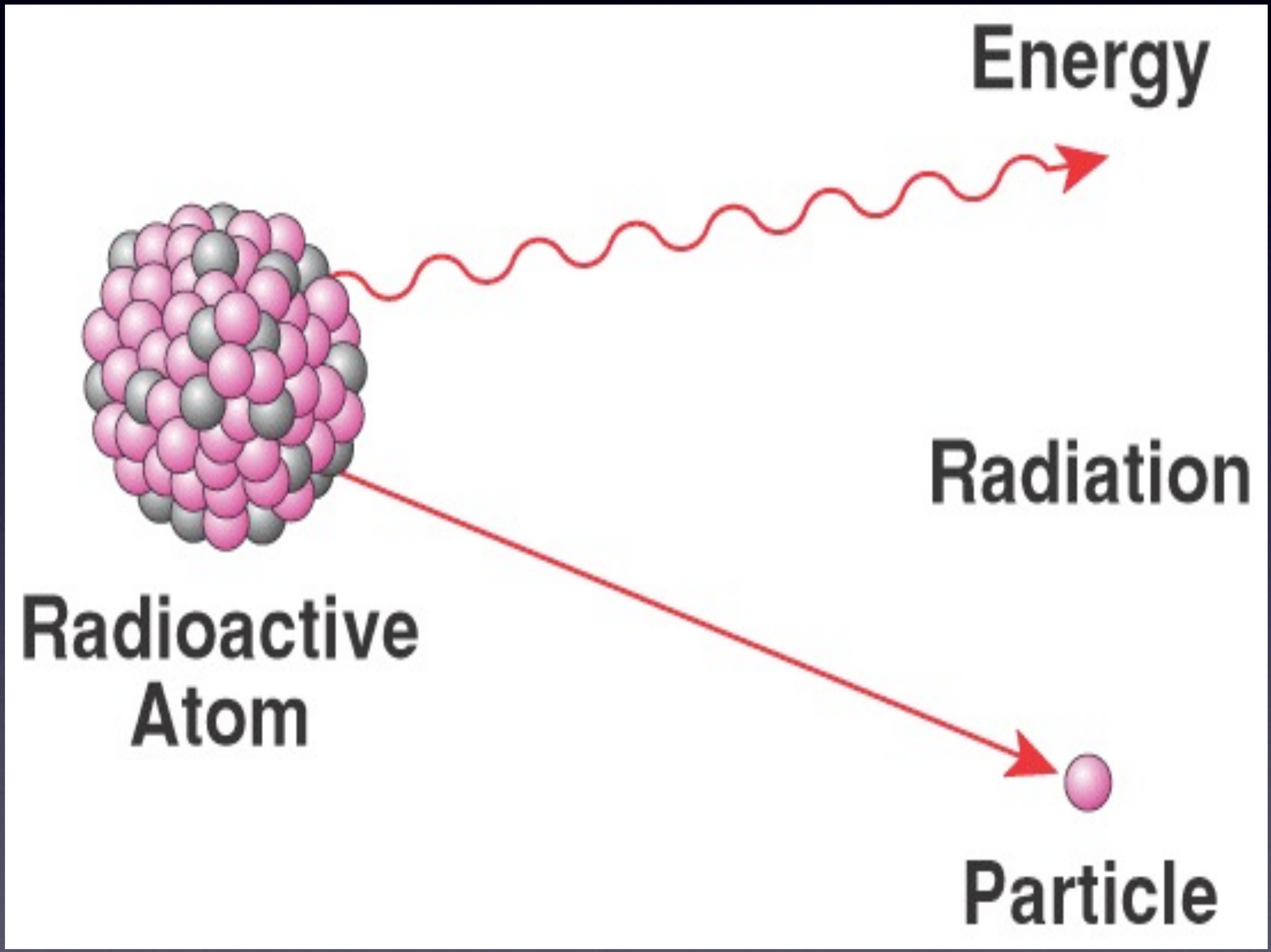
4 FORCES in the Universe

Strongest

- STRONG F through Gluons keep protons and nucleons together in nucleus
- WEAK F opposite of first one makes nucleus "explode" or decay ;
- ELECTROMAGNETIC F : between charged particles or electrons changing energetic levels
- GRAVITY F : between particles with mass
- S > EM >W > G (S=strongest force; G=weakest force)

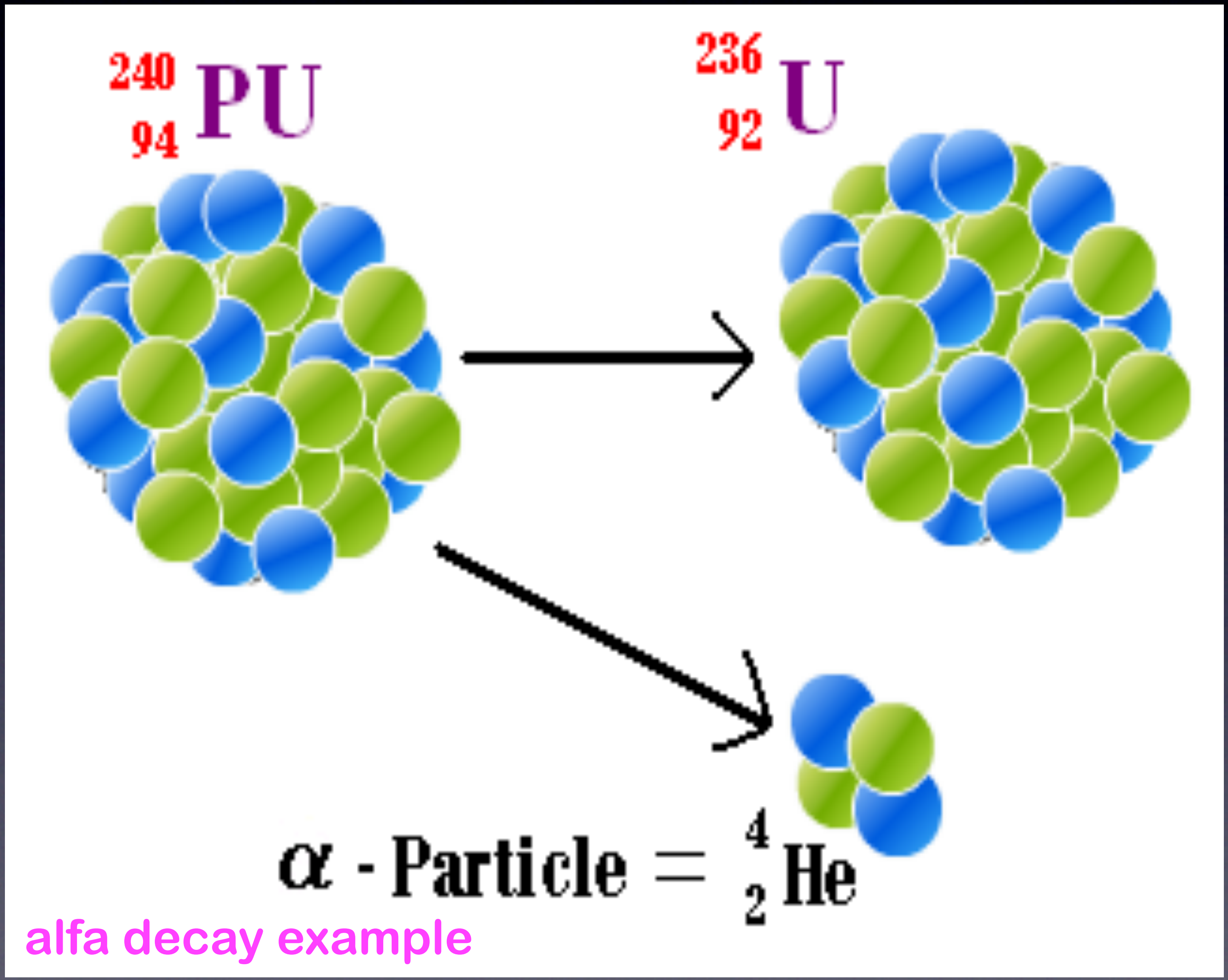
Weakest

Weak Force: Radioactivity : definition

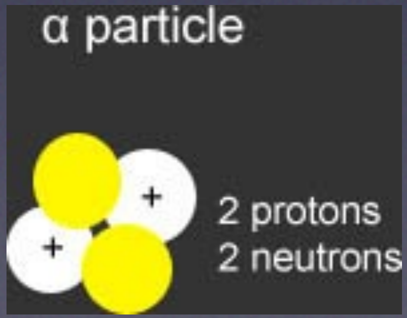


- Certain P/N (Protons/ Neutrons) ratios creates INSTABILITY so nucleus starts to lose "excess" particle to become stable (A/Z=stable) process called radioactive decay/radioactivity

Weak Force: Radioactivity -alfa particle



- there are 3 types of particles: alfa, beta + and beta - and one radiation -gamma- that the nucleus can lose in radioactivity.
- If nucleus loses 2P + 2N also called He nucleus or alfa particle this activity is called alfa radioactivity or alfa decay; usually Z>83



Radioactivity: beta negative particle

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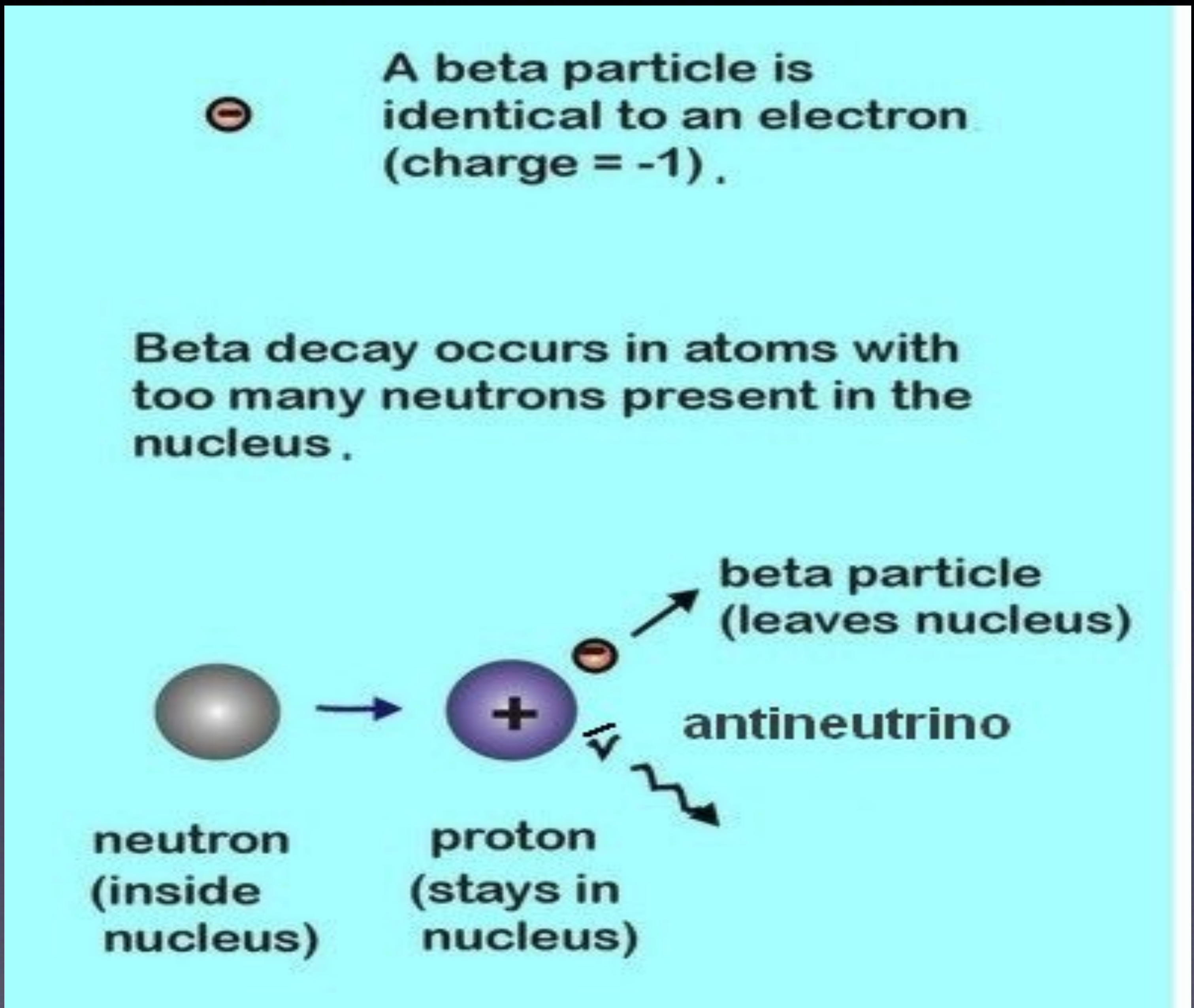
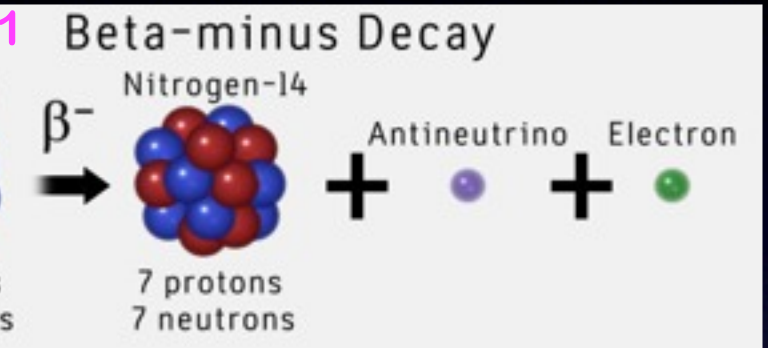
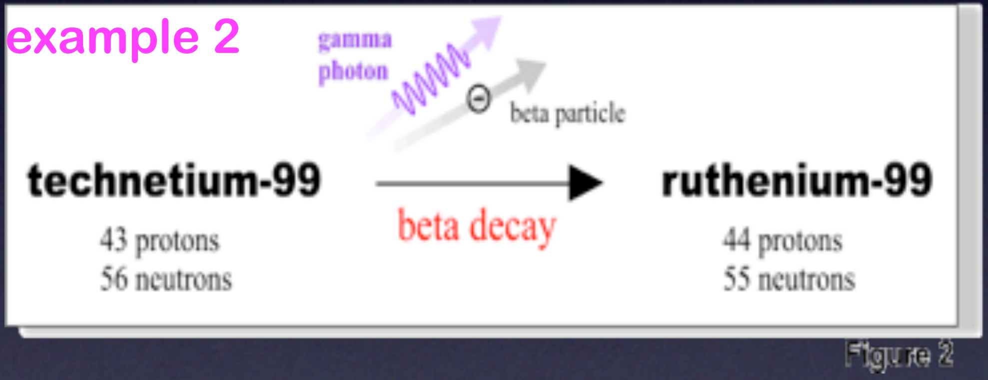


example1



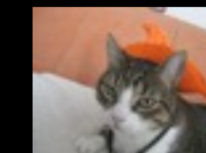
example 2



example 3

$$^{131}_{53}I \; \text{-->} \; ^{0}_{-1}e + {}^{131}_{54}Rn$$

Radioactivity: beta positive particle or positron



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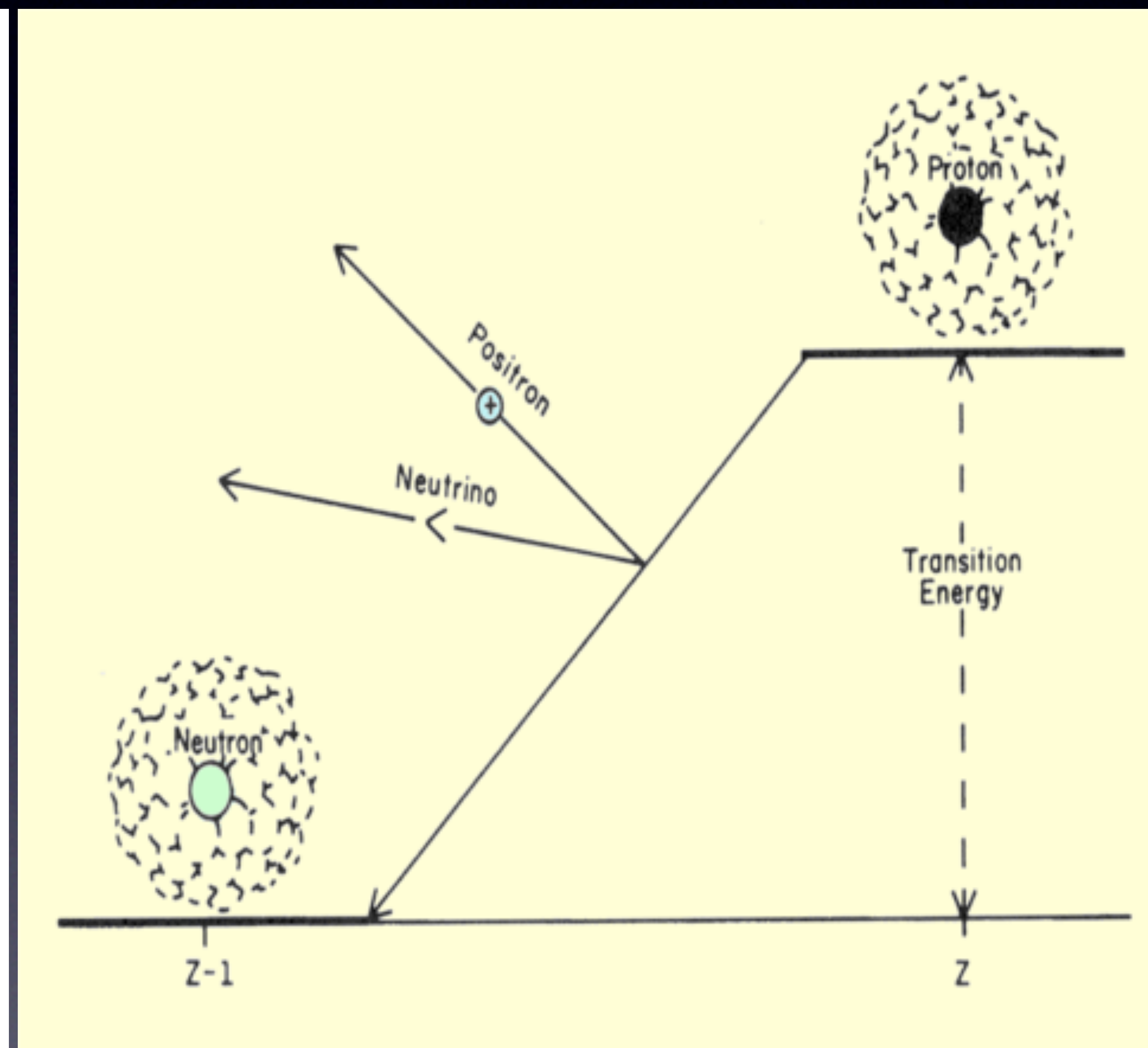
Positron Decay

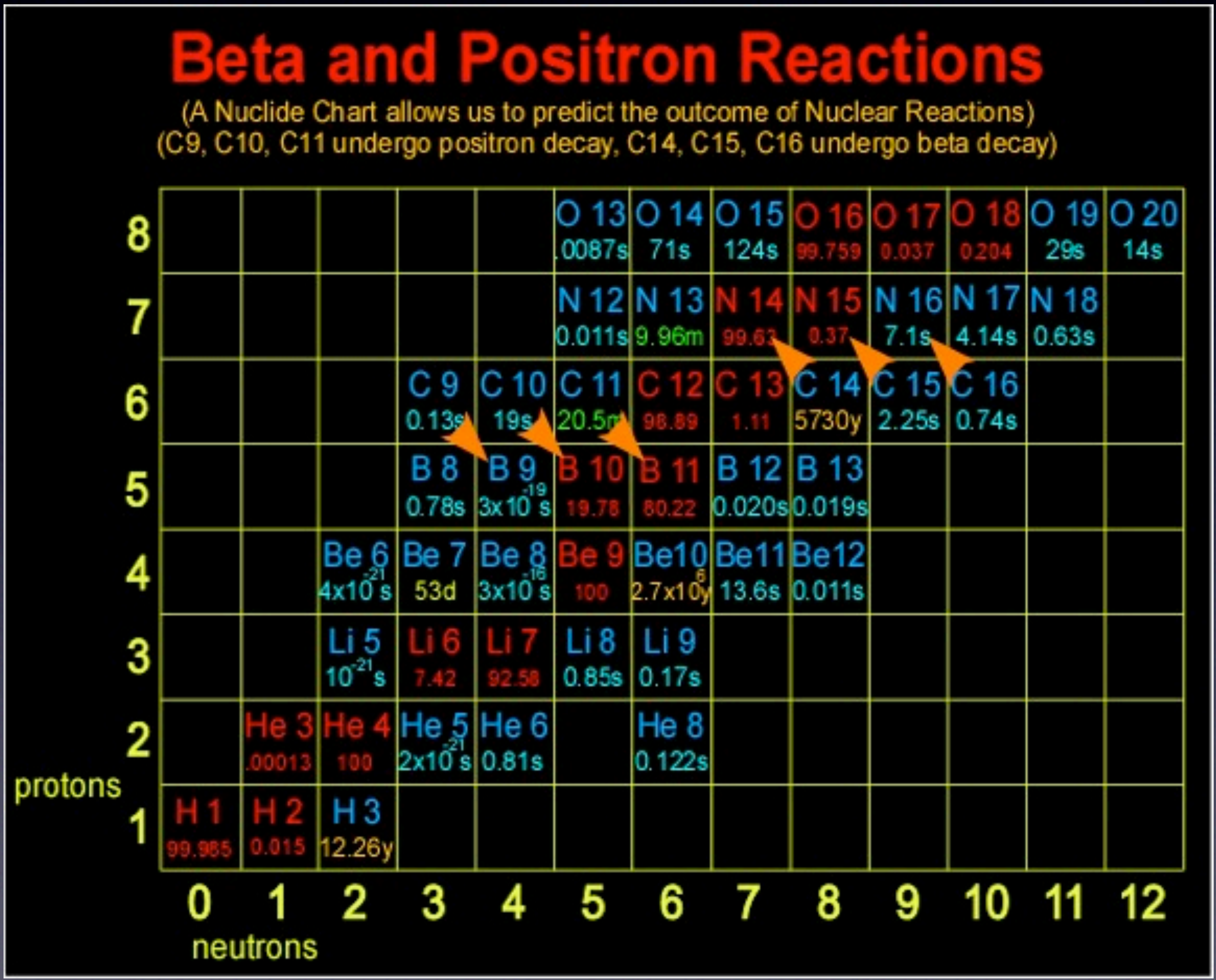
If the n/p ratio is too low, it may be increased by disintegration of a proton in the nucleus. This process is represented by the following equation:

$$ {}^{1}_{1}p \longrightarrow {}^{1}_{0}n + {}^{0}_{+1}e + \nu + \text{Energy} $$

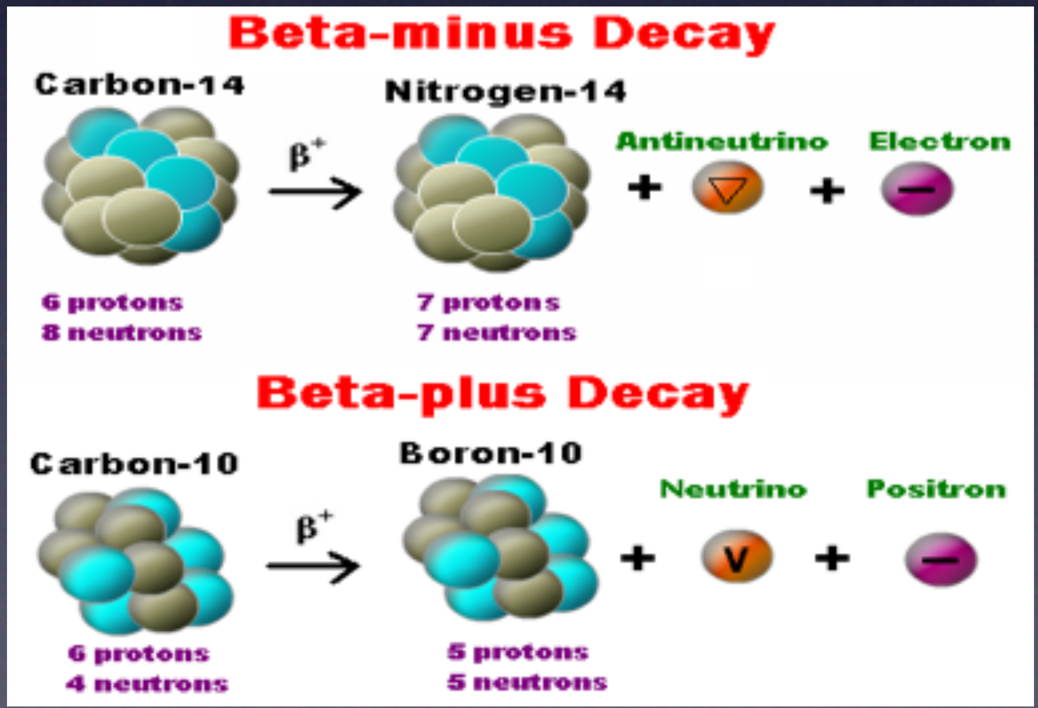
positron neutrino



Beta and Positron Reactions: how to predict the outcome



- Ratio Protons/Neutrons is determinant. Nucleus tend to lose excess particle.
- if N>P then N-> P (beta - decay) see C14, C15 and C16
- if P>N then P -> N aka beta+(positron) decay see C9,C10,C11

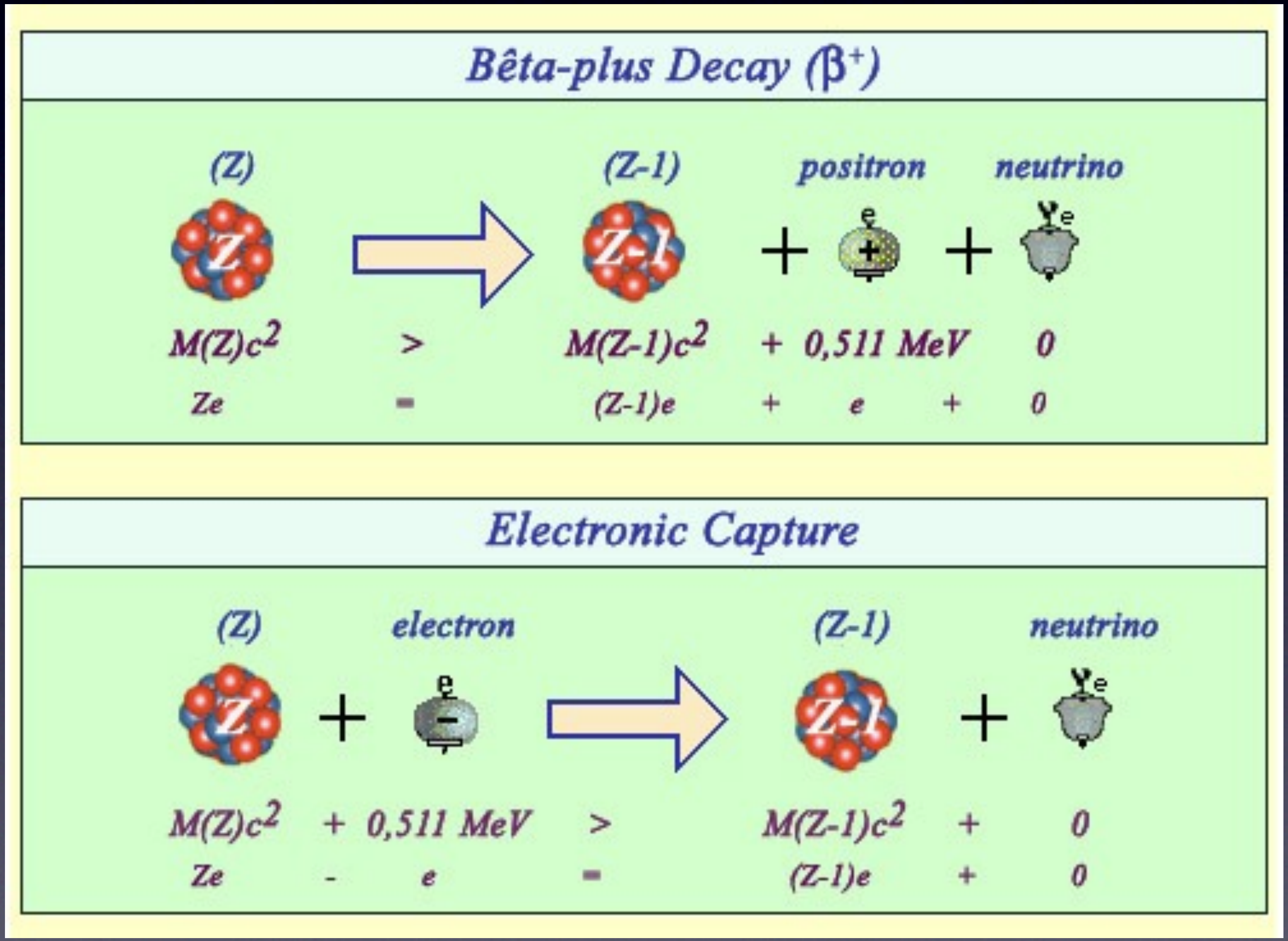


BETA RADIOACTIVITY: recap


Ask Mish

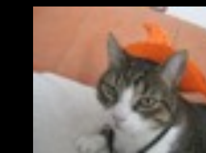
BETA +	BETA -
if excess P then P -> N	if excess N then N -> P
W+ boson carries weak force that produces this	W- boson
positron and neutrino = final products	electron and antineutrino
O, F used in medicine in PET	many elements more common than beta+

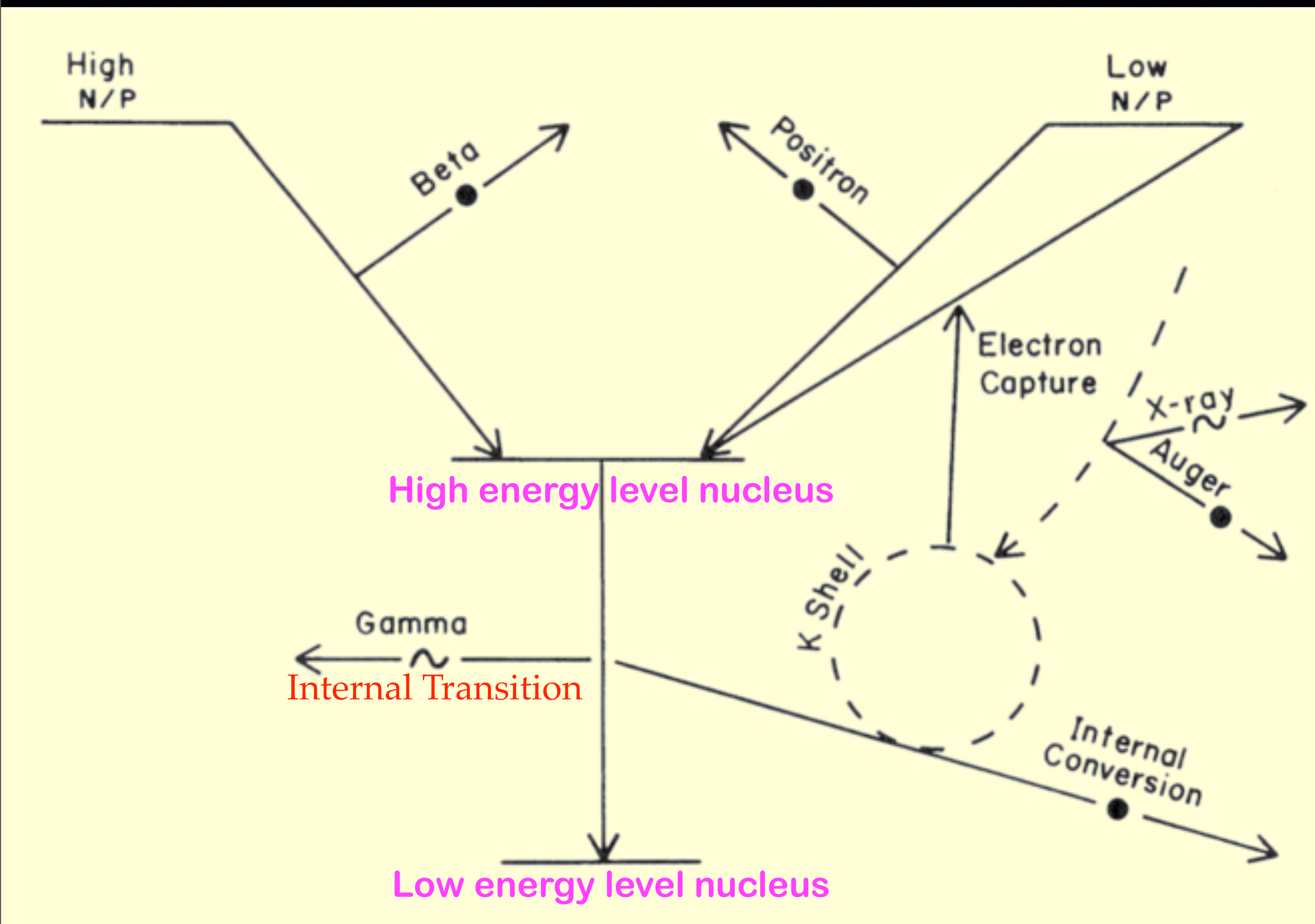
Weak Force - Beta Radioactivity particularity : electron capture



- Free energy is negative, delta G<0, for spontaneous reactions to occur (thermodynamics); massive E is released when nuclear bonds are broken : E=mc2 and here delta G=delta E, so for spontaneous decay : deltaE<0, delta m<0.
- in heavier elements, delta m is small and do not generate enough energy for P->N, so nucleus capture an -e from inner (K) shell, process known as K capture/inverse beta decay, no positron just neutrino freed

Weak Force: Gamma Radioactivity

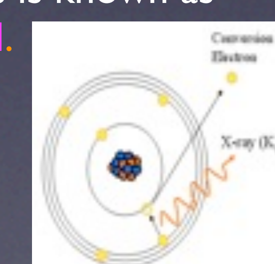




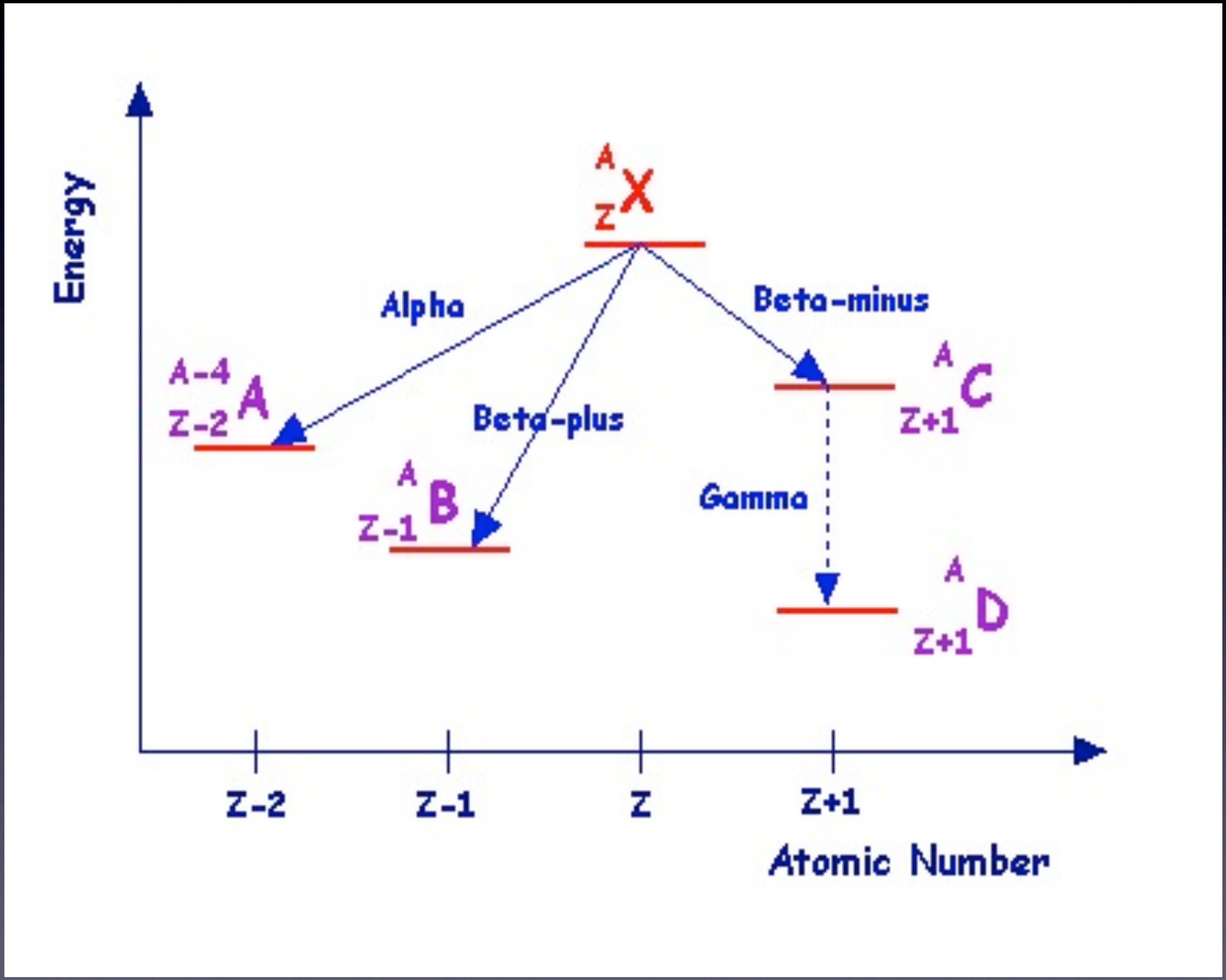
- An excited NUCLEUS (in a high state energy level) can lose excess energy and become stable (in a lower state energy). Nucleus becomes excited e.g.after alfa and beta radiation.
- There are 2 ways the excess energy is given away:
- DIRECT in the form of GAMMA radiation, process known as INTERNAL TRANSITION.
- E.g. :Tc99m-> Tc99. Tc99m is the most used isotope in medicine.

$$^{99m}_{43}Tc \rightarrow ^{99}_{43}Tc + \gamma$$

- INDIRECT: energy from nucleus is given to a K shell electron which usually is ejected. Another neighboring e- is taking the empty place and an X RAY is emitted when e- changes orbital. The process is known as INTERNAL CONVERSION.



3 Types of Radiation: variation of Z, A and energy level



- Different types of radioactivity left nucleus with different amount of protons/ neutrons ratio or Z/A ratio and different energetic levels.

3 Types of Radiation: recap

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alfa radiation	beta radiation	gamma radiation
2 P + 2 N =alfa alfa particle= He nucleus	3 types: beta - : electrons beta+ : positrons e- capture	photons
P/N ratio unstable : too many P	P/N ratio many N->P+electron many P->N+positron	excited nucleus
A-4,Z-2 Z>83 e.g.U,Ra, Pu	A=const. Z+1 beta - : most Z-1 beta + : F, O	A=const.Z=const. after @, beta decay

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3 Types of Radiation: symbol, composition, charge, mass

Type of radiation	Symbol	Composition	Charge	Mass (atomic mass units)
Alpha	α	2 protons and 2 neutrons (a helium nucleus)	+2	4
Beta	β^-	electron	–1	Negligible
Positron	β^+	antimatter electron	+1	Negligible
Gamma	γ	photons of electromagnetic energy	0	0

3 Types of Radiation : Interaction with various materials


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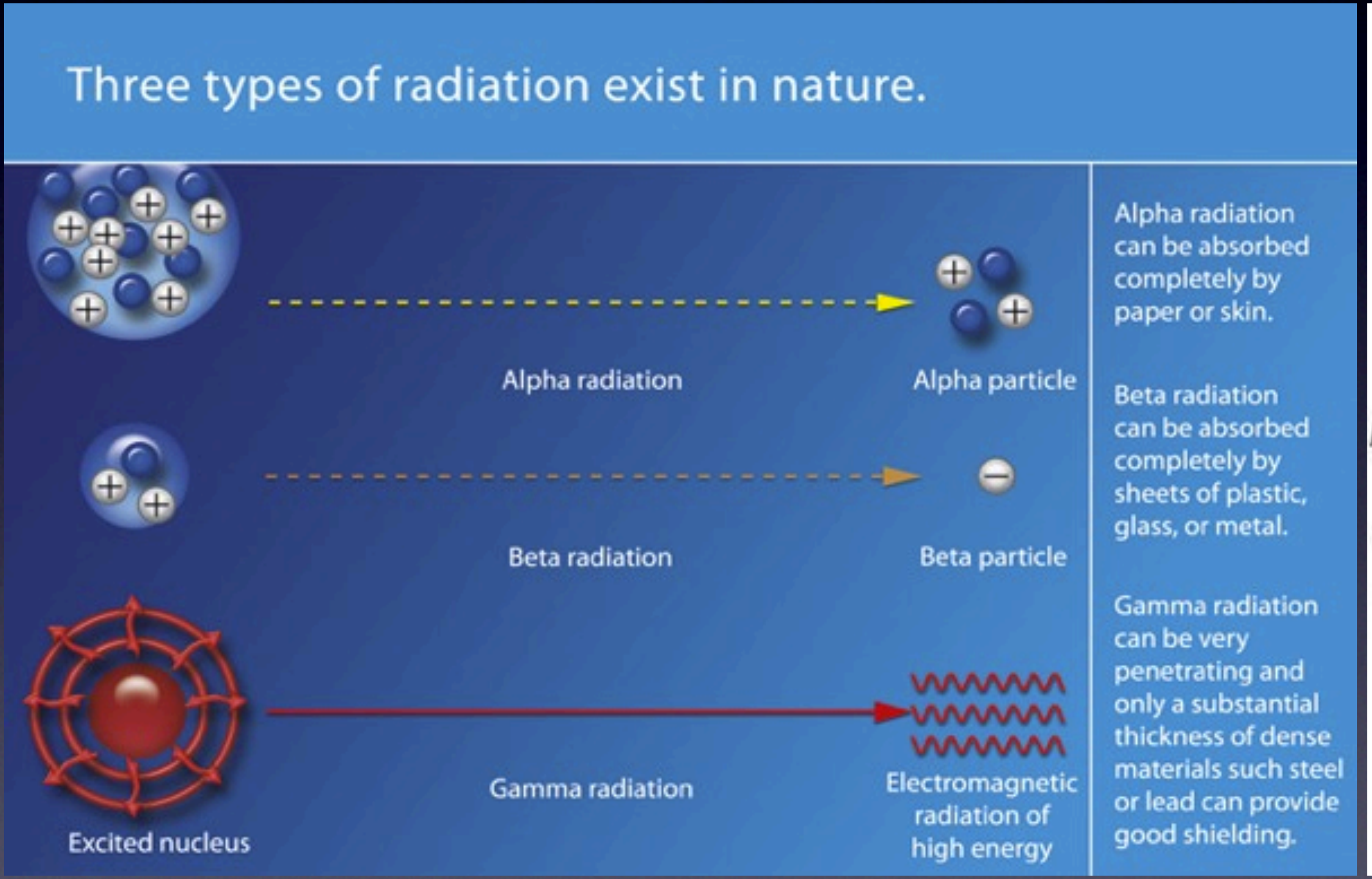
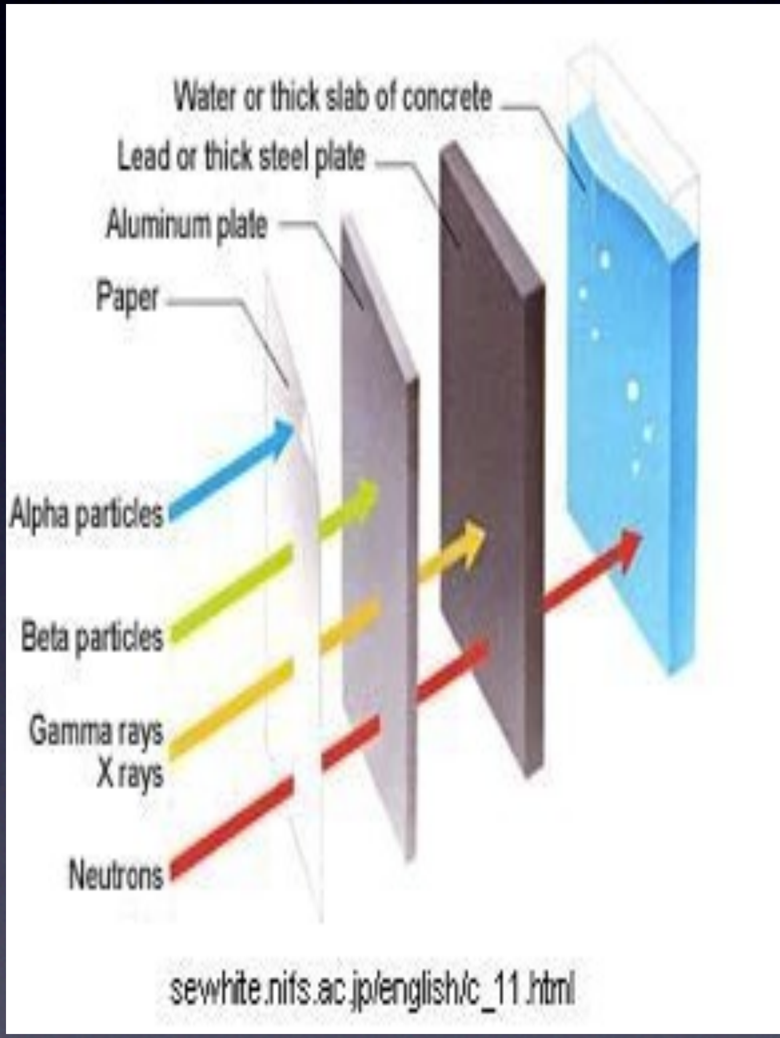
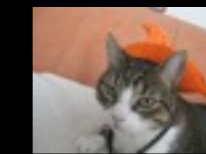
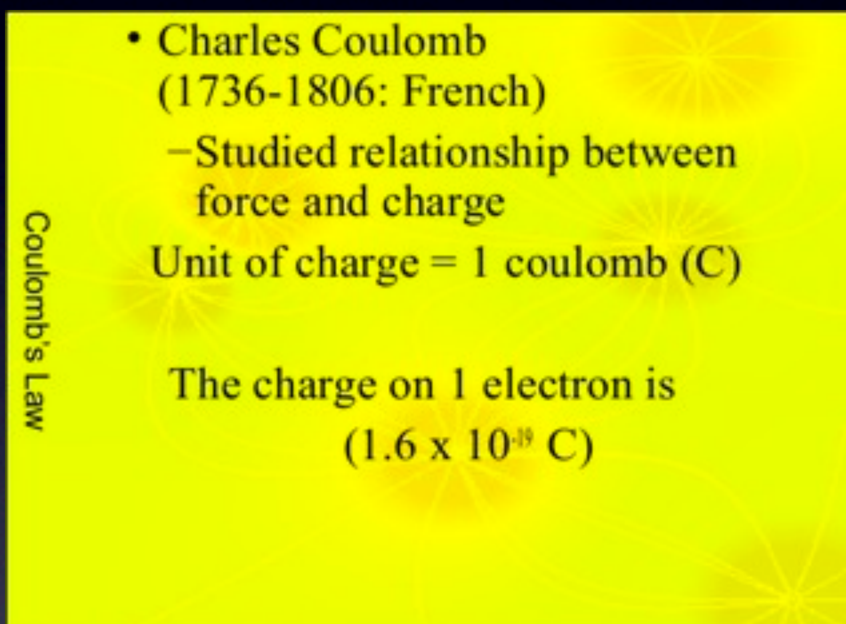
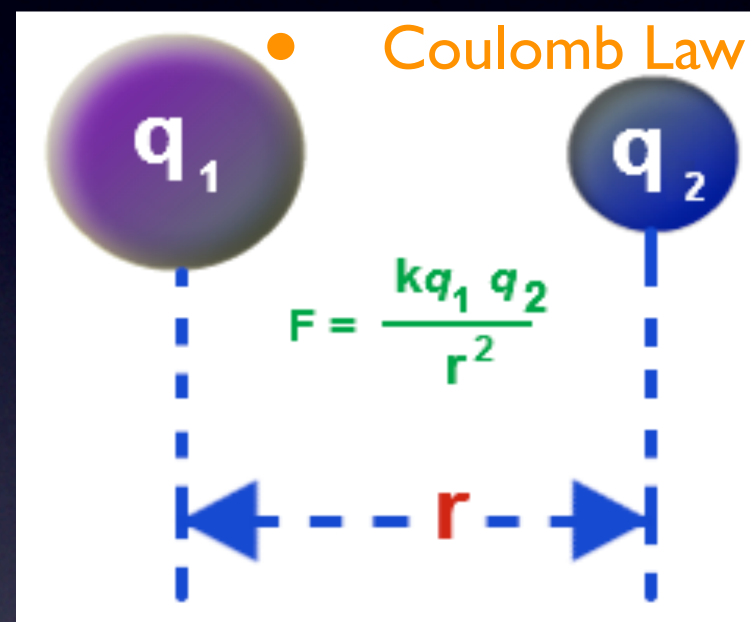


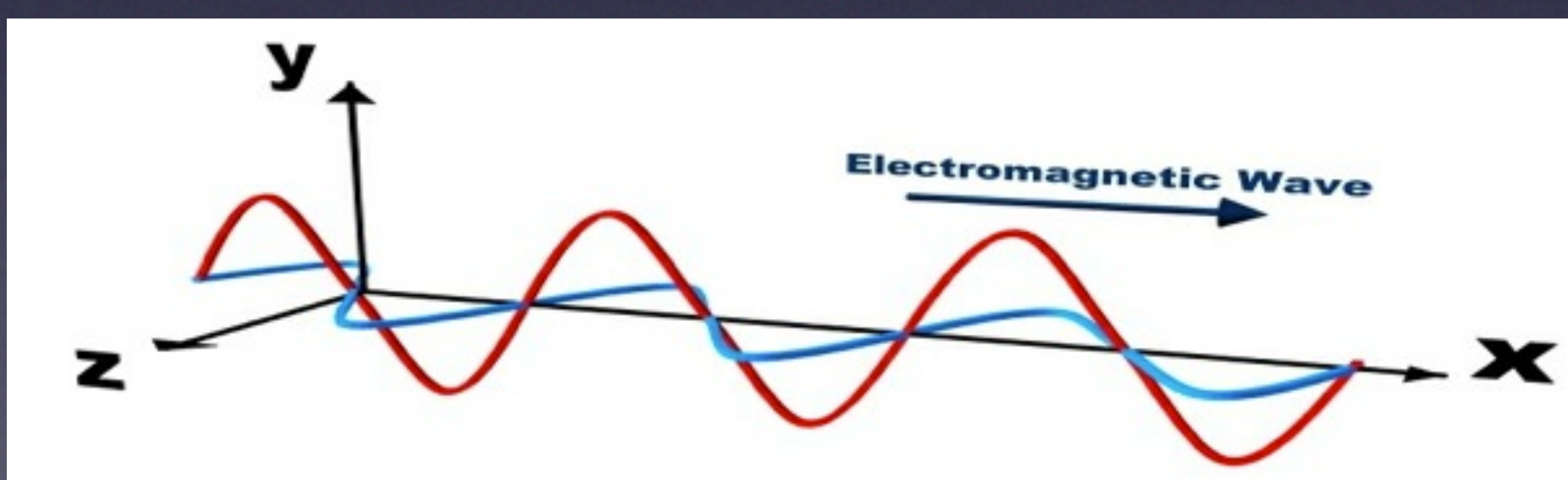


Electric charge, Electrostatic Force & Electromagnetic Force







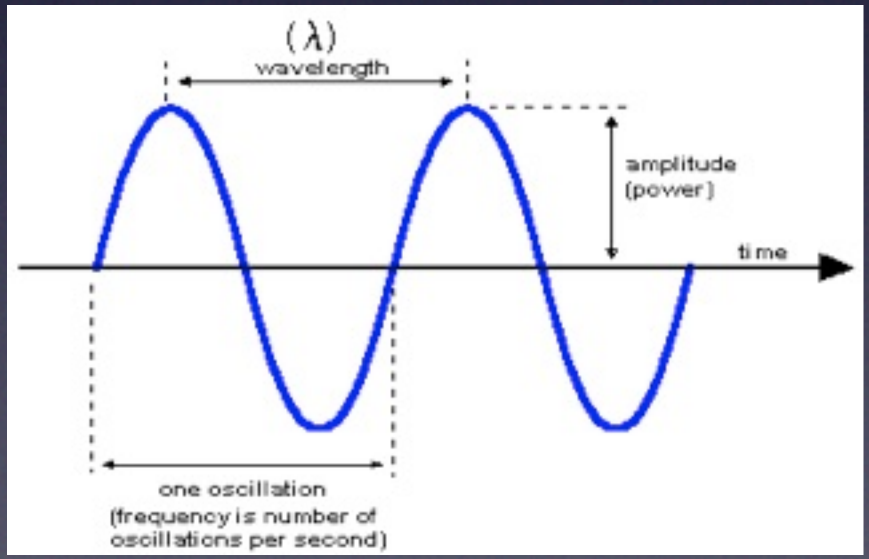


- Electric charge : of a particle +/- units or fraction
- If charged particles are not moving: Electrostatic Force between 2 charged particles q1 and q2 at r distance. Coulomb Law: q1xq2/rxr. 2 same charges repel, opposite attract each other.
- If charged particle is moving: Magnetic Force: is perpendicular on electric F (right hand rule), changing magnetic poles makes the particle to move further

Electromagnetic Force: Photons

Photon

energy = electromagnetic energy
velocity= 3 x 10^8 m/s
mass = 0
created by emission
destroyed by absorption
can collide with electrons and other particles

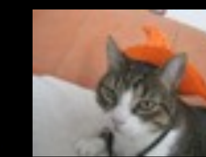


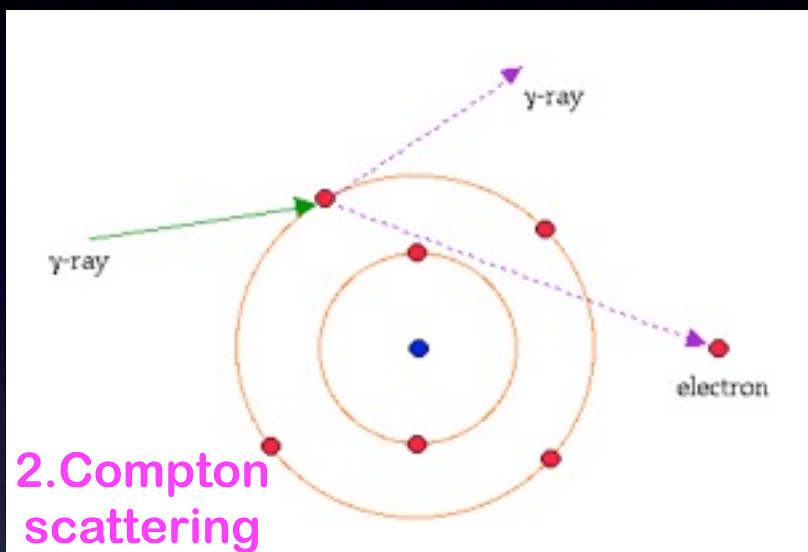
$$E = h\nu$$

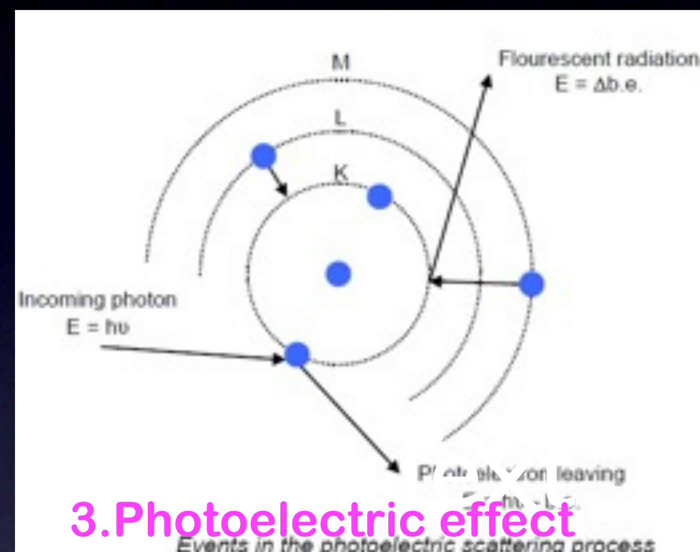
$$E = \frac{hc}{\lambda}$$

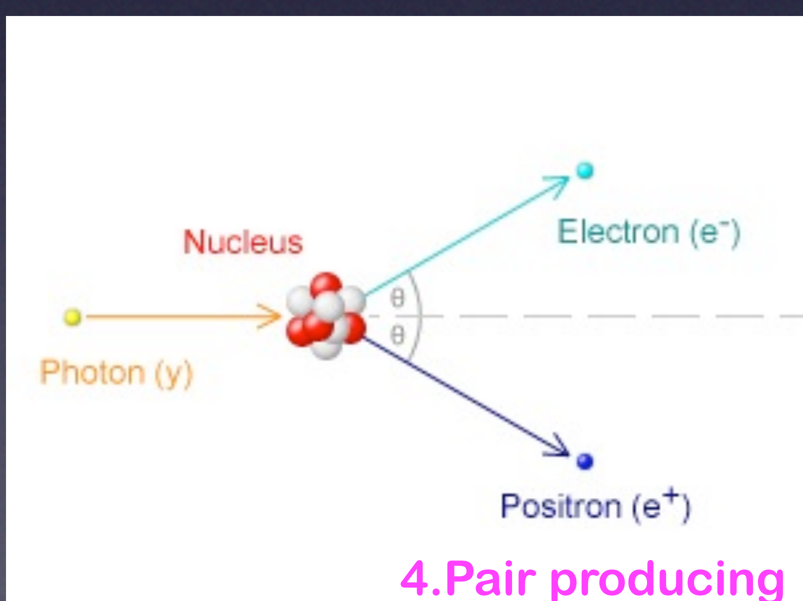
- Photons are produced when 2 charged particles interact, also when -e change the levels of energy by moving to a different orbital.
- Photons= quanta of energy (E)
- Photon: no mass, no charge, speed of light.
- This electromagnetic radiation has different frequency and length.
- Length x frequency =c
  c=speed of light 300000 km/s.
- Length: btw 2 peaks
- Frequency: cycles completed in 1 second.
- Energy of photon: E= h x f,
  h= Planck constant and
  f= frequency of wave

Interaction photon/matter

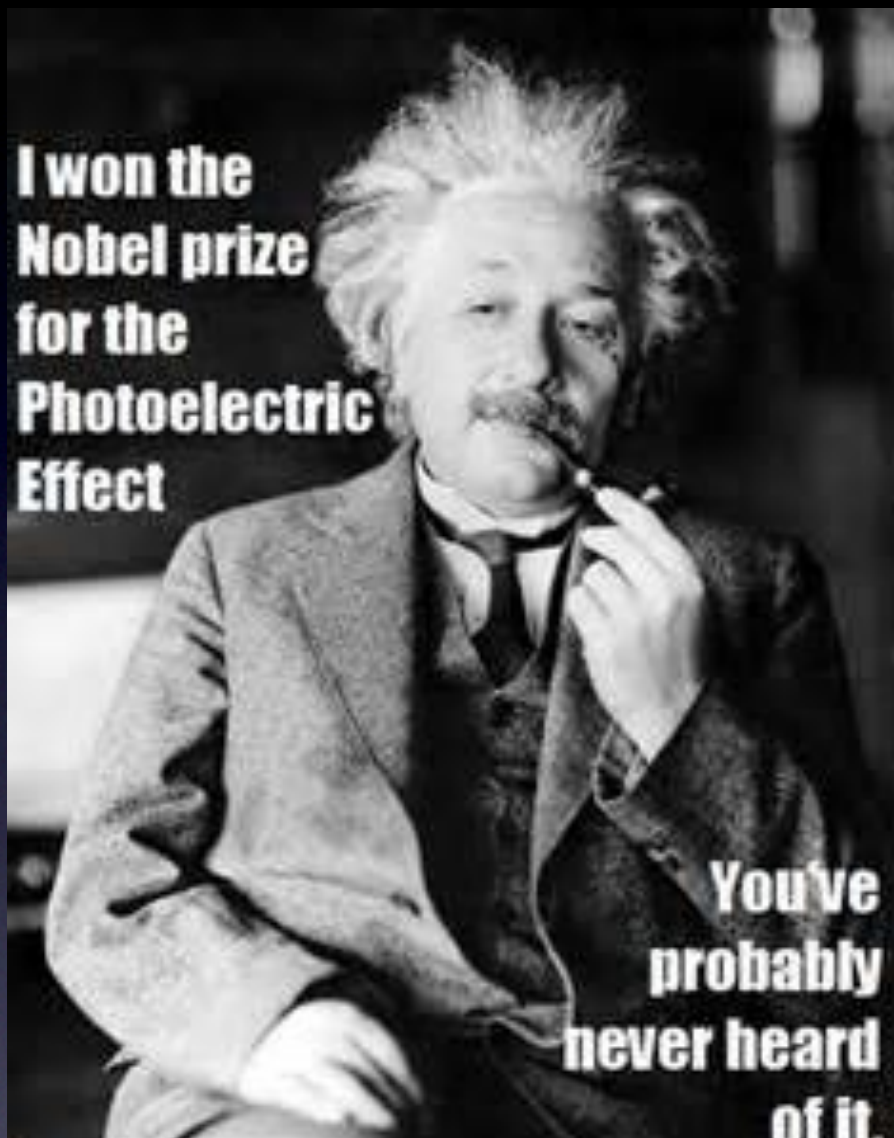




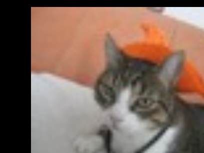




- 1.Elastic (Thomson) scattering only 8% of all: incident photon w/low energy makes outer shell -e excited and oscillating; incident photon disappears and osc.-e emits new photon, same hxf, scattered in a way that is not imp.
- 2.Inelastic(Compton)scattering: photons will hit free -e in outer shell and eject the -e ionizing the atom. Photon donate part of E in the collision and is scattered in various angles
- 3.Photoelectric effect: between photon and -e of inner shell(K), the whole photon E is used to hit -e and eject it creating an ion; new -e from L,M shell takes ejected e place. When moving from higher E to a lower level it emits photons.
- 4.Pair producing: photons excites nucleus: an -e and a positron are emitted (generally a particle and an antiparticle)
- 5.Photonuclear: photon hits nucleus, neutron or other fragments(photon, protons or alfa or more complex particles) are emitted


I won the
Nobel prize
for the
Photoelectric
Effect
You've
probably
never heard
of it.


ALBERT EINSTEIN
för hans förtjänster om den teoretiska fy-
siken, särskilt hans upptäckt av lagen
för den fotoelektriska effekten.
Stockholm den 10 December 1922
Kgl. Vet. Akns Praeses.



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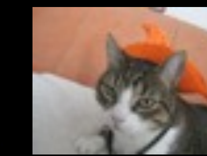
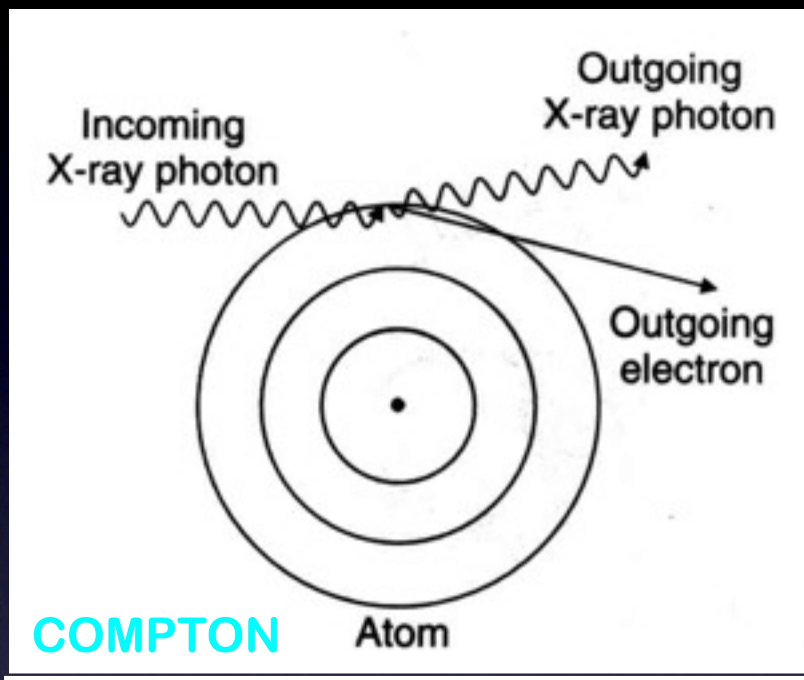
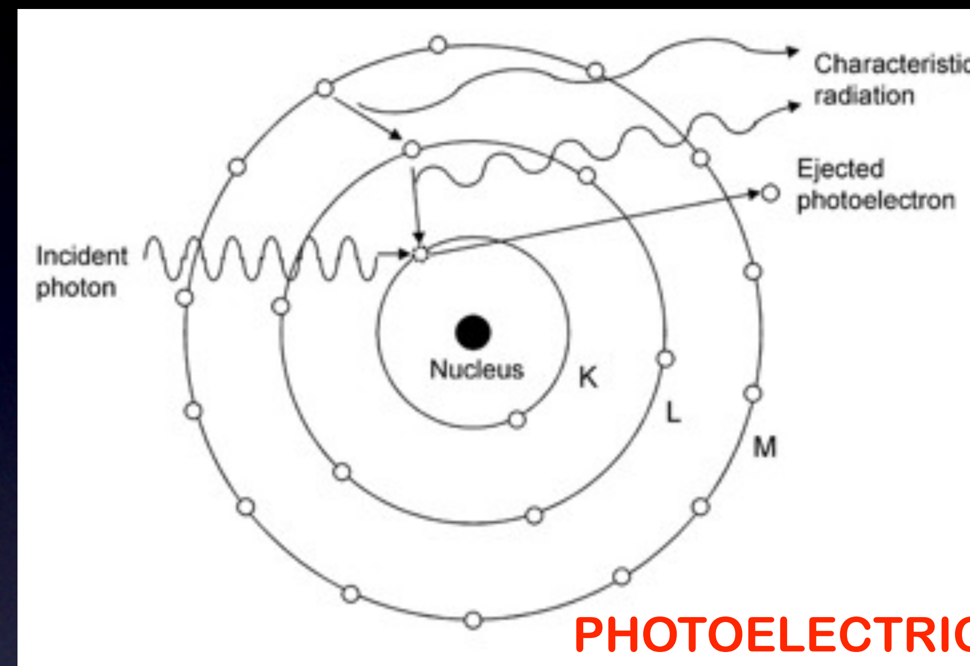
Compton scattering vs Photoelectric effect







	COMPTON	PHOTOELECTRIC
incident photons	scattered	absorbed
hit electrons from	outer shell	inner shell
hit electron leaves the atom	ionizing atom	ionizing atom
appearance on Xray/CT scan	grey fuzzy(less dense)	white (dense materials:Ca, contrast,

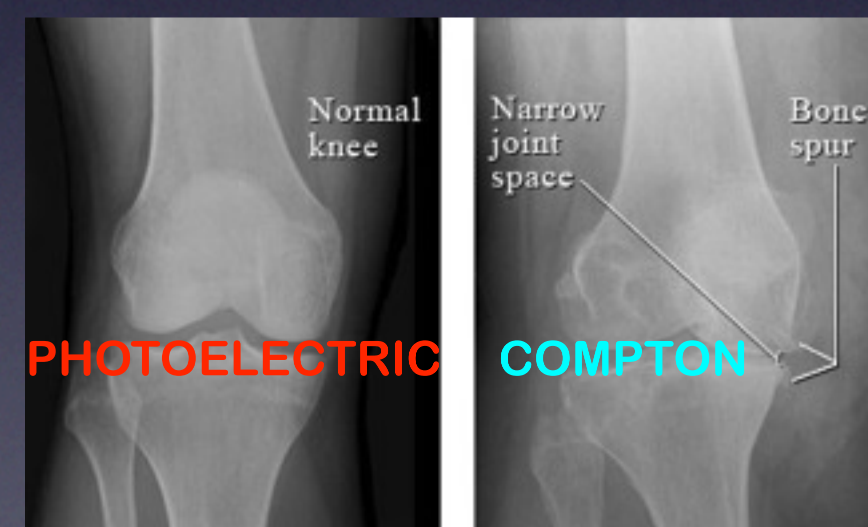


Figure 1 Figure 2

Interaction photon/matter:comparison

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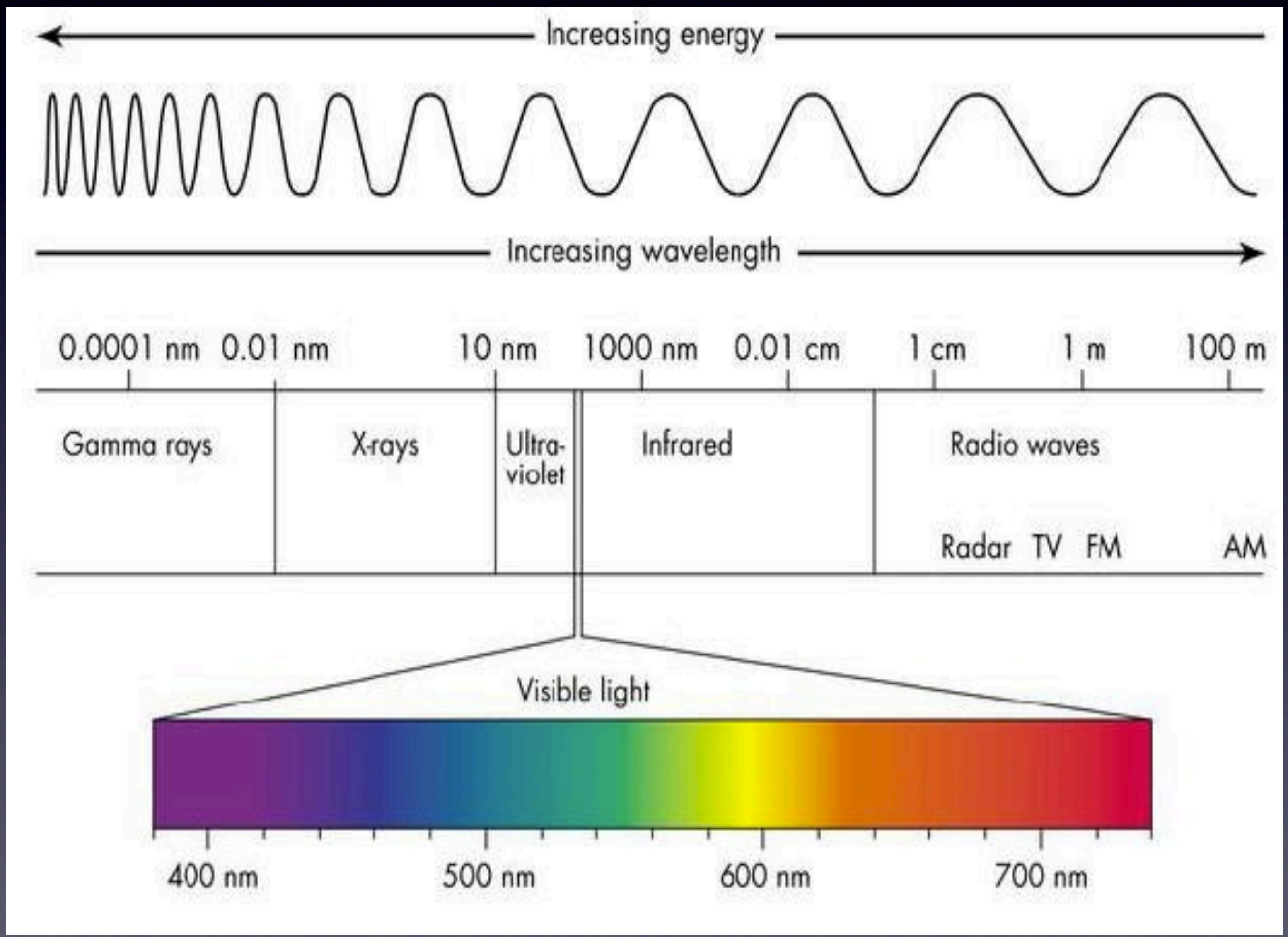
Process	incident photon	electron interact.	nucleus interact	Medical use
Elastic scattering	disappear	outer shell oscillation	-	none
Inelastic Compton	scattered	outer shell eject :ions	-	Xray Dx.
Photoelectric effect	absorbed	inner shell eject:ions	-	Xray Dx.
Pair producing	absorbed	-	electron +positron	Xray Tx
Photonuclear r.	absorbed	-	neutron, other	Xray Tx

Dx= diagnostic

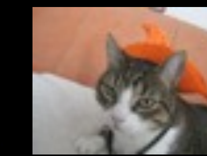
Tx= treatment

Electromagnetic Radiation



- Definition: stream of photons of different frequencies/length of wave/energy
- Highest freq. = Gamma rays : from nucleus
- Next: X rays : excited electrons
- Ultraviolet, Visible light, Infrared
- Microwaves
- Lowest freq.= Radio waves

ELECTROMAGNETIC SPECTRUM



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	gamma	X	UV	light	IR	MW	radio
Wavelength	smallest L <1nm	> nm ->10nm	>nm ->400nm	>nm ->700nm	>nm- 0.1mm	>mm- 10 cm	>mm ->km
	highest frequency	<	<	<	<	<	<
Natural occurrence:	cosmic	cosmic	sun	stars	body w/ heat	cosmic	cosmic
Penetration	P:soft tissue	P:soft tissue	P: skin	reflected	emitted	NP	NP

NP=not penetrant to tissue/ skin

Scintigraphy, SPECT and PET Scan

Gamma and Xray in Medicine (1)

Type	GAMMA < 1nm (10to-9 m)	X RAY 0.1-10nm
Origin/ Definition	excited nucleus after alfa, beta radiation	excited electrons changing orbitals
Occurrence	1.cosmic NP to E 2. natural radioactivity	1.cosmic NP to E 2 X ray tube
Detection	scintillator	X ray film
Medical use	scintigraphy/SPECT/PET	Xray/ CT scan

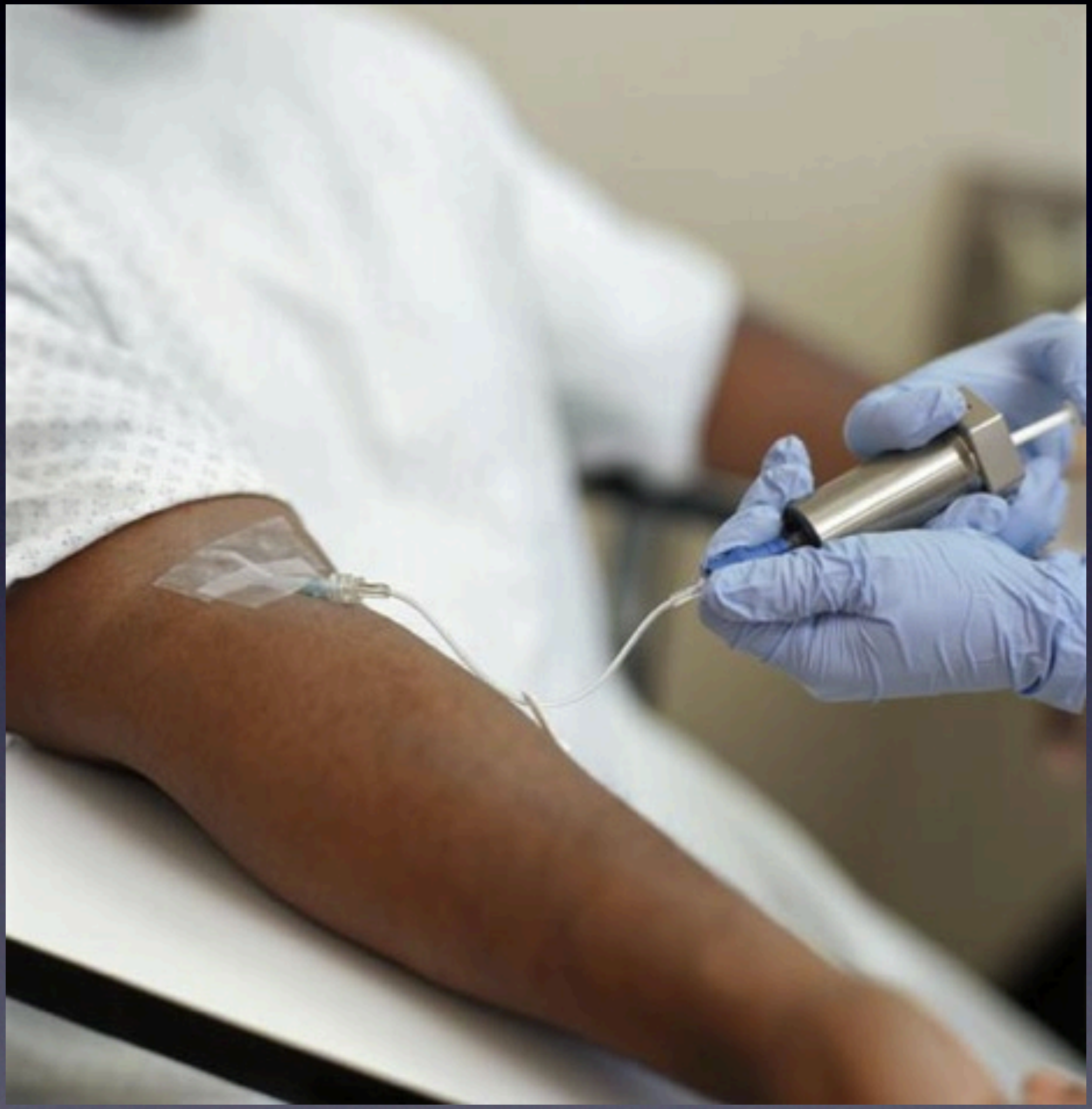
NP to E = non penetrant to Earth

Gamma and Xray in Medicine (2)

Medical use	Gamma	X ray
Source location / body	in the body: emission	out of the body: transmission
Source	Radiotracer	X ray tube
Detection	gamma camera scintillator Anger camera (syn.)	Xray image

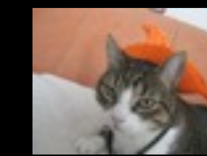
Gamma rays: medical use in radiotracers


Ask Mish



- Radiotracer =gamma emitter is injected IV
- Next: flows w/ blood
- Next: cell uptake, normal/ increased in: repair (bone fracture), infection, tumor
- Dx tool for : blood flow obstruction: heart, lung, brain and increased cell uptake

Radiotracer : gamma radiation emission



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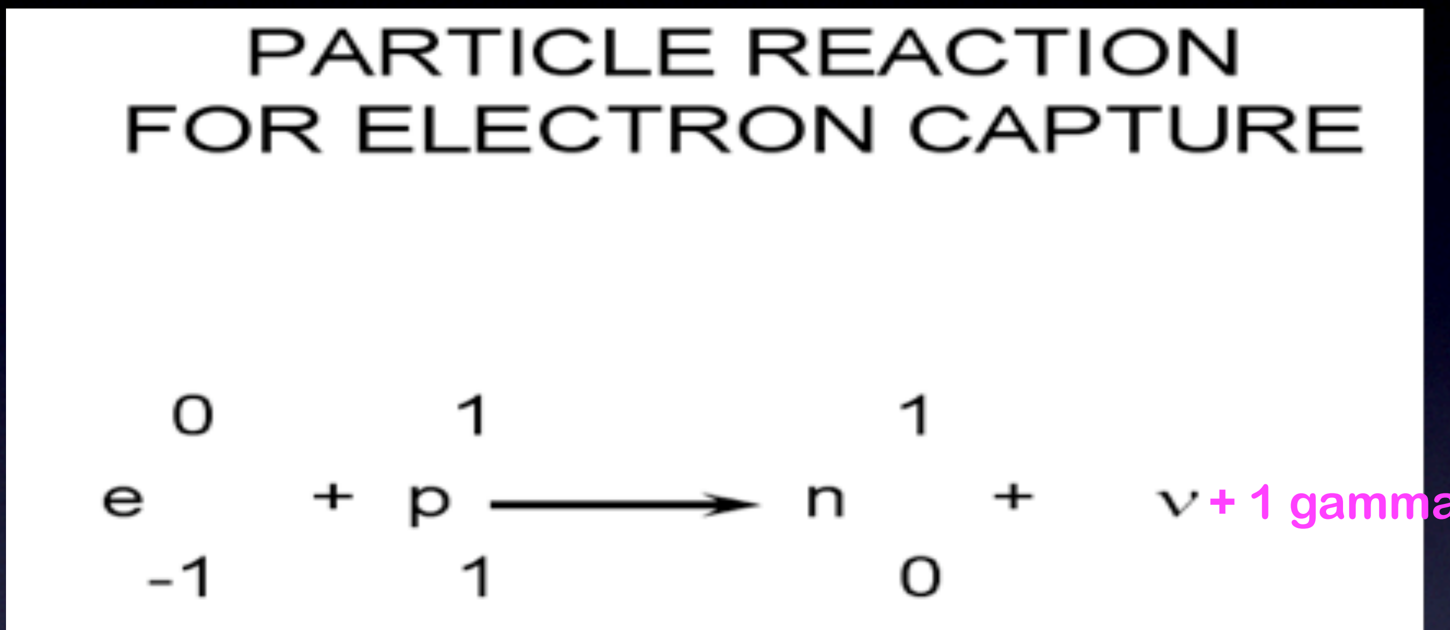
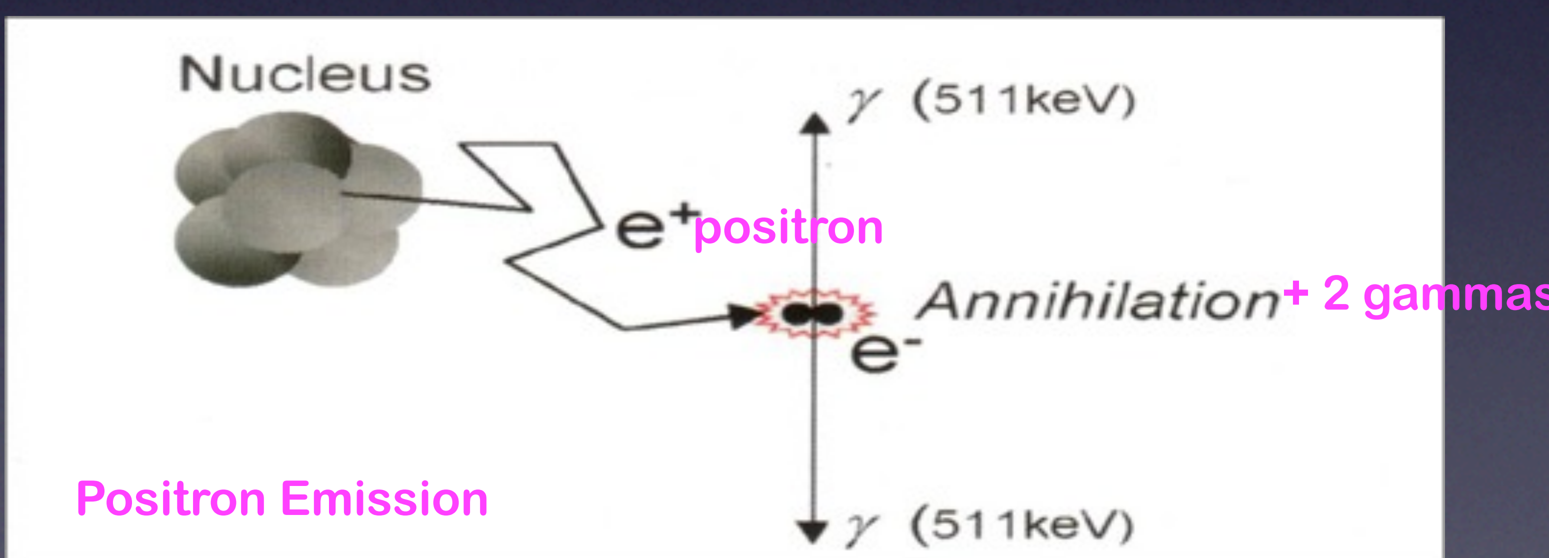




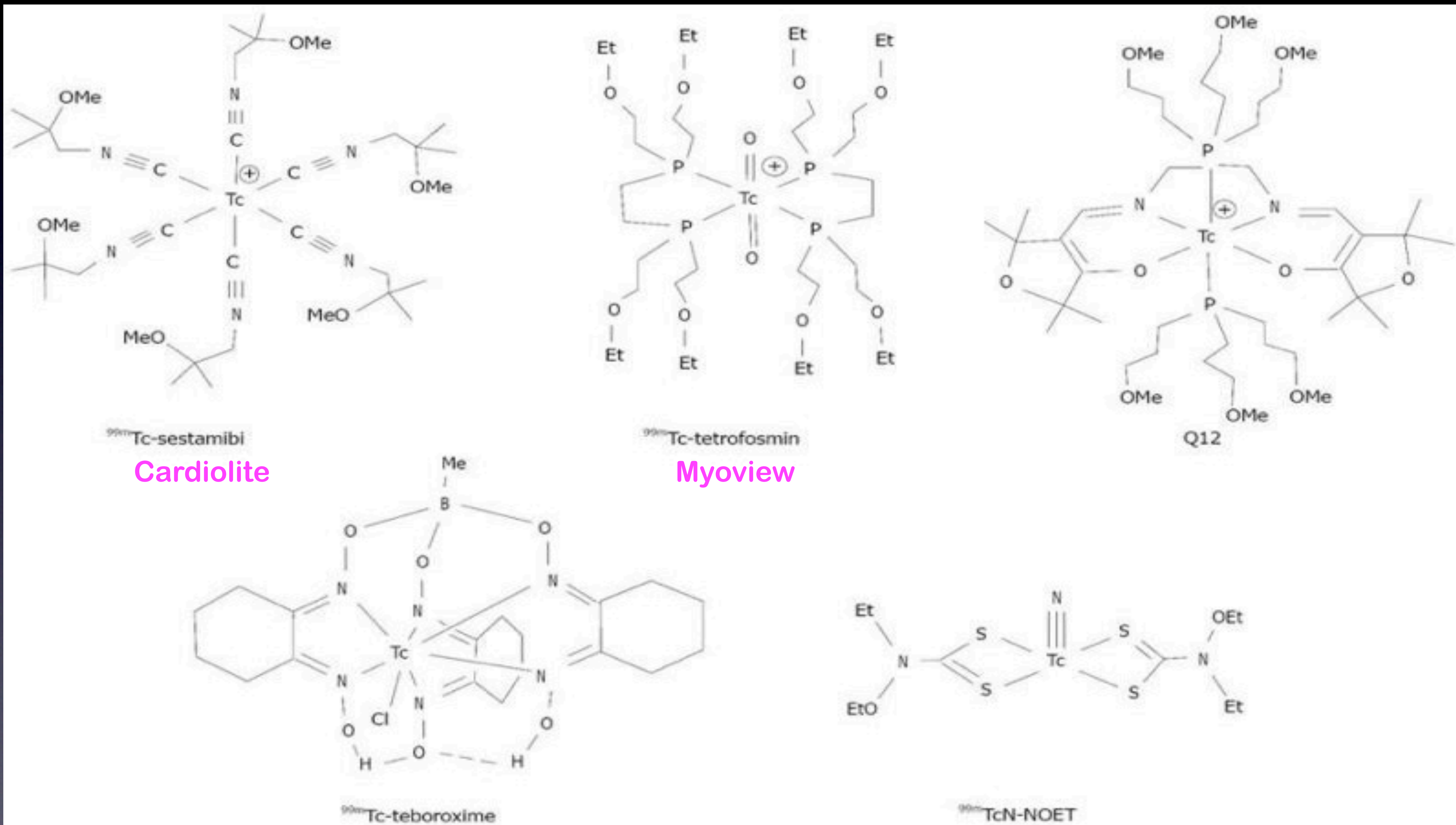
- Principle: Radiotracer is a radioactive isotope meaning it has an artificially created unbalanced Z to N ratio which makes excess PROTON transforms into-> NEUTRON
- One way is electron capture: proton+ electron= neutron + l gamma
- Second way is positron emission: proton-> neutron+positron +neutrino
- then, positron +electron->annihilation(disappear)+2gamma opposite

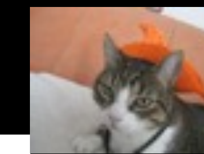
Ask Mish

Making a radiotracer: bombarding with neutrons or protons

- by artificially unbalance Z/N ratio:
- one way is bombarding w/ neutrons in nuclear reactors making long live isotopes into shorter live; sometimes these shorter live isotopes are put into a portable generator since they decay further into very short live isotopes. E.g. Tc99m which is attached to another molecule carrier (ligand) and used as a radiotracer.
- another is bombarding w/ protons in cyclotrons (charged particle accelerators, a linear accelerator rolled up into a spiral) E.g. F18. FDG (fluorodeoxyglucose) is produced by placing F18 in position 2 on glucose ring, replacing -OH.

Tc 99m LIGANDS





Ask Mish

How to obtain unstable isotopes to make a radiotracer

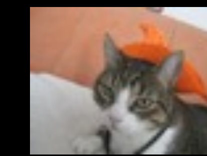
Place	Reaction	Final product	Next
Nuclear reactor	neutron bombard-> nuke fission	unstable isotopes	separation &move to generators
Generator	unstable isotope from fission decays	unstable isotopes	IT: isomeric transition EC:e capture
Cyclotron	proton bombard	unstable isotopes	B+: beta + decay

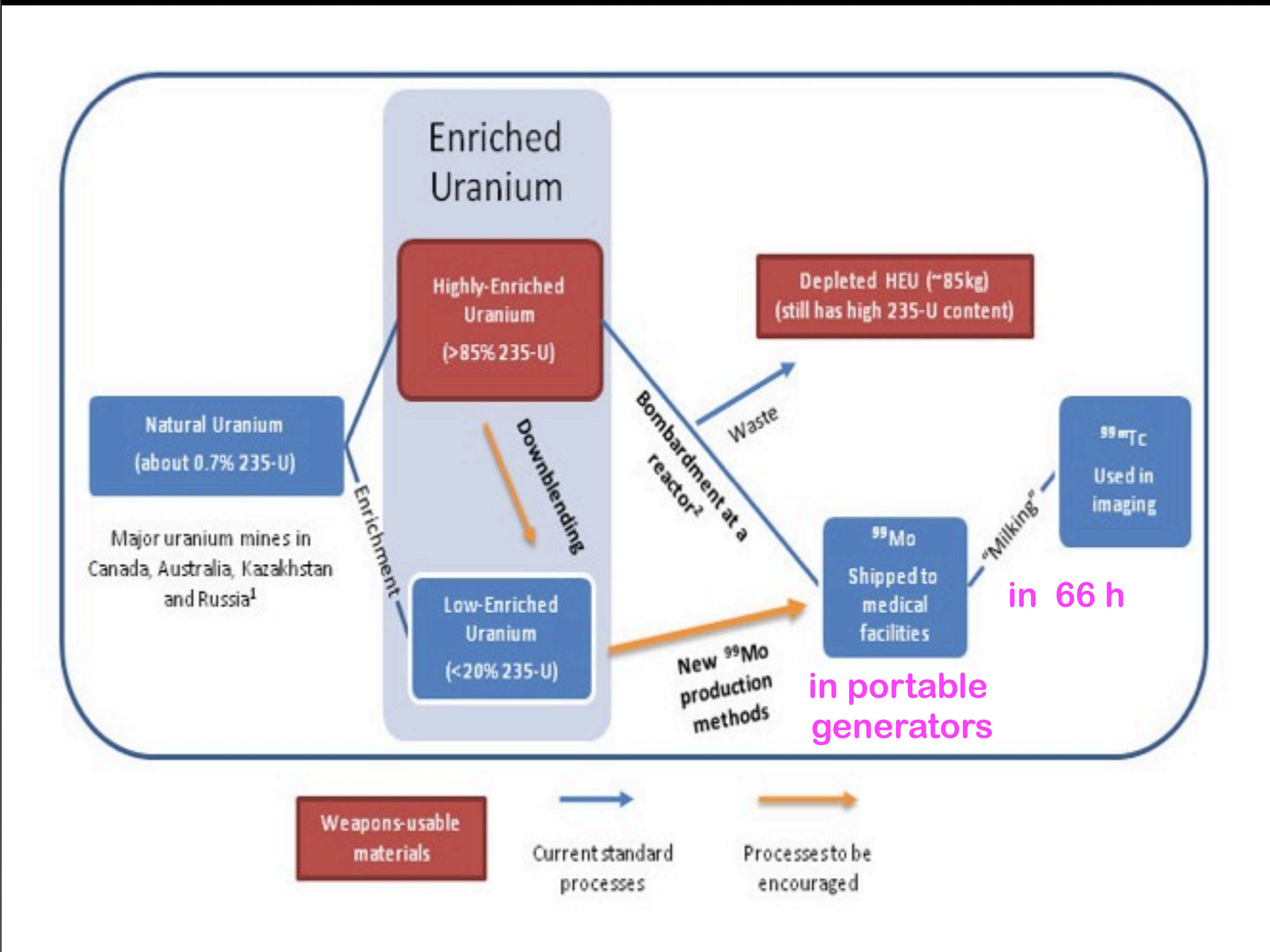
Radiotracers: Tc99m vs F18

Ask Mish

Radiotracer	Tc99m	F18/ FDG
Definition	metastable	fluorodeoxyglucose
Dx tool in:	2D, SPECT	PET
Place production	reactor/generator	cyclotron
Production	U235->Mo99	F18
Radioactivity	IT	Beta+, EC
T1/2	6 hrs	110 min
Other		N13, O15, Rb82

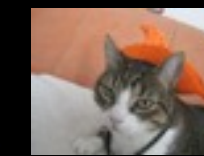
Tc 99 m production in reactor and generator





- metastable refers to longer T1/2 of 6 hrs in comparison w/ 10to-16 for natural isotopes
- Tc99m production: in reactor: U235+neutron -> U236 unstable ->nuclear fission ->Mo99+other products
- in portable generator: Mo99-> decays in 66hrs to Tc99m

Tc 99 m production in generator and use as an IV radiotracer



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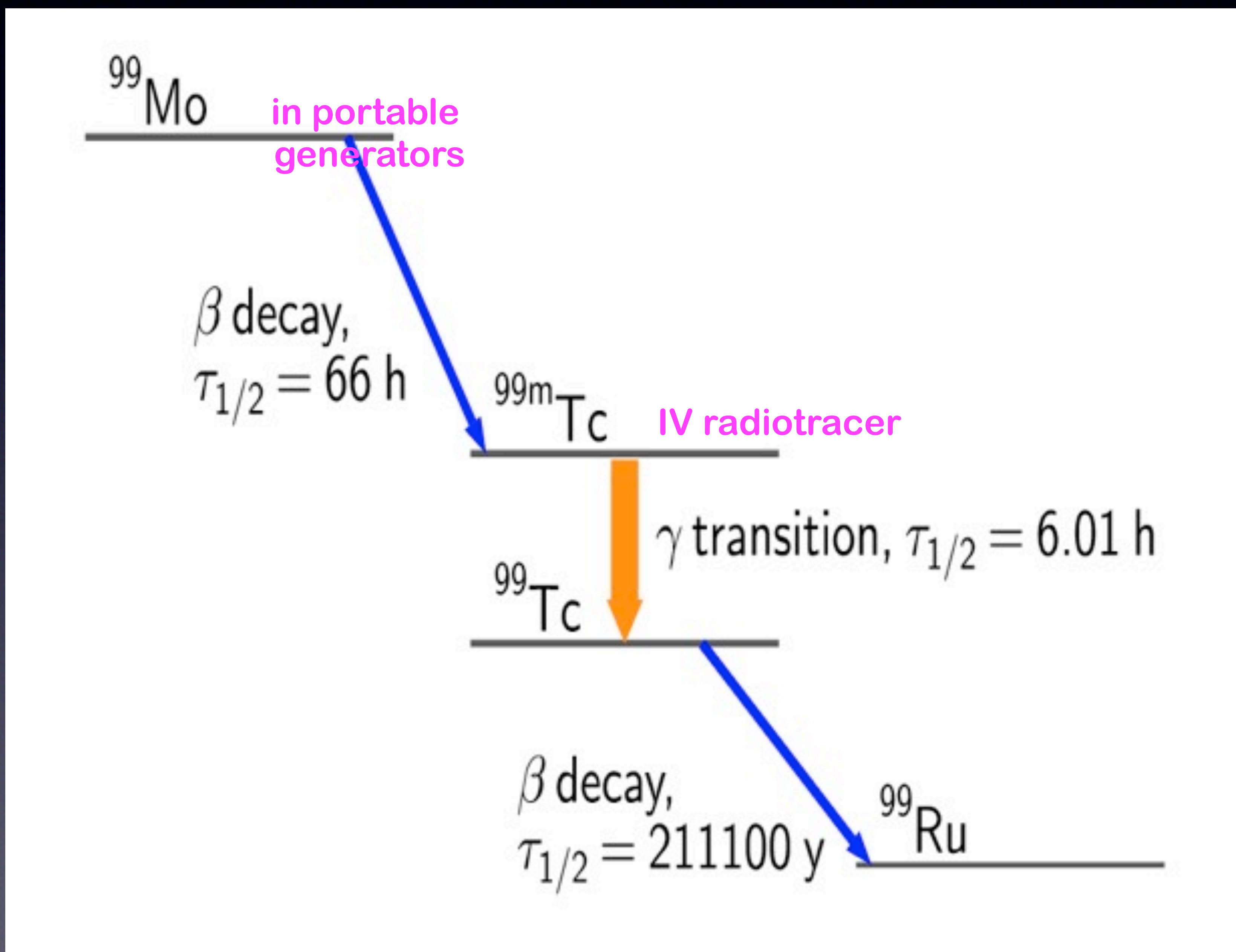


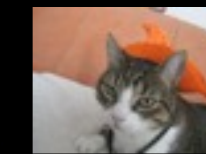
- Other way of producing Tc99m is Mo98 in cyclotron-> Mo99, this is first way to obtain Tc99m in 1938
- Tc99m->Tc99 in 2 ways:
- 88% IT : long excited state with decay in 6 hrs(Tc99m) -> short excited Tc99 through gamma emission
- 12% energy released ejected electron(K/L/M) producing ionization IC : internal conversion
- Tc99m vs Tc99, difference: SPIN
- T1/2 physical :6hrs for Tc 99m=decay in 6 hrs
- T1/2 biological: 24 hrs for leaving the body

Scintigraphy vs SPECT vs PET


Ask Mish

Dx tool	Scintigraphy	SPECT	PET
gamma emission	IT, EC (1 gamma)	IT, EC (1 gamma)	B+ decay (2 gammas)
time	1h	1-2 hrs	2 hrs
cost	<400$	$400	3-6000$
necessities	generator	generator	cyclotron
Advantage	2D	3D	3D; short, best image

Gamma detection: scintillator(Anger camera)



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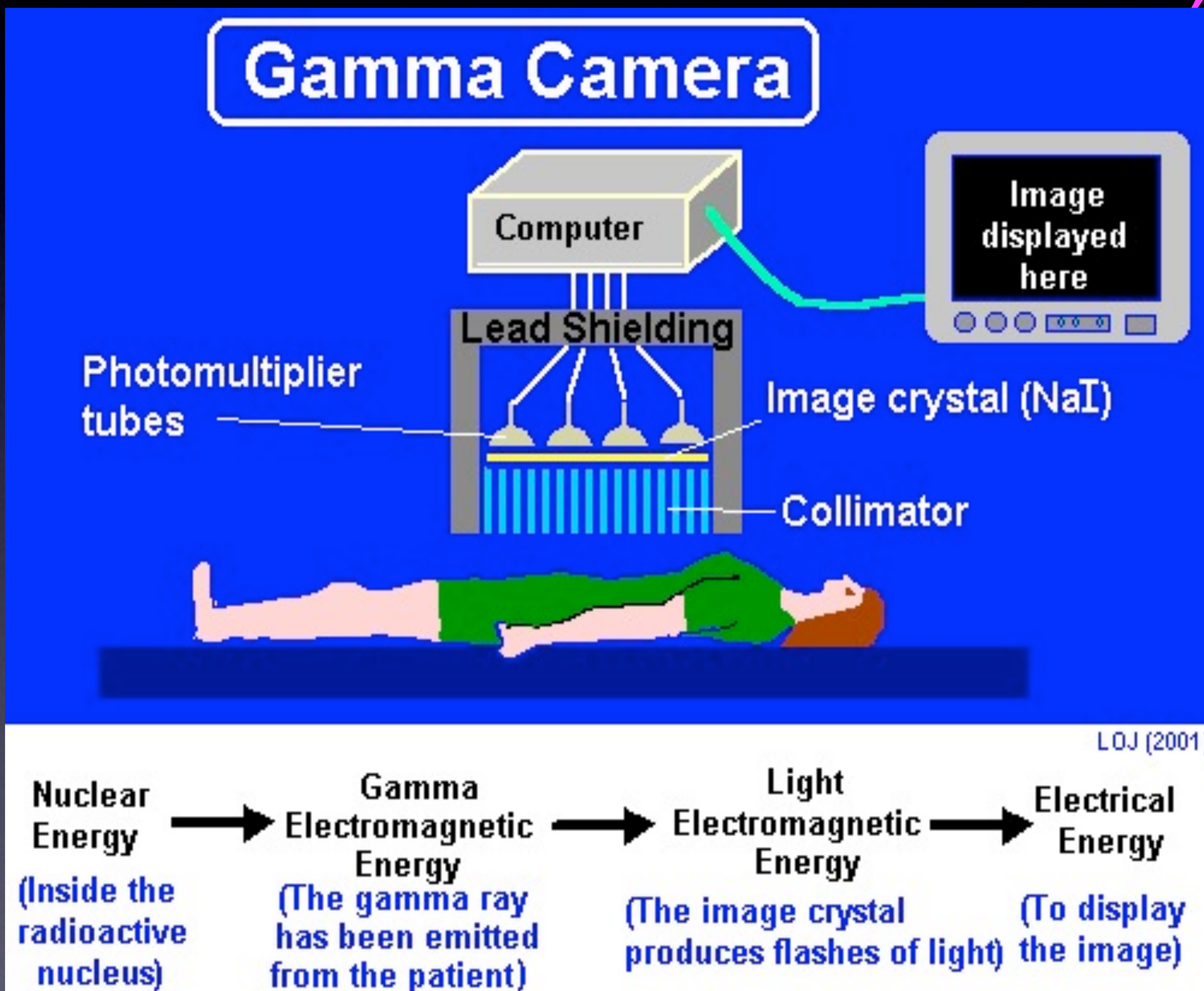


- Principle: photons(gamma) interaction w/ matter made of atoms
- when gamma hits NaI atoms from a crystal it produces photons in the form of green light. This photons are collected and amplified and transformed in a current, then the information read on computer. This device is called scintillator/Anger camera.
- if 2D= scintigraphy,
  if 3D(rotating camera): SPECT(single photon emission computed tomography)
- Tomography = process of generating a tomogram which is a 2D image of a slice or section through a 3D object. From Greek tomos=slice, section and graphein= to write.
- isotopes used: 80% Tc99m
  other: Iodine 123, Iodine 131, Ta201 etc for both 2D and 3D (SPECT)

Ask Mish

Scintillator vs SPECT scanner vs PET scanner

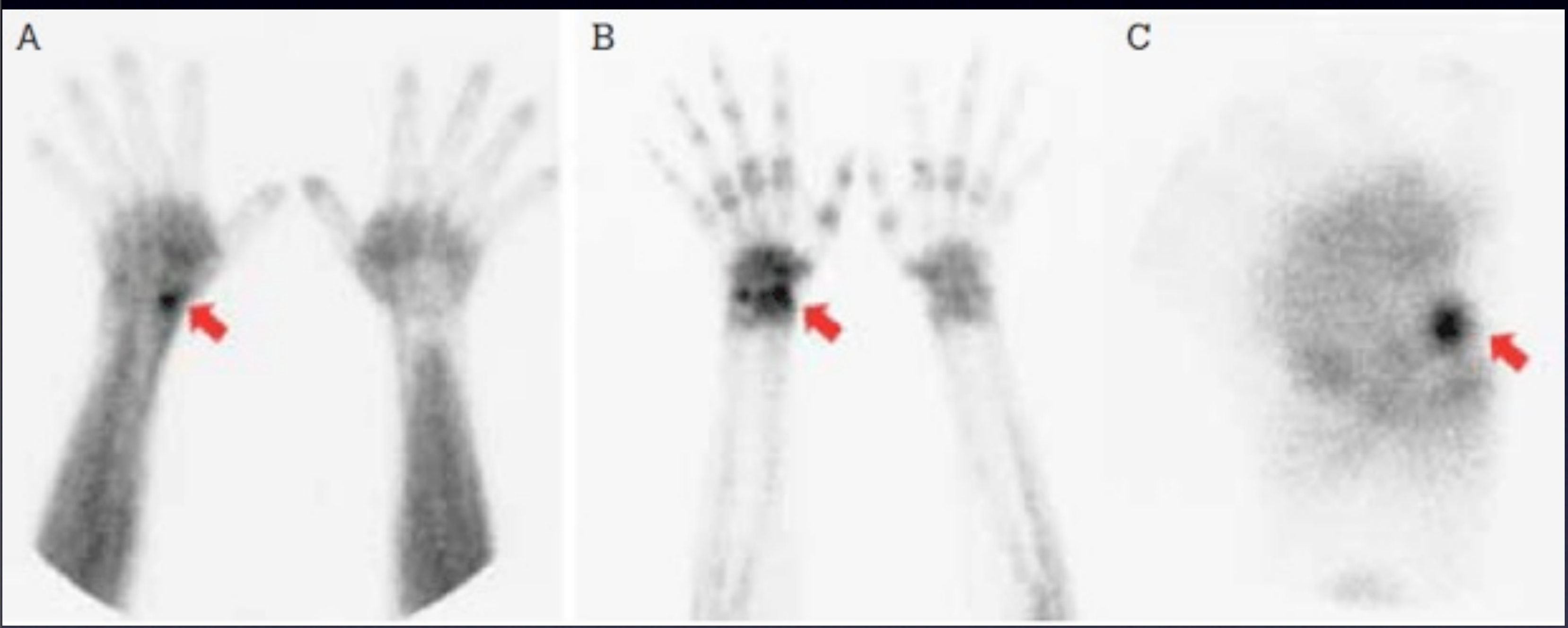
Scintillator 2D

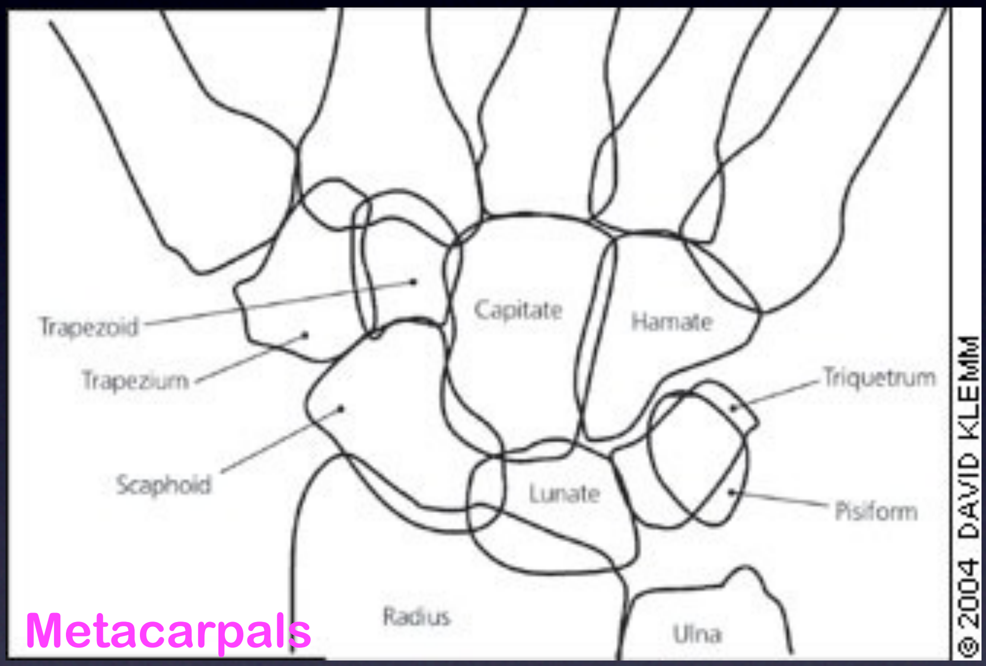
SPECT scanner 3D

PET scanner 3D

Bone scan example: scaphoid fracture

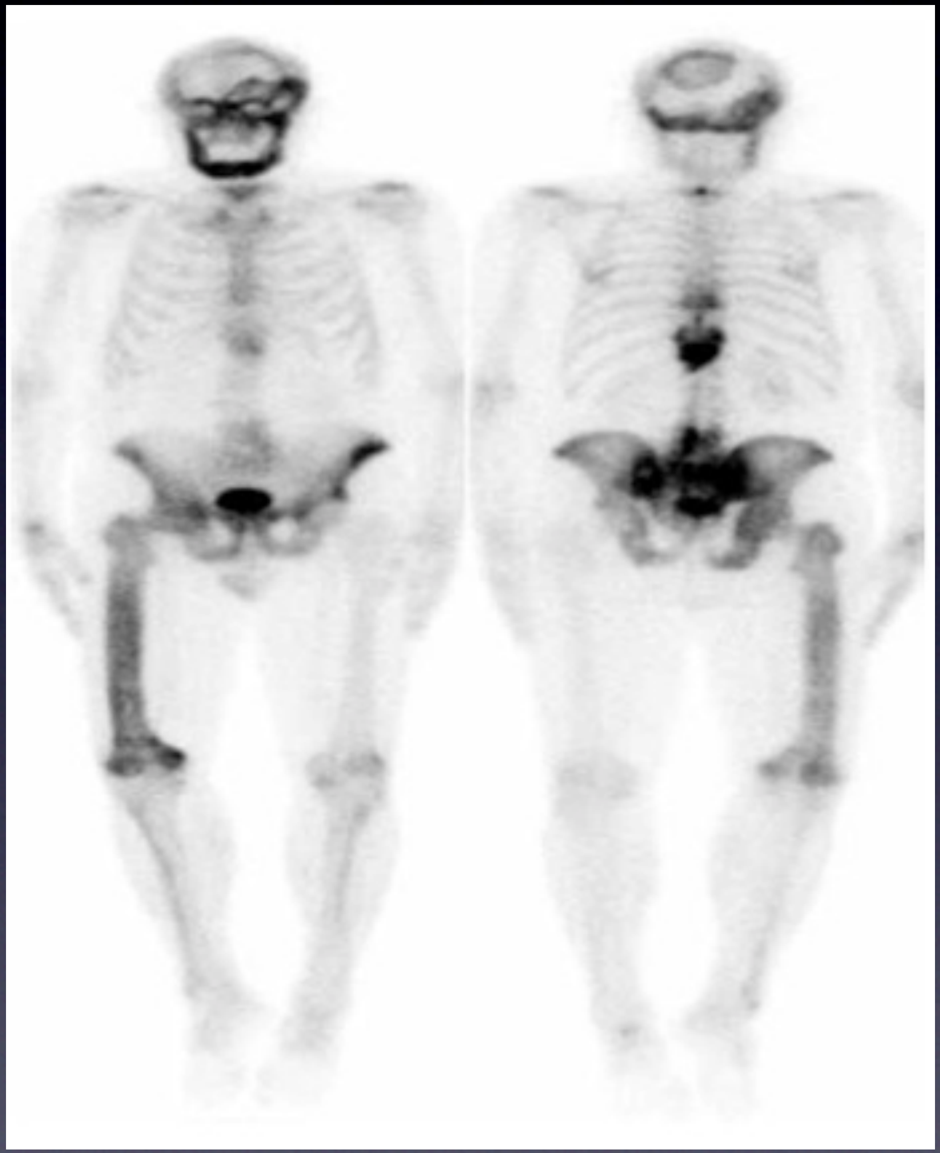
Ask Mish





A man, 28 years of age, had persistent pain in the right anatomical snuffbox following a fall onto his outstretched right hand. X-ray was normal, prompting referral for a bone scan. It demonstrated focally increased radiotracer accumulation in the scaphoid on both blood pool (A) and delayed images (B), typical of a scaphoid fracture. C is magnified delayed image.

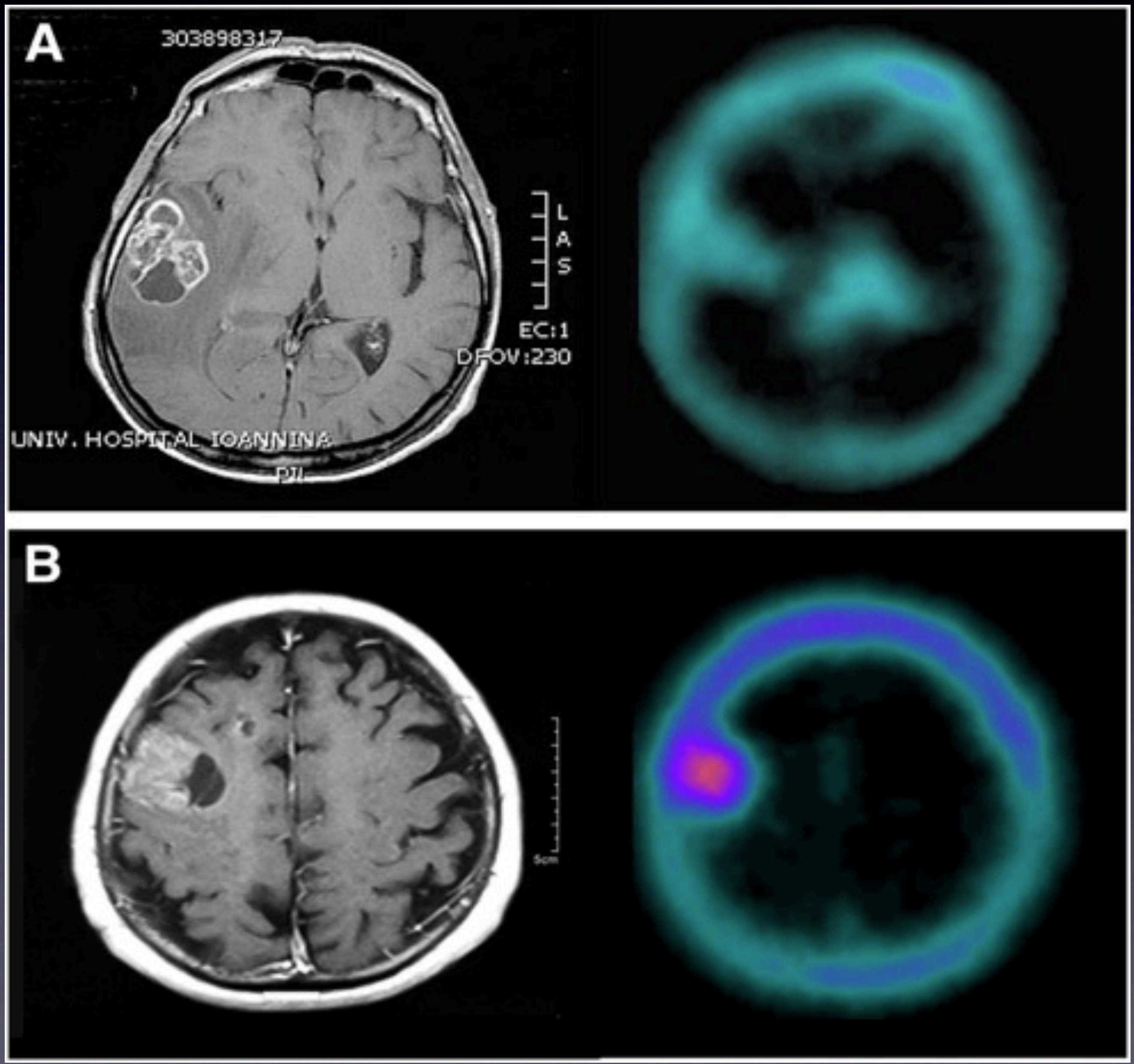
Bone scan example: Paget disease



A man, 72 years of age, sought investigation of 3 months of chronic tiredness. He had no other specific symptoms. Blood count and biochemical profile were normal, apart from an isolated elevation in serum alkaline phosphatase level. Bone scan showed abnormal, intense radiotracer uptake in the calvarium, jaw, multiple vertebral bodies, pelvis and an expanded and bowed right femur. These findings are typical of polyostotic Paget disease.

Ask Mish

Brain SPECT scan example

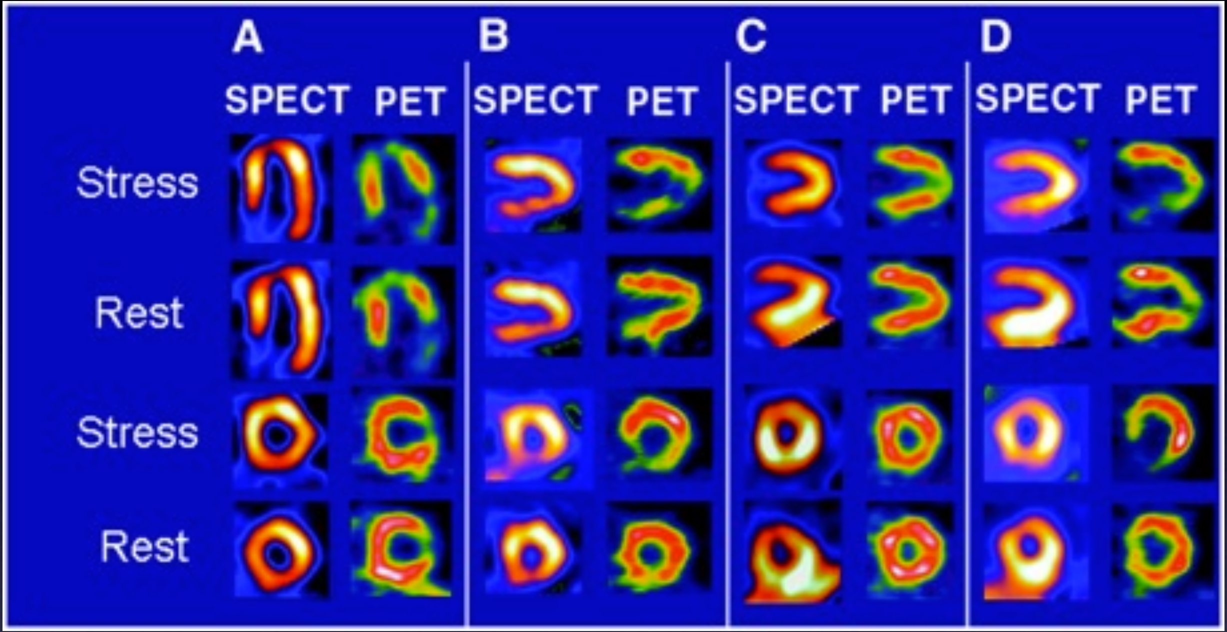


The Value of 99mTc-Tetrofosmin Brain SPECT in Predicting Survival in Patients with Glioblastoma Multiforme

Contrast-enhanced T1-weighted MR image (left) and 99mTc-tetrofosmin SPECT image (right) in one GBM patient exhibiting low tracer uptake (A) and in another with high uptake (B).

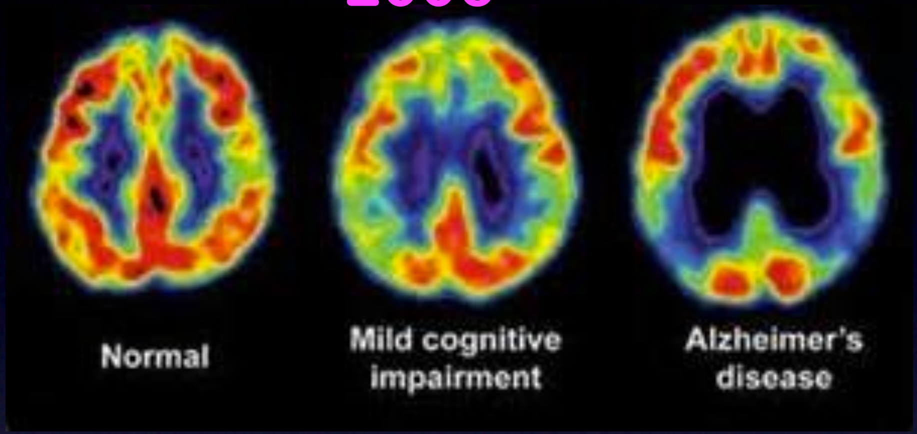
PET scan use: myocardium and brain examples

Myocardial perfusion w/ PET and Rb 82 vs SPECT



Examples of improved diagnostic reliability of PET vs. SPECT MPI in the same patients. (A) A 70-y-old man status post CABG with no history of MI. Exercise/rest SPECT images are normal but left ventricular ejection fraction was surprisingly reduced at 0.39. PET MPI within 2 wk discloses a clinically occult posterobasal MI. (B) A 53-y-old man with exertional left arm pain. SPECT images with dipyridamole stress are normal. PET MPI within 2 wk demonstrates a reversible inferoseptal perfusion defect. Ninety percent circumflex stenosis found on coronary arteriography. (C) A 46-y-old woman with chest pain. SPECT images are equivocal for reversible ischemia in inferolateral wall. PET images are normal. (D) A 59-y-old woman with chest pain. SPECT images are equivocal for reversible inferolateral ischemia as in C. PET images demonstrate reversible inferoseptal perfusion defect, treated with PTCI of 95% dominant right coronary artery stenosis.

UCLA Health Sciences study 2006



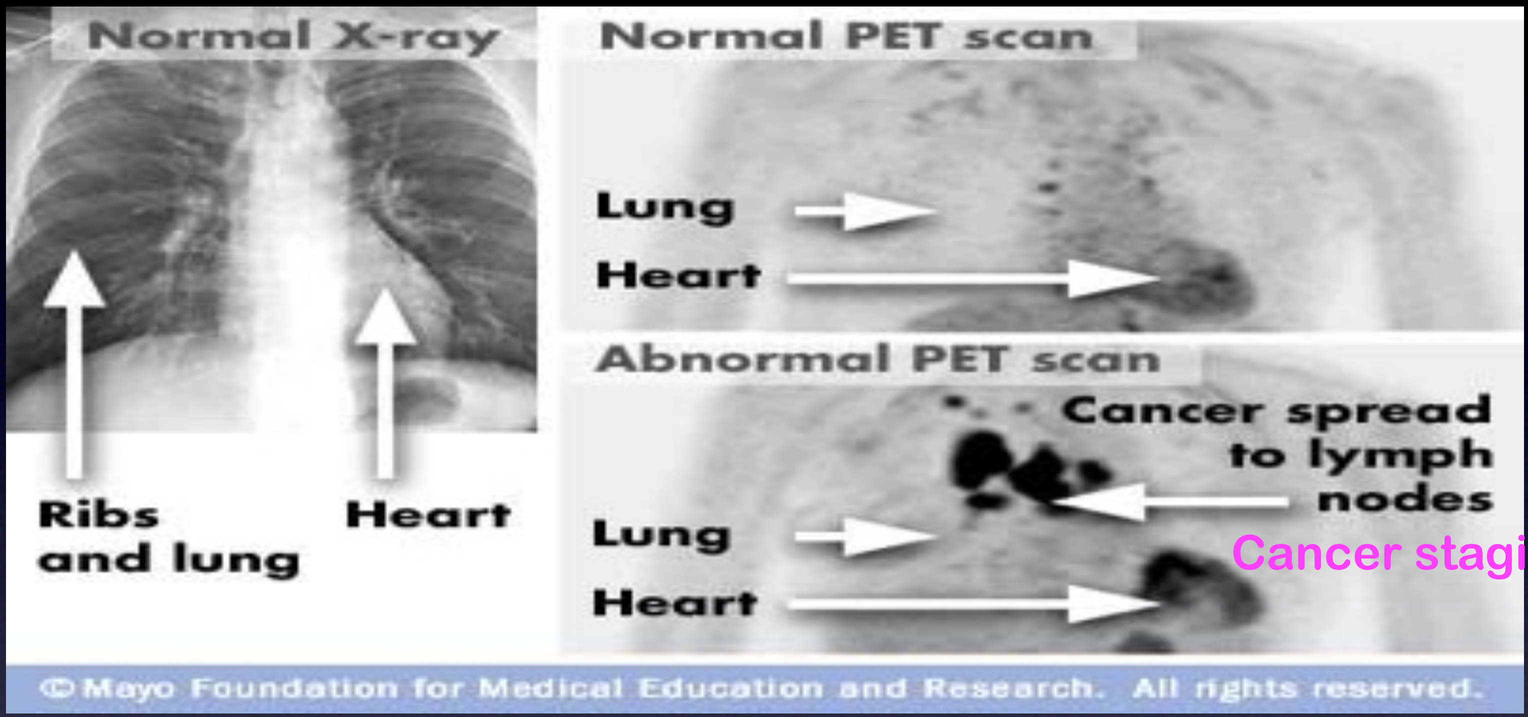
Brain PET scans from a healthy volunteer (left), a subject with mild cognitive impairment (middle) and a subject with Alzheimer's disease (right). Red and yellow areas show the new chemical marker FDDNP binding to abnormal brain proteins or "plaques and tangles."

The study included 83 volunteers aged 49 to 84. Based on cognitiv testing, 25 patients had Alzheimer's disease, 28 had mild cognitive impairment and 30 were normal controls.
Researchers performed PET brain scans after intravenously injecting the volunteers with the new chemical marker called FDDNP, the molecule that binds to the plaque and tangle deposits found in Alzheimer's disease.
Scientists found distinct differences among people with normal brai aging, patients with Alzheimer's disease and people with mild cognitive impairment.

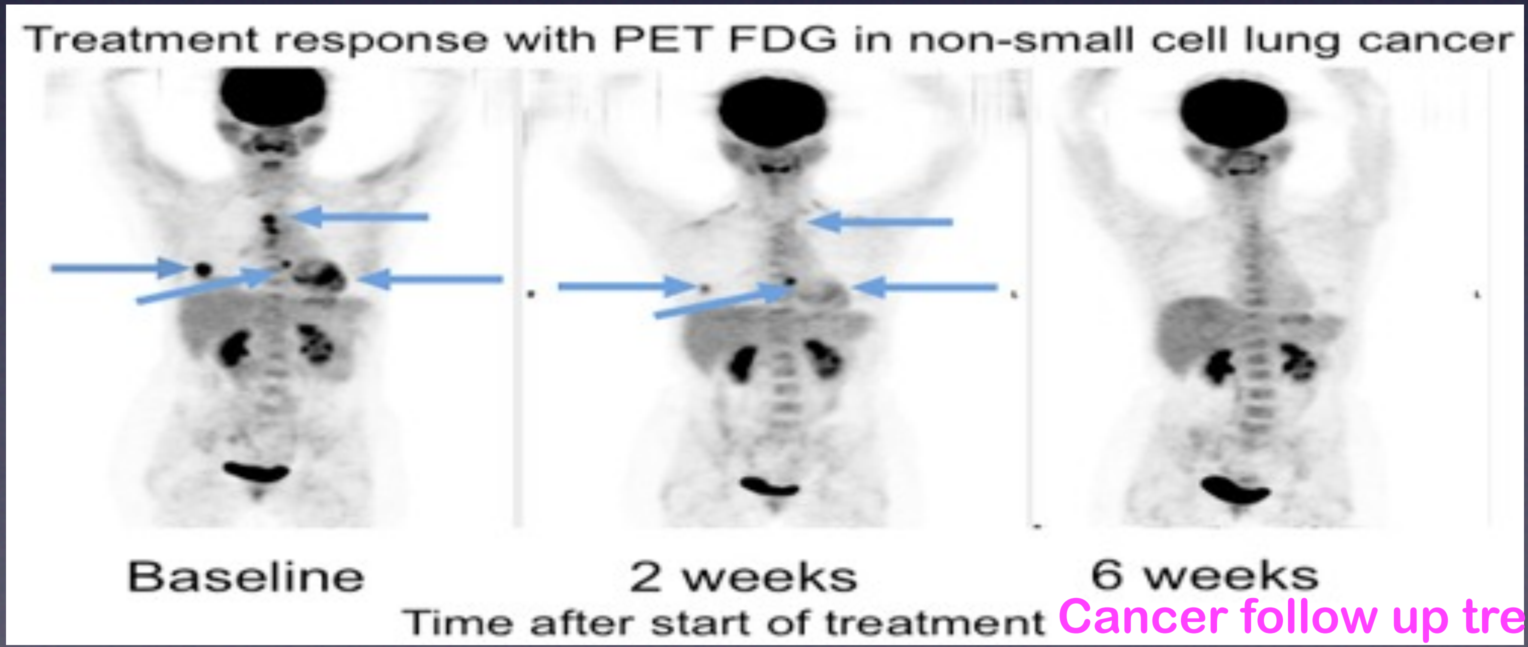
"This is the first time this pattern of plaque and tangle accumulation has been tracked in living humans over time in a longitudinal study,"

PET scan use : cancer staging and cancer treatment


Ask Mish



Cancer staging



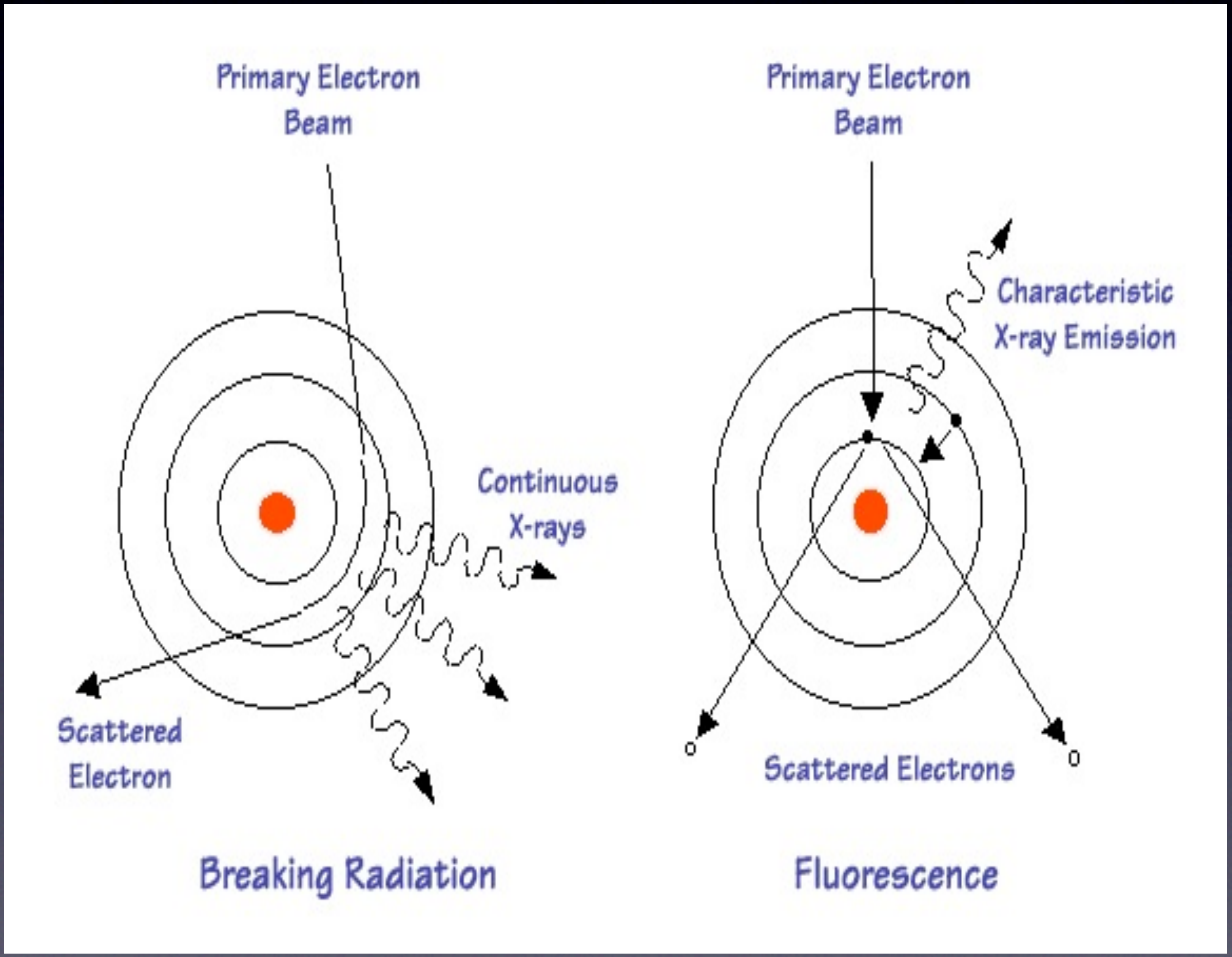
Cancer follow up treatment

- PET image has higher resolution since the device take 2 gammas in opposite direction in the same time in comparison w/Anger camera: only one gamma, one direction.
- PET drawbacks: need a cyclotron next to PET scanner cos the radiotracer, usually must be used immediately. The cost is high, thousands of dollars/ PET scan.
- use: all for blood flow&cell uptake in : brain, myocardium, lung, liver, kidney (investigate FUNCTION)
- PET mostly used for tumor staging & follow up treatment;
- 80% of PET scans use F18, then O15, Rb82, N13


Ask Mish

X RAYS

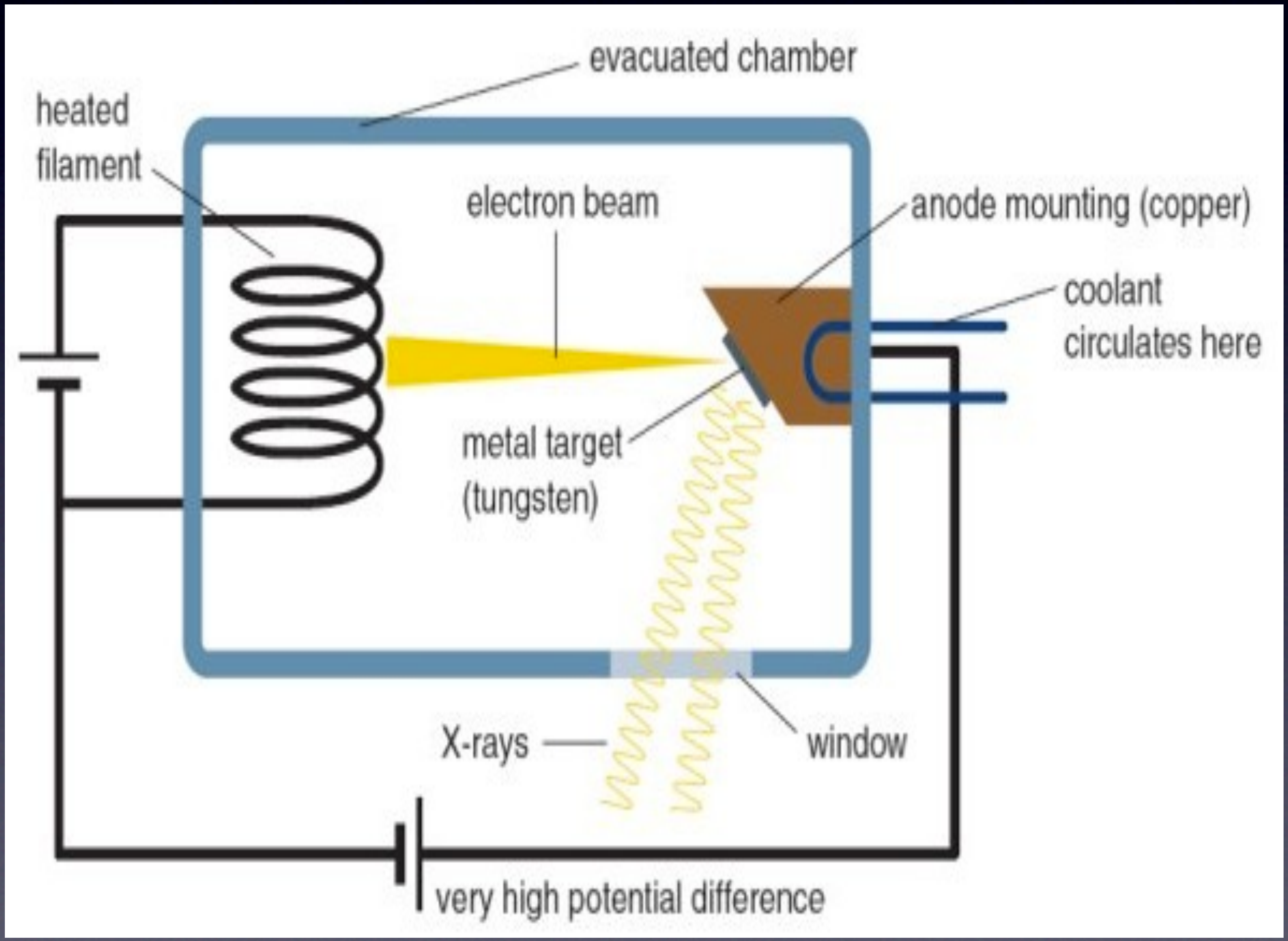
X ray production:



- Principle: excited electrons :
- 1. losing energy (E)
- 2. changing orbitals from high to low E
- can obtain this by hitting a metal w/ electrons:
- 1.-e deceleration 90% = Bremsstrahlung or breaking radiation
- 2.K shell expulsion: hit -e(K) is replaced
- Bremsstrahlung =German for breaking radiation : -e hitting atoms of a metal once they come closer to nucleus they are decelerated by the positive field around it. Electrons change direction = breaking radiation and lose E in the form of X rays.
- K shell expulsion: free-e are hitting -e from K shell when hitting the metal's atoms; the K -e leaves the atom and is replaced by an -e from higher energetic orbitals L,M which lose E by moving to K in the form of X rays

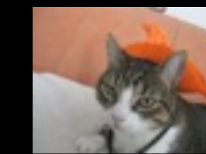
X ray tube: working principle


Ask Mish



- Free -e accelerated w/ potential difference(ten to hundreds) between the two electrodes, cathode(-) and anode(+) hit a metal which is anode. What happens?
- 99% of the electrons E is lost in heat-> this means that metal should have a high melting point: Cu, Mo, graphite, tungsten etc
- 1% of lost E is producing X ray (see on the left)

X ray tube: the beginning



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- X ray : discovered by Wilhelm Roentgen in 1895 while studying a Crookes tube. In 1901 he receives the 1st Nobel Prize.
- History of tubes: Geiger-> Crookes ->Coolidge (today's tube)
- Main difference btw them is the source of free -e : ionization of gas in Geiger and Crookes vs free -e emitted by heating cathode made of tungsten in Coolidge

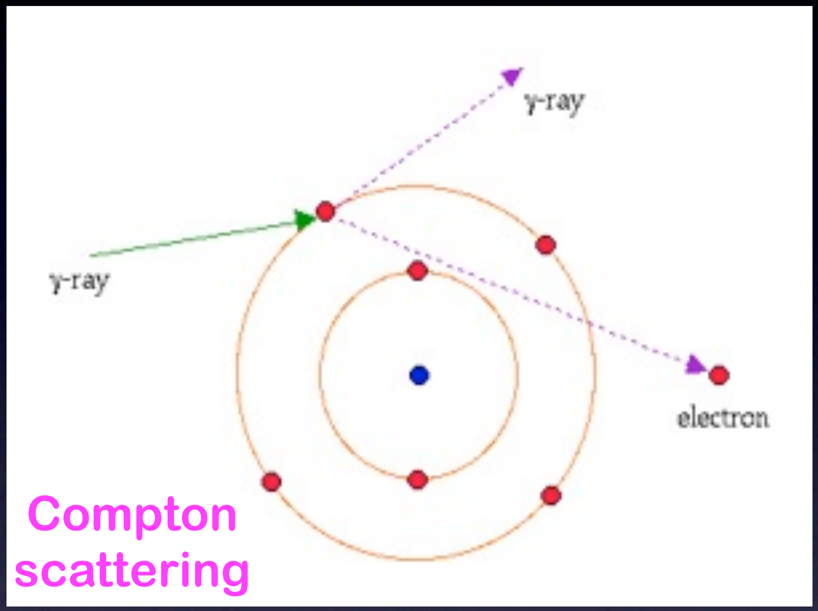
History of X ray tubes

Ask Mish

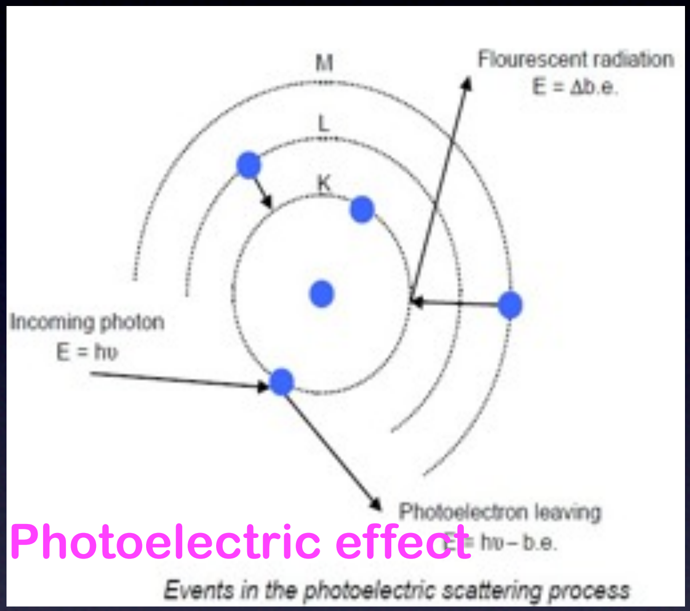
Tube	Geiger (cold tube)	Crookes (cold tube)	Coolidge (hot tube)
Position in time	1st	2nd	3rd (last)
Filled w/	noble gas	air (partial)	vacuum
Source of -e	gas by ionization	air by ionization	cathode by heating
Advantage/ drawback	neon tube developed	air absorbed/stop function	today's tube, do not stop function

Ask Mish

X ray:interaction w/matter

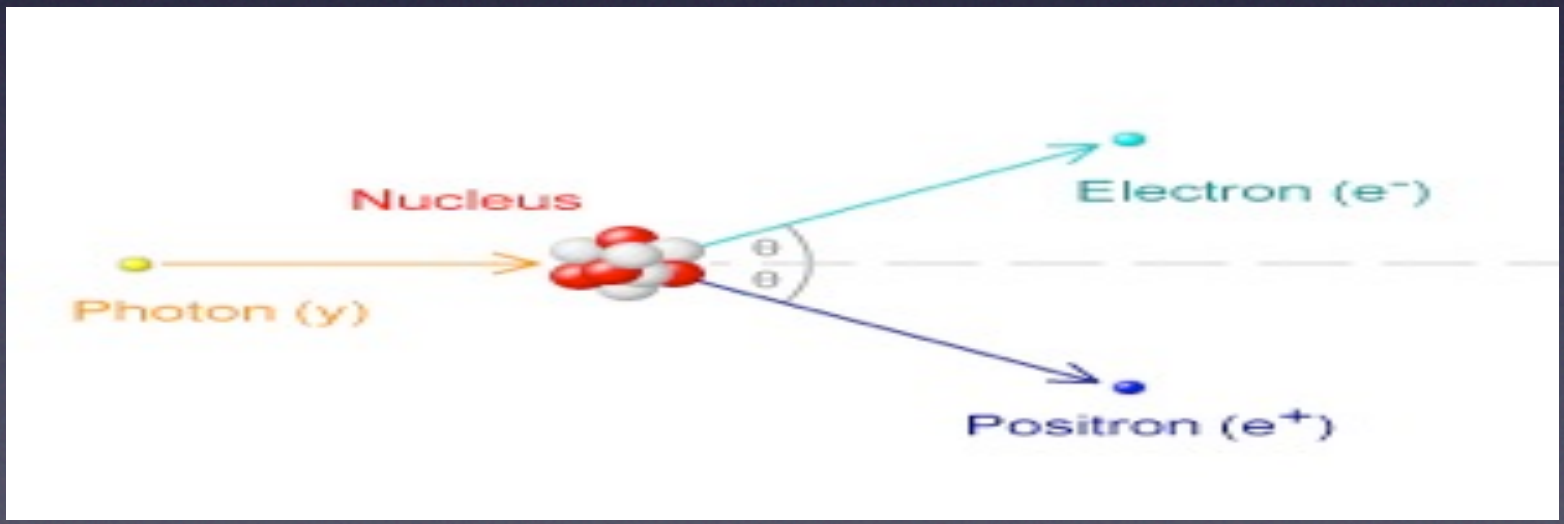


Compton scattering



Photoelectric effect

Events in the photoelectric scattering process

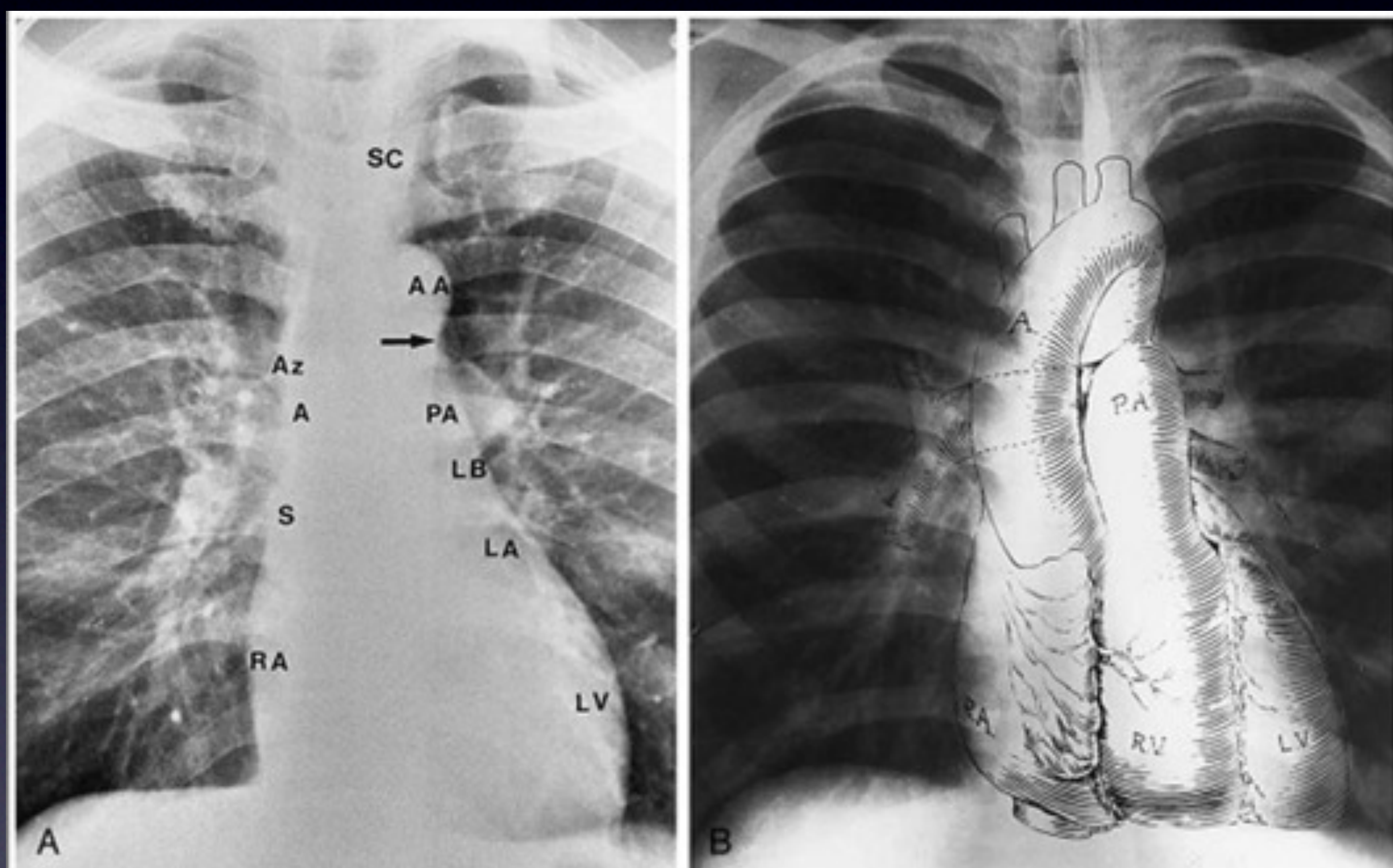


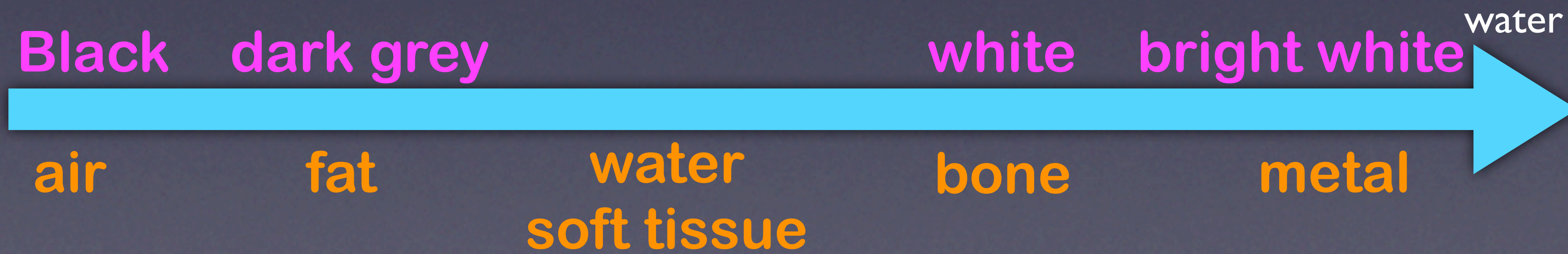
Pair producing

- All 5 types photon interaction w/matter
- Compton scattering and photoelectric effect is important for radiologic diagnostic or in radiologic imaging
- Pair production and photonuclear disintegration is important for radiologic therapy by destroying matter's structure
- Compton effect : photons of X ray hit e of outer shell, exchanging E; both photon now w/ less E and hit electron scatter in different angles. This scattered photon w/changed direction will produce the grey fuzzy effect on radiologic image
- Photoelectric effect is predominant in atoms w/ big Z value e.g. Ca and contrast. The photon is absorbed. The effect will appear white on radiologic image.

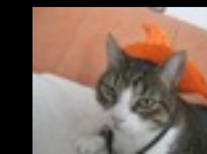
Xray image

- Based on:
- Photons passing through matter: dark on X ray film
- Photons w/photoelectric effect:(absorbed) white on Xray film, char. for dense matter: Ca and contrast
- Compton effect: photons scattered, grey and fuzzy on X ray film
- above the blue arrow, some colors on Xray and their main correspondent in tissues.
- Despite their popularity, X rays presented 3 major drawbacks: 3D structures were seen in a 2D film, the quality of the film was not very good, and some tissues cannot be differentiated by others, e.g. water and soft tissue.





CT scan: history and working principle



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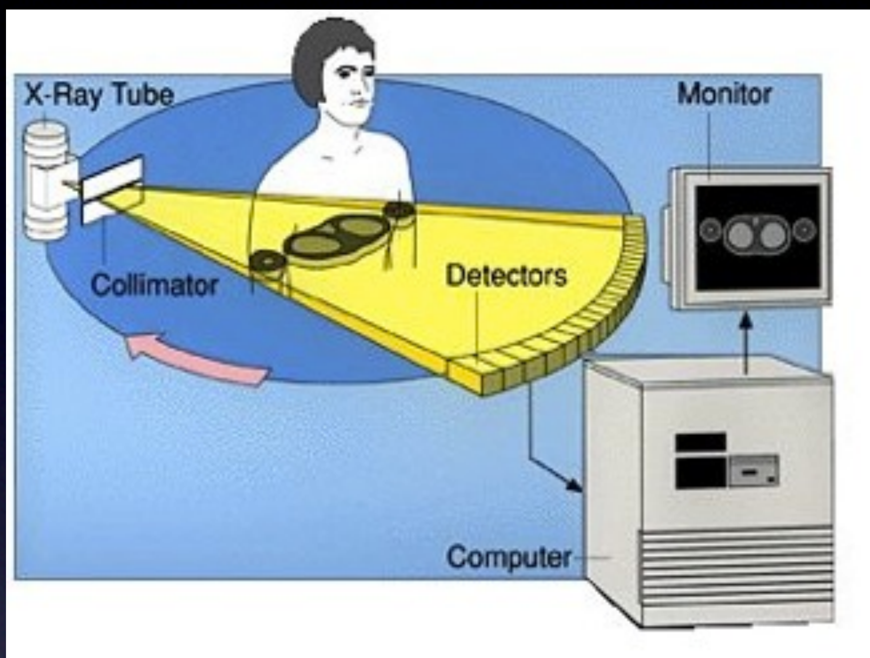
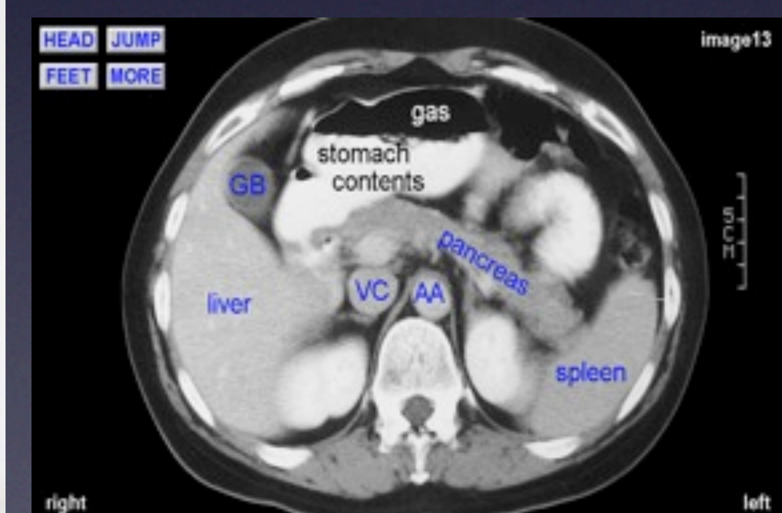


Sir Godfrey Hounsfield

CT scanner today



Abdominal CT scan today

In the late 1950ties, a British engineer working for EMI Laboratories named Godfrey Hounsfield received a sabbatical to investigate England's business computer new applications in the emergent computerized technology and he turned his attention to radiology. In the late 1960ties, the success of British pop band The Beatles under the label of EMI created a fond for Mr. Hounsfield research in CT.

Hounsfield had the idea to use the computerized technology to recreate an object by taking multiple radiographic images around the object. The idea was based on Johann Radon's mathematical principle that says that if you take multiple projections of the object, you can reconstruct this object in space.

Hounsfield built his first prototype in the late 1960ties. It consists of a lead box with a pinhole that has inside Americium, a radioactive material that emitted X rays. The rays in the form of a pencil beam passed through an object and that information was recorded by a detector connected to a computer. Once the beam passed, the object will rotate 1 degree and another beam will pass and then again one degree and another beam will pass and so on until a rotation of 180 degrees. This prototype operated 9 days for a single image.

Today, the source of X rays is an X ray tube and the beam is in the form of a fan and there are multiple detectors connected to a performant computer. The principle is the same, the collimator is rotated 1 degree and then another one degree up to 180 degrees for a CT scan image. CT= computed tomography former CAT (computed axial tomography)


Ask Mish

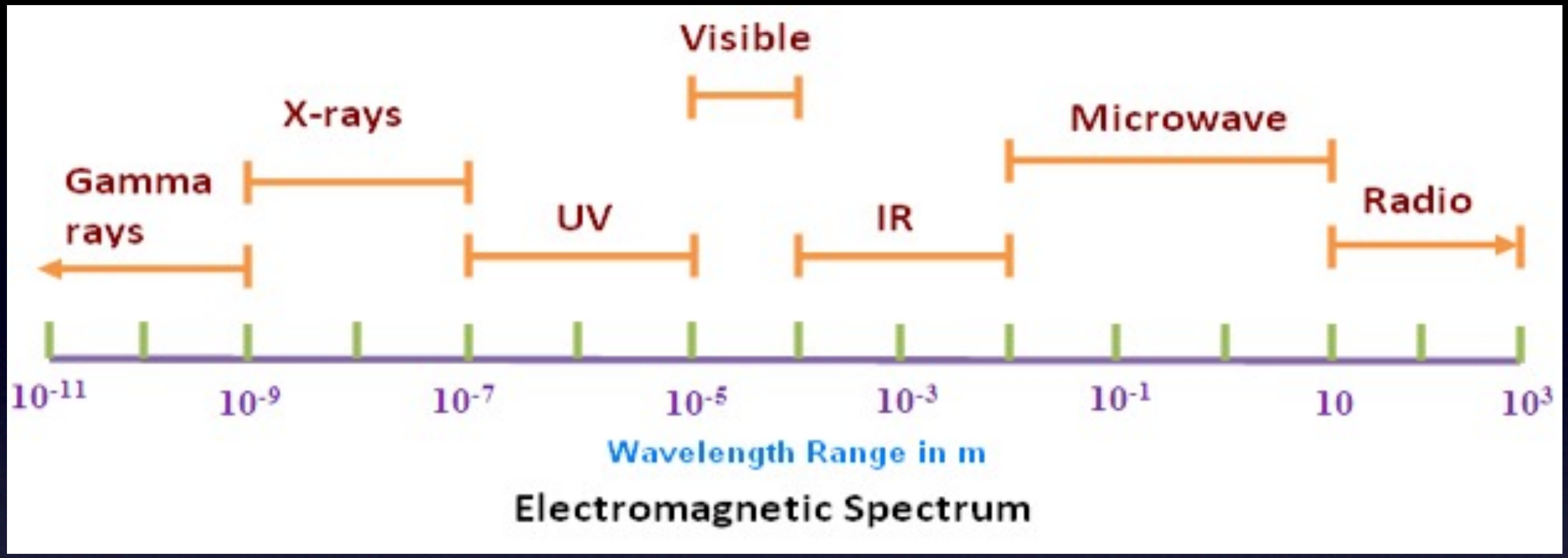
MRI

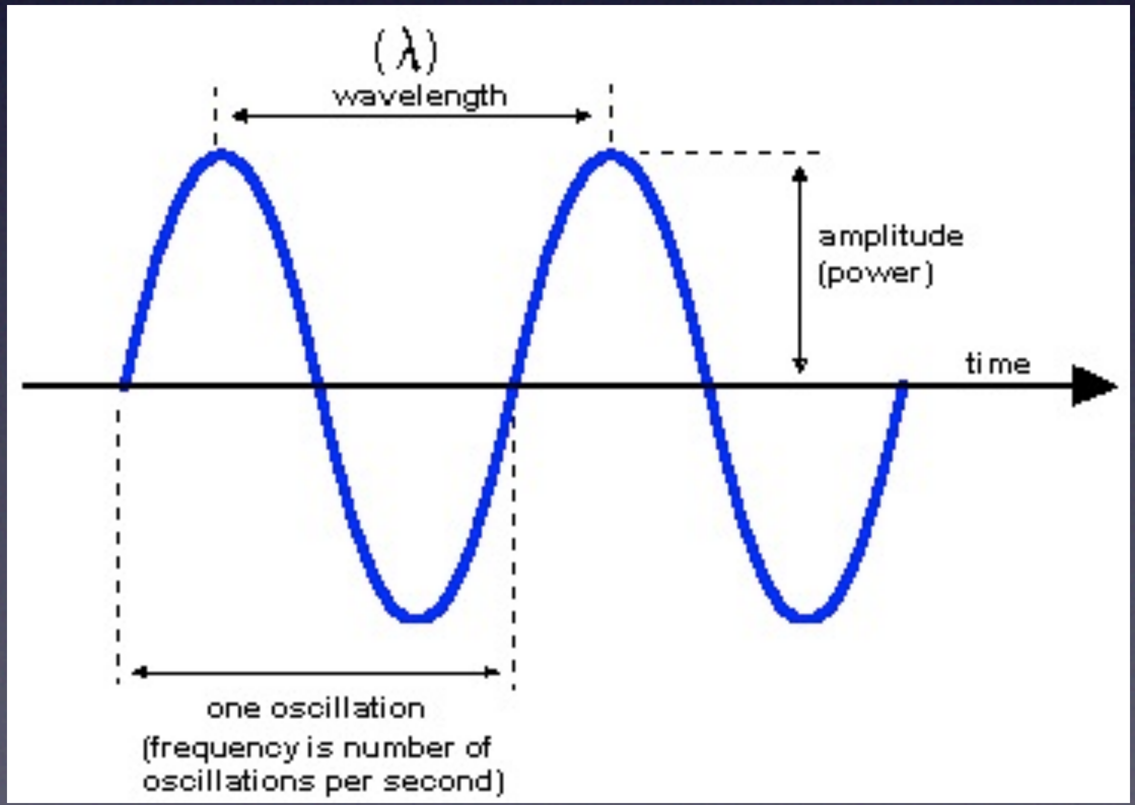
MRI vs NMR

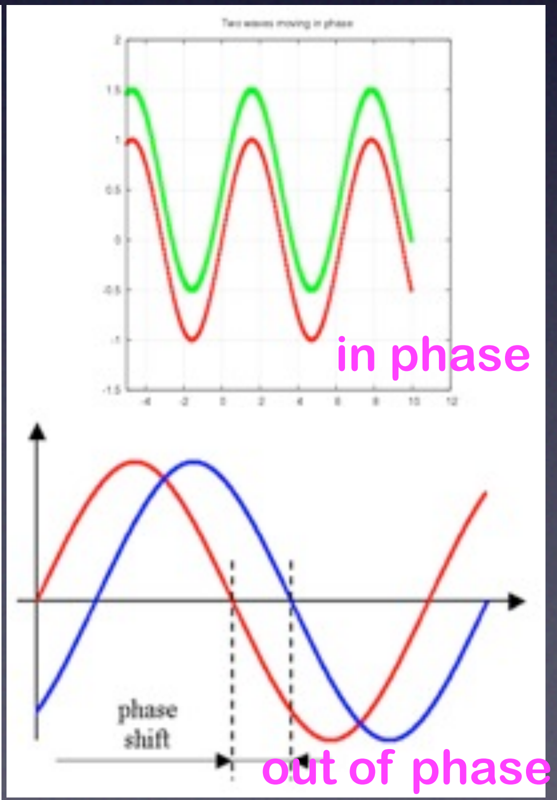
- nuclear is a word that general population associates with radioactivity
- Magnetic resonance imaging (MRI) is a technique based on a physics' phenomenon called nuclear magnetic resonance (NMR) which was first described in the 1930-1940ties.
- The basic principle of NMR refers to interaction of atomic nuclei (protons) with radio frequency energy and a strong magnetic field.

Radio frequency waves

Ask Mish



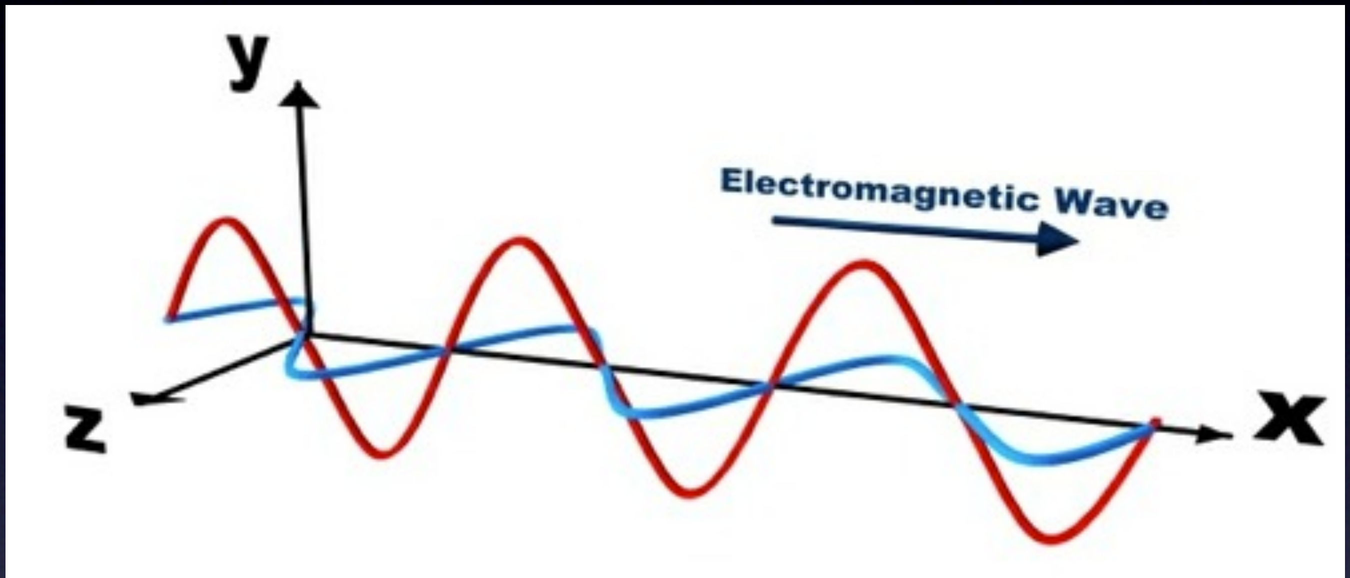




- Radio frequency waves are electromagnetic waves that are part of electromagnetic spectrum together with X rays and visible light. Radio waves are located at the end of electromagnetic spectrum, based on wavelength, the longest in the electromagnetic spectrum

- Any wave has:
- A WAVELENGTH btw 2 peaks
- A FREQUENCY = number of cycles completed in one second aka Hertz (Hz)
- An AMPLITUDE : or power
- if 2-more waves : IN PHASE if they line up completely (start @the same time) or OUT of PHASE or PHASE SHIFTED if not.
- Radio frequency waves are described by their unique PHASE and FREQUENCY

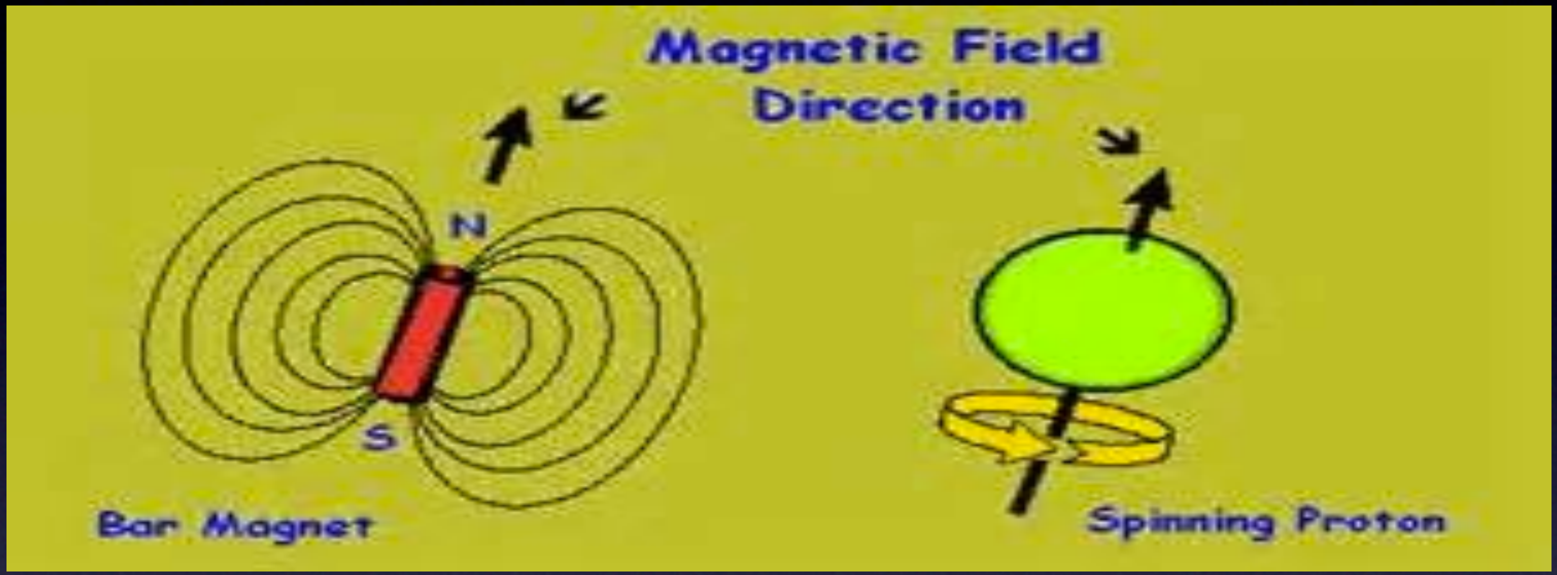
Magnetic Field - how to create a MF : flow of electrons

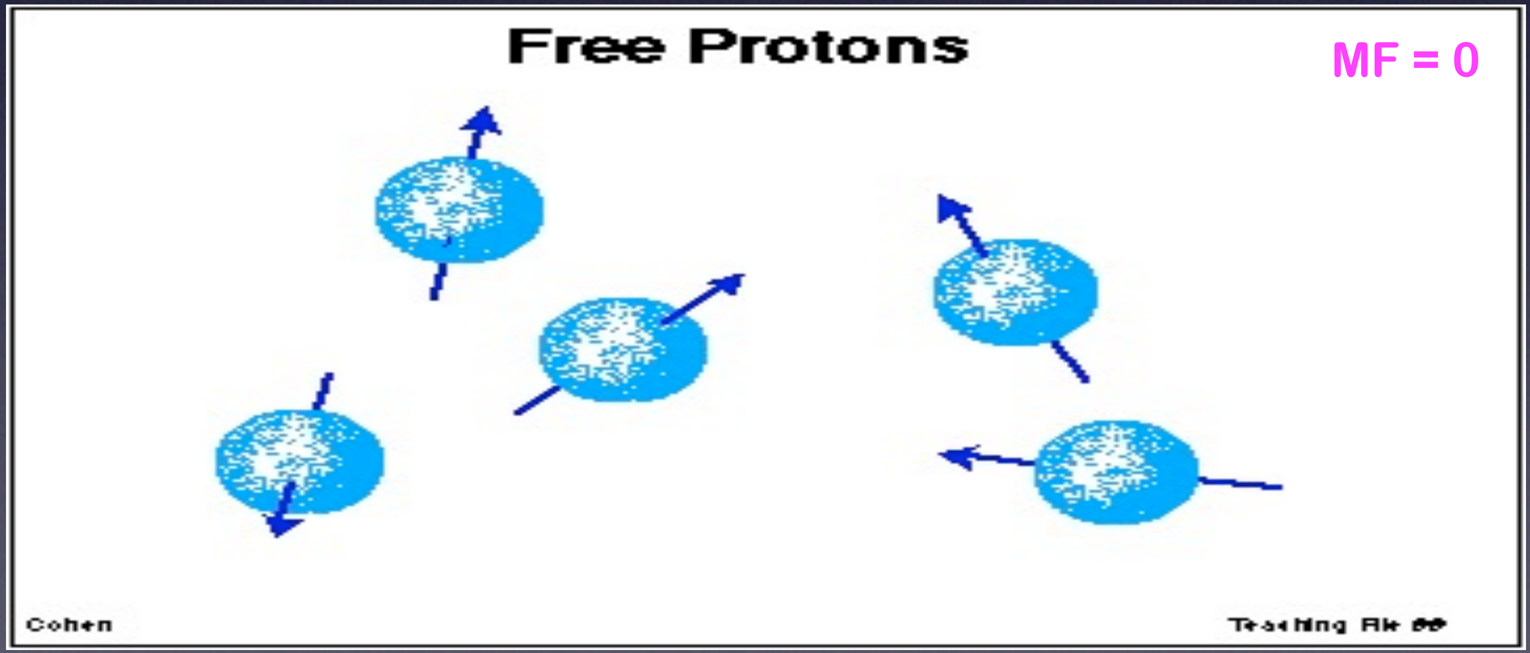


- Current electricity=flow of free e- moving thru wire
- produced by batteries,generators
- develop a force perpendicular on flow =Magnetic Field =lines in/out of poles N&S.
- DIRECTION OF MF : you apply right hand rule (see pic): fingers on the direction of current and outstretched thumb shows the direction of MF.
- Just as a current can create a magnet, a magnet can create a current. If we have a coil of wire connected to an ammeter and we place a magnet thru the coil, we will generate an electrical current thru the wire. When we pull the magnet back, the current flows in the opposite direction. If we spin the magnet, we generate a sinusoidal or alternating current, the basis of a generator.

Magnetic Field - how to create a MF : proton spin

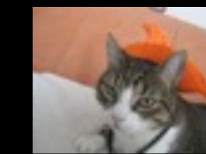
Ask Mish



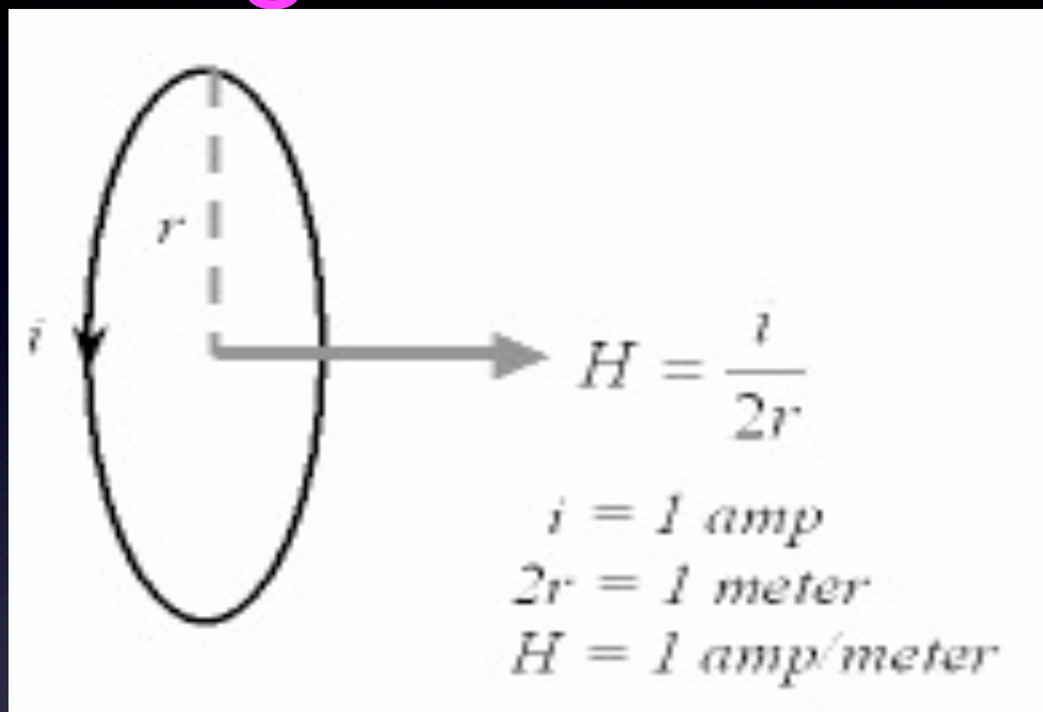


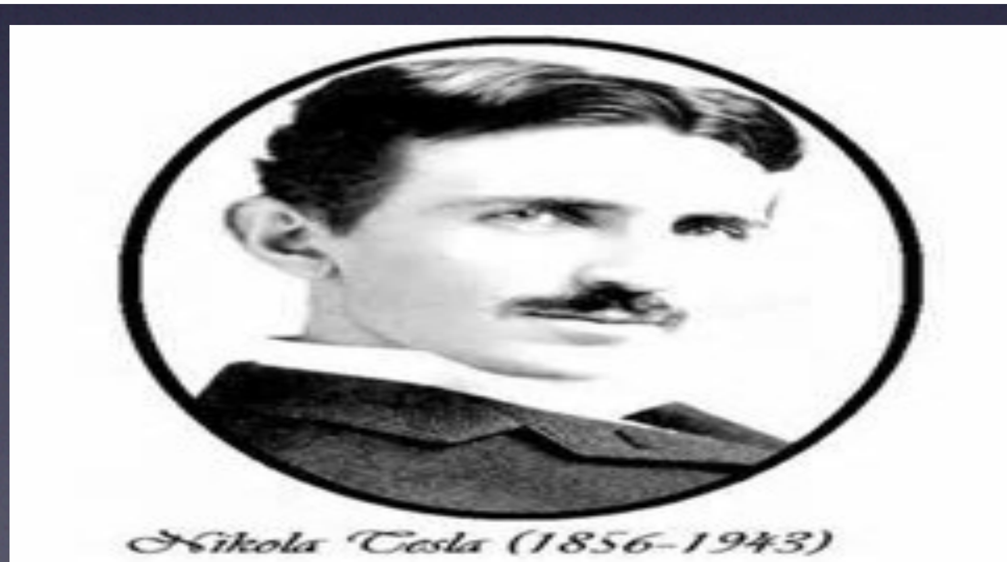
- MF is produced by any moving electrical charge
- inside the atoms: protons because of spin behave like small bar magnets producing a MF that has a direction given by right hand rule (see first pic on the left).
- electrons - spin and movement in the orbital create a MF; 2e- in the same orbital have opposite spin, their total MF=0;
- also because atoms have all directions in many substances MF=0
- b/w atoms: flow of free e- thru a wire = current electricity produce MF
- Magnet: term from Magnes, a Greek shepherd who noticed attraction b/w Fe and lodestone (AKA magnetite, a mineral based on Fe_3O_4 produced by interaction of $Fe(OH)_2$ w/ H_2O 10% in sand. Origin of the name lodestone = middle English for leading stone, used as magnet for early navigation).
- Magnet: Fe, Co, Ni- spin unmatched, atoms align in certain directions= permanent MF

Magnetic field density and MF strength



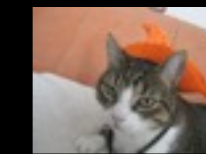
Ask Mish

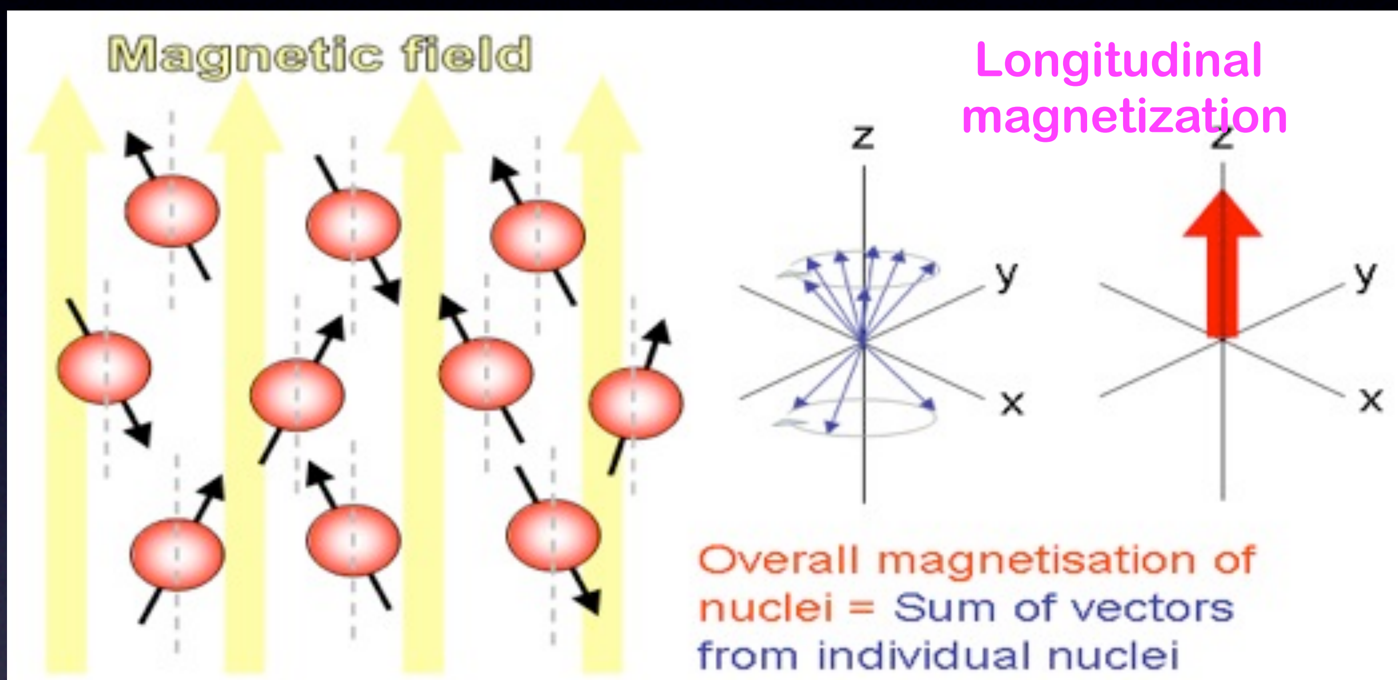


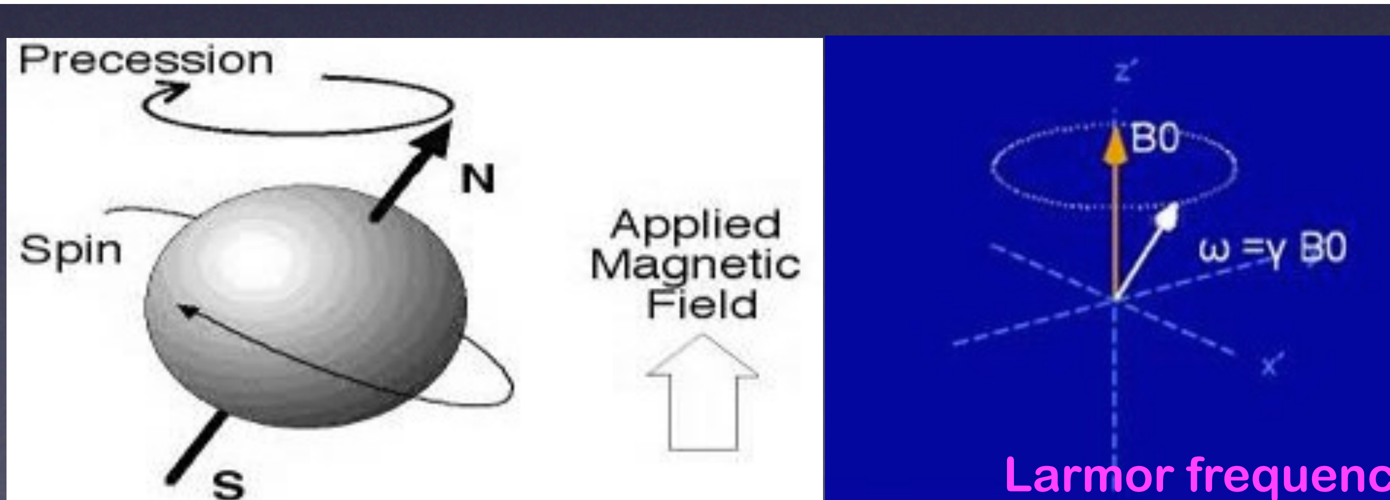


- B= μ (H+M) where:
- B=MF density or induction,
- H= MF strength in A/m and M=magnetization of the material in A/m,
- μ =magnetic permeability of the space
- B is expressed in Tesla. 1T=10,000 Gauss
- Nikola Tesla discovered in 1882 rotating MF
- <0.2 T =weak MF
- 0.2-0.6T =medium MF
- >1-1.5T =strong MF

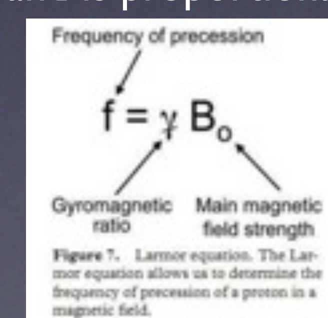
Longitudinal magnetization, Precession and Larmor frequency





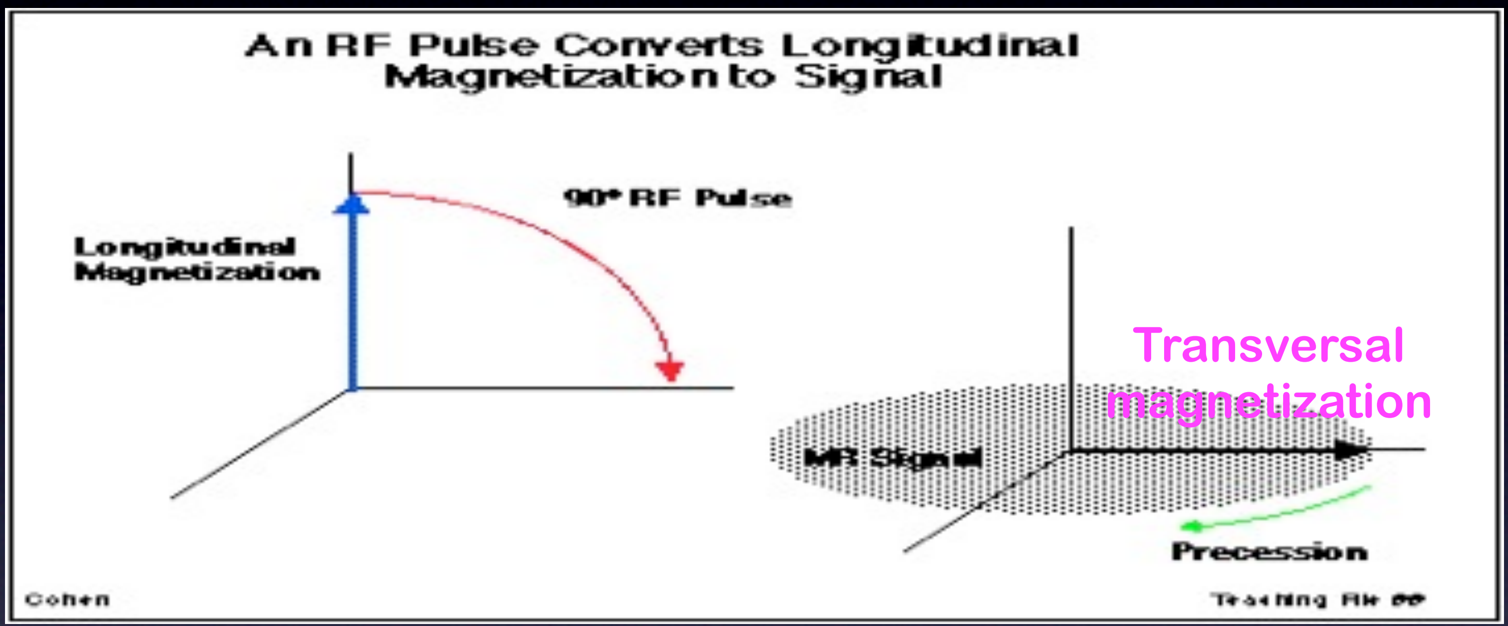


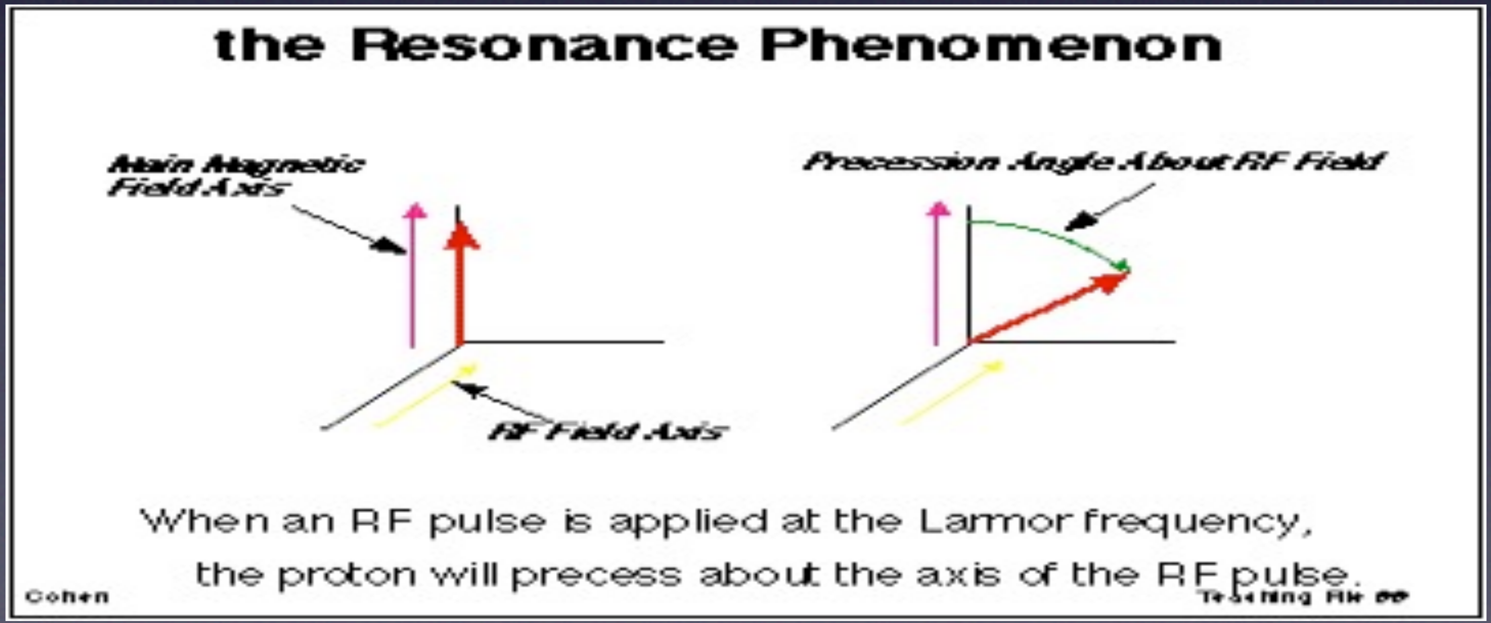
- H atoms have in nucleus just one proton w/ an unmatched spin that normally creates a small MF. Placed in a weak MF (like the Earth's MF) the small bar magnets (protons) are oriented in all directions. But when they are placed in a strong MF (MRI scanner) they can follow one of two ways:
- most of them line up w/ the strong MF, in the direction of the MF and these are the low energy p+
- few line up in a direction opposite to the main MF= these are the high E p+ (they can have extra E from some heat in the surrounding tissues).
- The net vector obtained from adding all vectors (protons) together is called LONGITUDINAL MAGNETIZATION and it cannot be measured directly since it is in line w/ the strong external MF but it can be inferred.
- Also, when placed in a strong MF, p+ are not just pointing in the direction of MF. They have a movement called PRECESSION. The rate of rotation (precession) is given by LARMOR frequency and is proportional to the strength of the MF applied (Bo)



Radio Frequency Pulse, Resonance and Transversal Magnetization

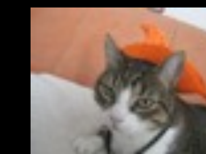
Ask Mish

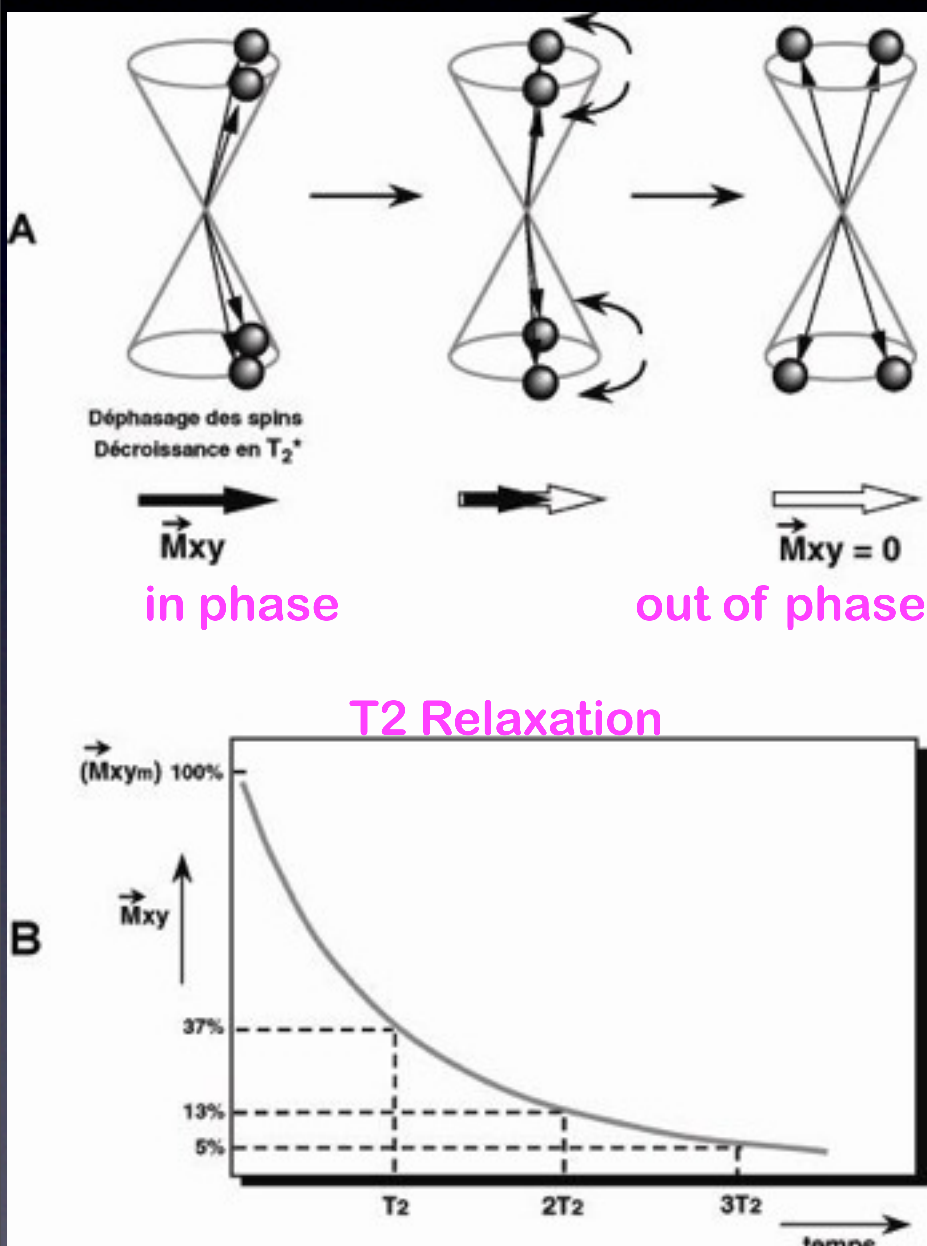


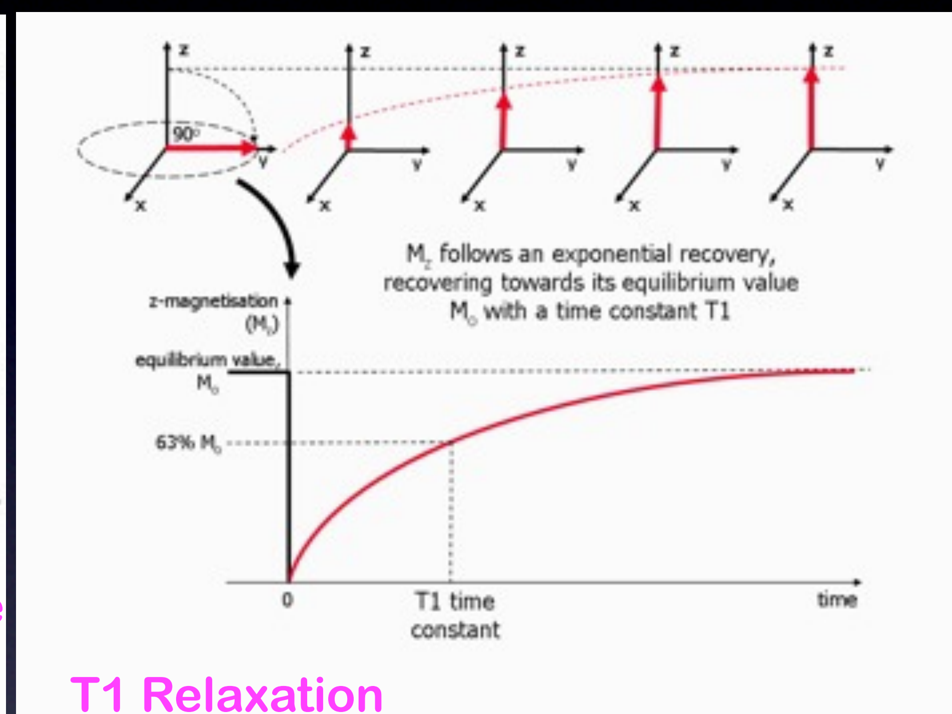


- So, the precession rate is proportional to the strength of MF.
- At 1T the rate is 42.58MHz,
- at 2T is 2x 42.58MHz,
- at 3T is 3x42.58MHz.
- Let's assume we applied a MF of 1T. If we apply now radio frequency energy aka RF PULSE at the precessing rate of 42.58 MHz then the protons are able to absorb this energy. 3 things will happen next:
- First, the absorbed E will flip some p+ from low state E into high state E. When we'll have 50% p+ on both sides (low and high state E) then the longitudinal magnetization vector=0
- Second, the absorbed E will make p+ synchronize in phase and spin together, process called RESONANCE (word included in RMN)
- Third, the p+ will precess along the axis of radio frequency waves. If we add up all the magnetic moments of the p+ we'll obtain a vector oriented 90 degrees to the previous (longitudinal) vector called TRANSVERSAL MAGNETIZATION. This vector generates a current (SIGNAL) that can be detected by a coil or antenna. This is the result that we are looking in NMR.

T1 and T2 relaxation







- When we remove the radio frequency signal, the protons will relax back into their baseline position.

  1st:

  p+ spins being positively charged will repel each other and move apart (out of phase) and this is why they will lose the transverse magnetization. The process is called T2 or “SPIN-SPIN” RELAXATION because it involves the p+ and their spin. No energy transfer occurs.

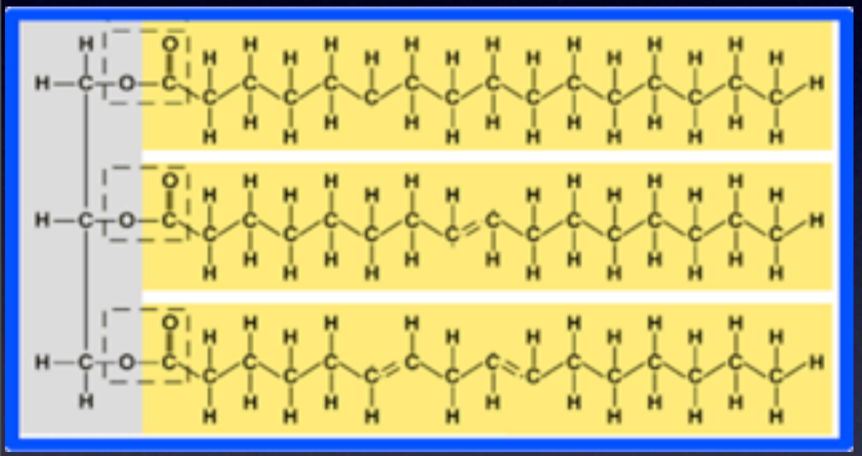
- 2nd:

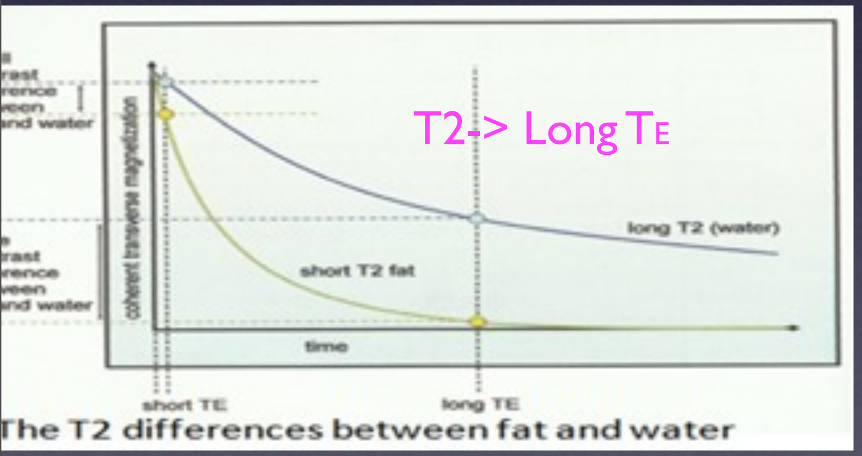
- In T1 or “SPIN-LATTICE” RELAXATION the p+ will give back the absorbed energy in the form of heat to the surrounding tissues and will regrow the longitudinal magnetization as they go back to the lower energy state.

T1 and T2 relaxation in various structures: fat and water

Ask Mish

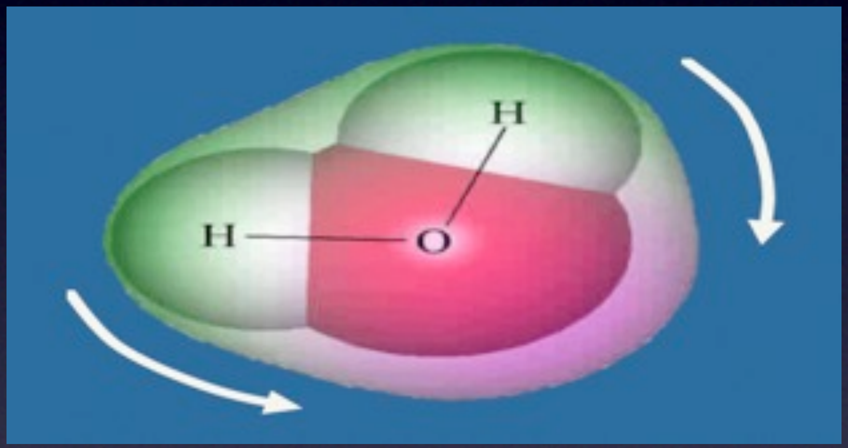
FAT molecule: fixed, low E

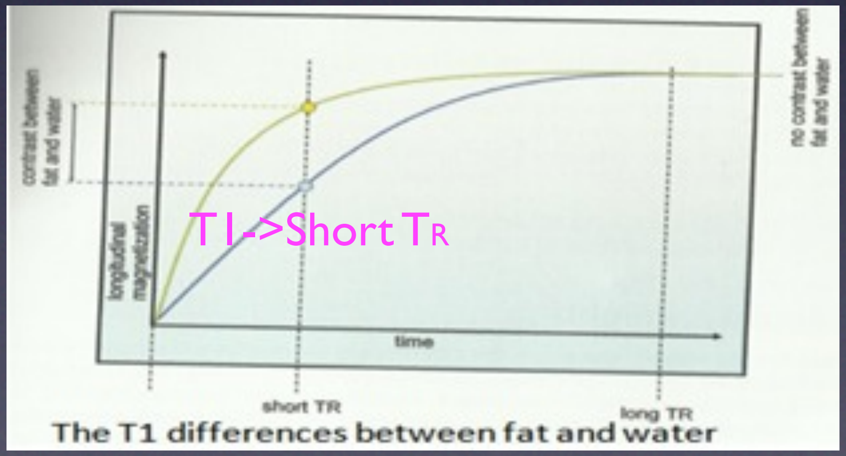




The T2 differences between fat and water

WATER molecule: free flow, high E



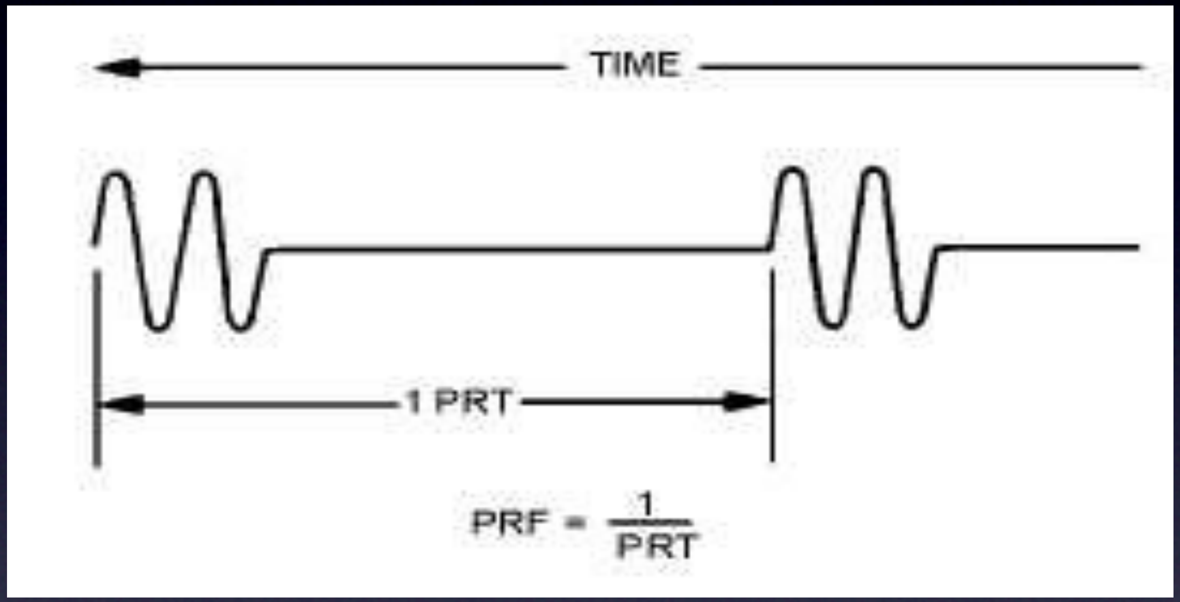


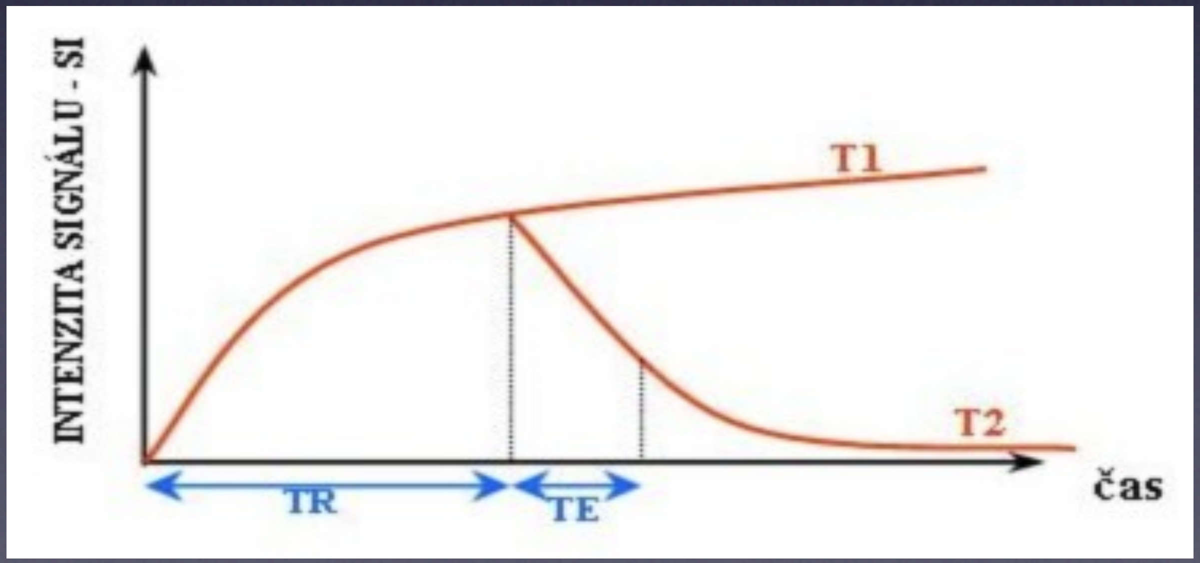
The T1 differences between fat and water

- Various tissues have different T1 and T2
- If we compare FAT and WATER we will find a different T1 and T2 for p+ in these two. In water, p+ are associated with free flowing molecules while in fat, p+ are in fixed positions in the structure of these energy storing molecules.
- In fat, being a very fixed structure, with low E the absorbed energy is given back quickly (T1)and the p+ interaction w/each other is strong producing a quick out of phase (T2) so both relaxation times will be very short (yellow line on the 2 graphs below). Because the energy is given back quickly, the transversal magnetization disappear and so does the signal which becomes very weak. By convention the weak signal appears dark grey or black on MRI image.
- Water, which is a free flowing molecule, needing high E, hold on the energy maintaining the p+ precessing in phase, long T2 and also maintaining the transversal magnetization , long T1, which produces a STRONG SIGNAL. By convention the strong signal appears white on MRI .

Repetition Time , Echo Time and Pulse Sequence: definitions


Ask Mish





- Repetition time TR is given by how quickly (in time) we put in again radio frequency energy
- Echo time TE is given by how quickly we listen for the return signal in transversal magnetization.
- Pulse sequence (PS) is the sequence of radio frequency pulses and magnetic gradients used to generate a MRI.
- We variate TR and TE to accentuate the differences between various tissues e.g. fat and water in T1 T2 or PD weighted images.

Repetition Time , Echo Time and Pulse Sequence: accentuating differences in tissues e.g. fat & water

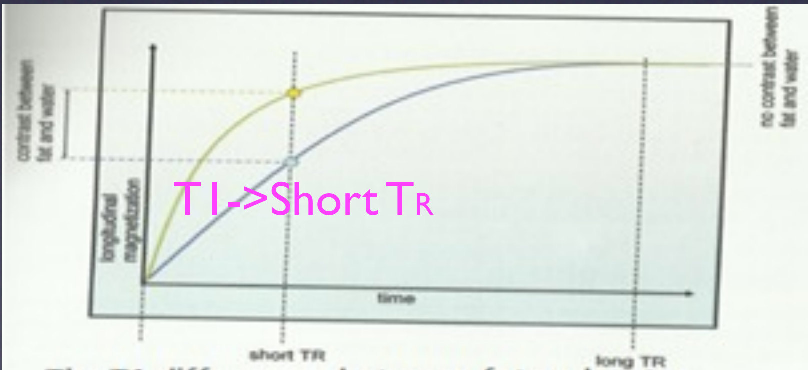
Ask Mish

Contrast, TR and TE

TR \ TE	Short	Long
Long	Proton Density	T2-Weighted
Short	T1-Weighted	X

Cohen Teaching File

The T2 differences between fat and water



The T1 differences between fat and water

- To enhance T2 among various tissues we have to wait long time btw Radio Pulse refer as long TR and a long time to listen for the return signal or echo refer to as long Te. P+ in the fat tissue will first start quickly to desynchronize and become phase shifted (short T2) while the more energetic p+ in water will take longer time to become out of phase (long T2).
- To enhance T1 btw fat and water, we need to apply a short TR and read the signal quickly (short TE). Fat p+ will lose E quickly, returning to the low E level or longitudinal magnetization (short T1) A quick reapplied pulse will produce a transversal magnetization and a strong signal on T1 weighted image (WHITE)
- In highly energetic water, the process of giving back the energy is much slower so a quick new RP will find the p+ still in transversal magnetization. (long T1).What can the new E do is to flip back in the high E state more p+ from the low E state, process known as 180 degree pulse. No new transversal magnetization occurs so the signal is weak for water p+ on T1 weighted image in comparison w/ signal from fat p+.

- The image in btw T1 and T2 weighted w/ long TR and short TE is called PROTON DENSITY. Long TR minimizes T1 and short TE minimizes T2 so the image resulted gives information only about the p+density.

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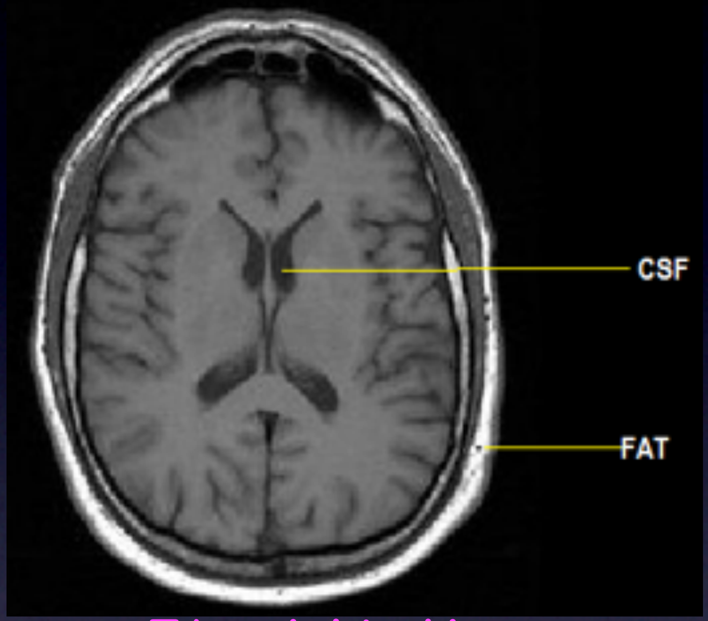
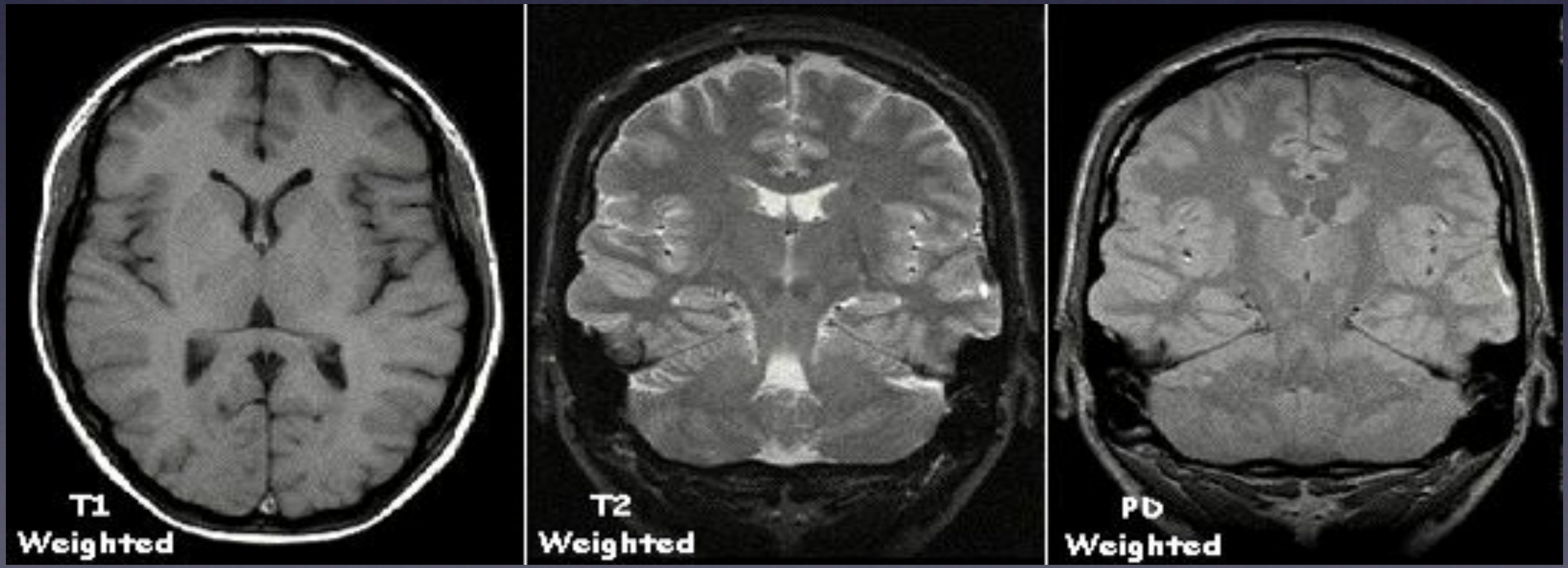
T1, T2 and Proton density weighted images



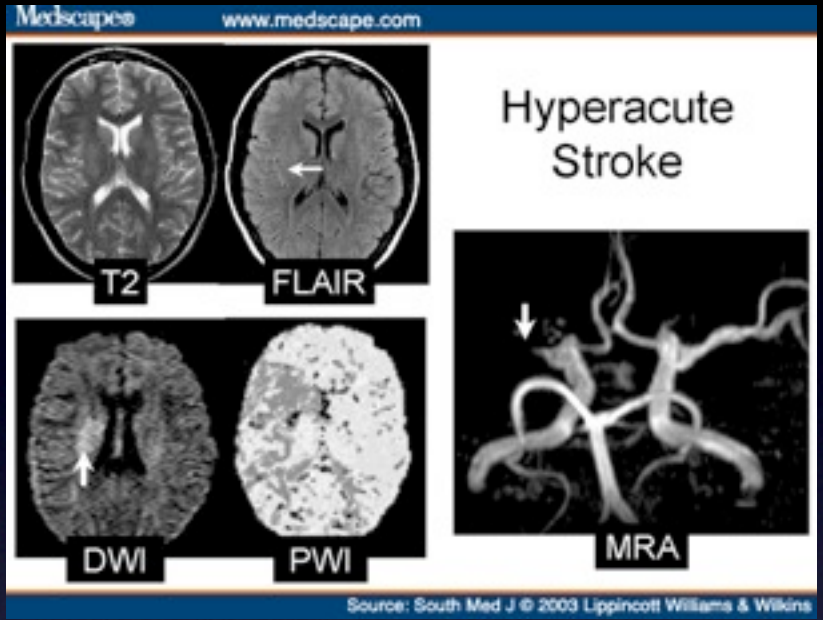
T1 weighted image

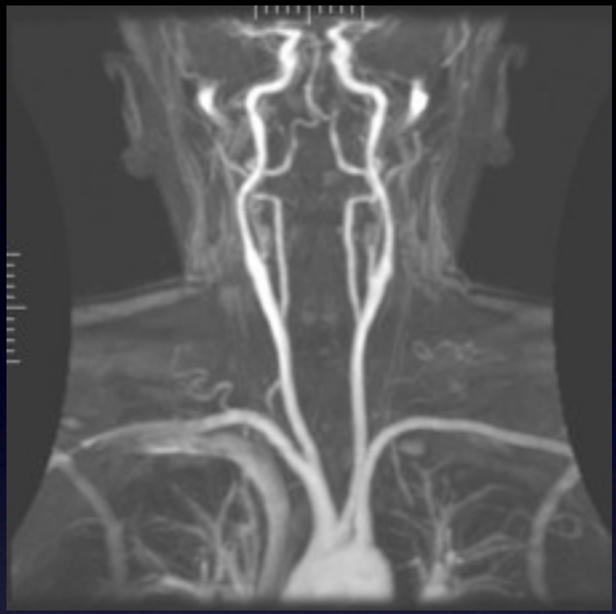


- We create a T1 weighted image by changing TR meaning using a short TR. We use T1 image mostly in:
- cerebral cortex
- identifying fatty tissue
- focal liver lesions
- post contrast images
- We create a T2 weighted image by changing TE. We'll use a short TE. We use T2 image mostly in:
- edema
- white matter lesions
- prostate or uterus anatomy

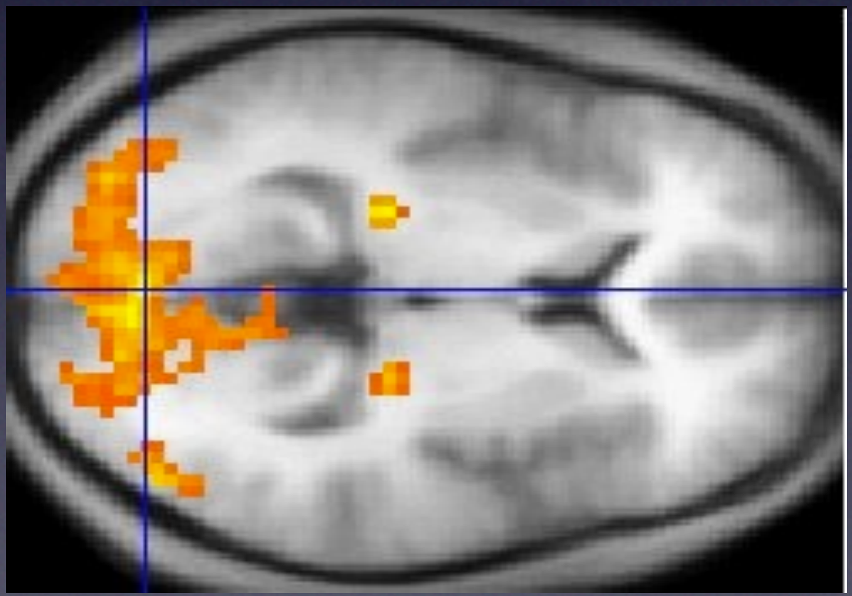
Various applications of MRI

Ask Mish

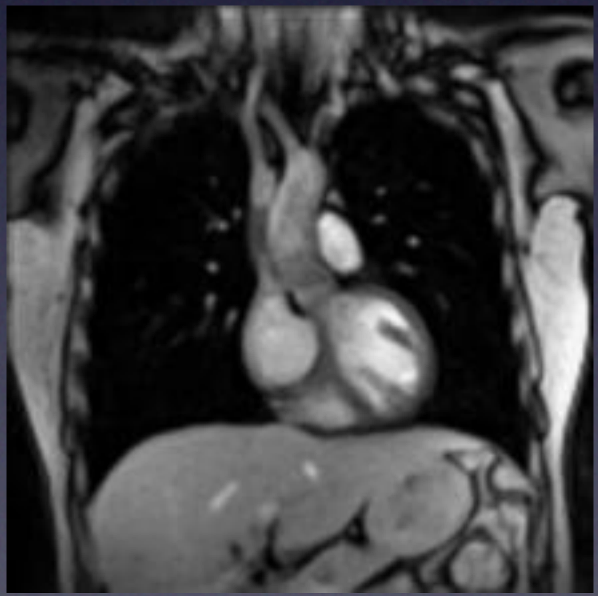




Magnetic resonance angiography



A fMRI scan showing regions of activation in orange including the primary visual cortex



Real-time MRI of a human heart at a resolution of 50 ms

- DIFFUSION MRI: measures diffusion of water molecules in biological tissues; used for Dx of strokes and multiple sclerosis. Strokes appears in 5-10 min on DWI opposite to 4-6h :CT scan
- MRI Angiography: evaluate arteries for stenosis and aneurysms. Similar for veins there is MR venography.
- MR Spectroscopy: measures levels of tumor metabolites in brain. MRI signals produces a spectrum of resonances for different arrangements of metabolite molecules to be excited. Used in Dx of tumors.
- FUNCTIONAL MRI measures signals in brain due to neural activity. Increased neural activity produce an increased demand for oxygen and vascular system compensates for it (BOLD= blood oxygen level dependant). Oxygenated hemoglobin produces an increased BOLD MRI signal while deoxygenated Hb produces a decreased signal.
- REAL TIME MRI is a continuos filming in real time is used for diseases of joints and heart.
- INTERVENTIONAL MRI: used during minimal invasive procedures for guidance

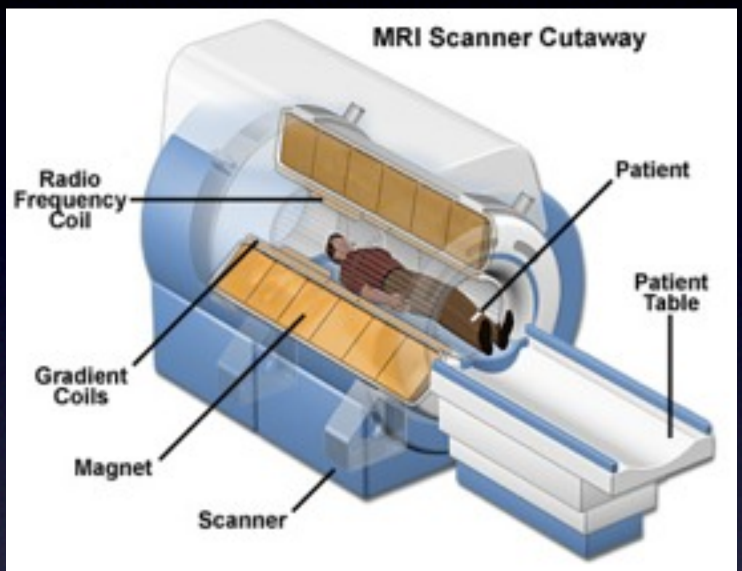
MRI vs CT scan

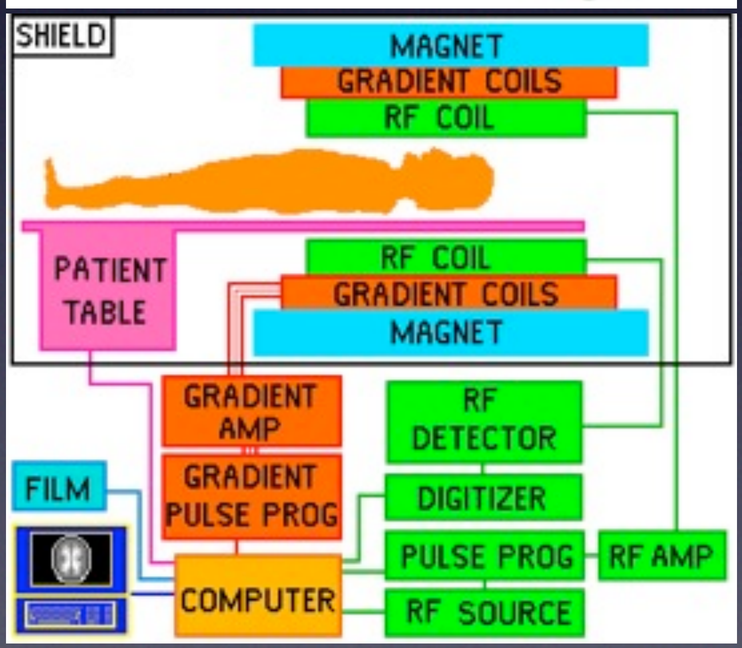

Ask Mish

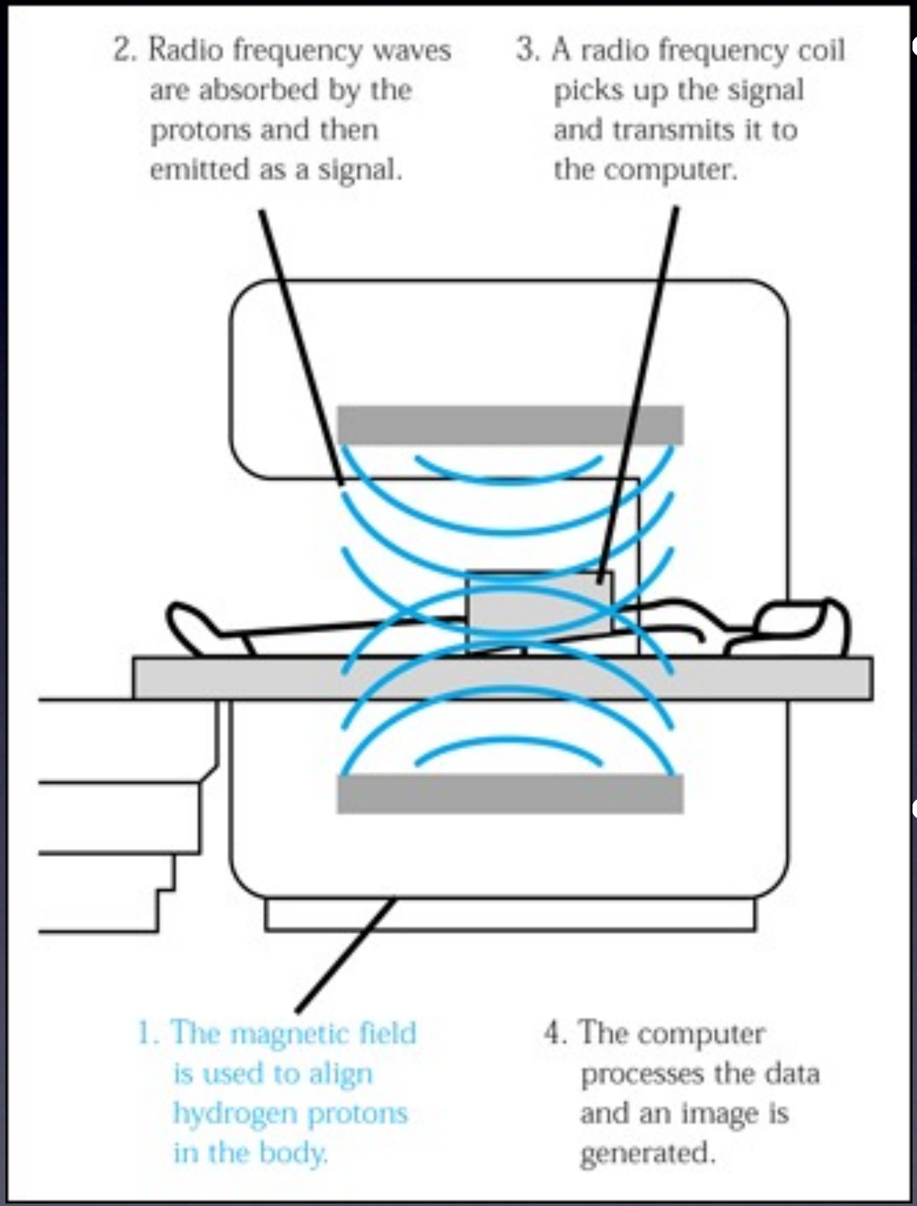
	MRI	CT scan
based on	NMR	ionizing radiation
harmful for living beings	not enough evidence	Yes
cost	> 500$	300-1800$
time	20-40 min	less
investigates	structure	structure
contrast	Gadolinium	Iodinated contrast
contrast side effects	nephrogenic systemic fibrosis	anaphylaxis, nephrotoxicity
Contraindication	any metal implants, pregnancy?	pregnancy

MRI scanner: working principle

Ask Mish



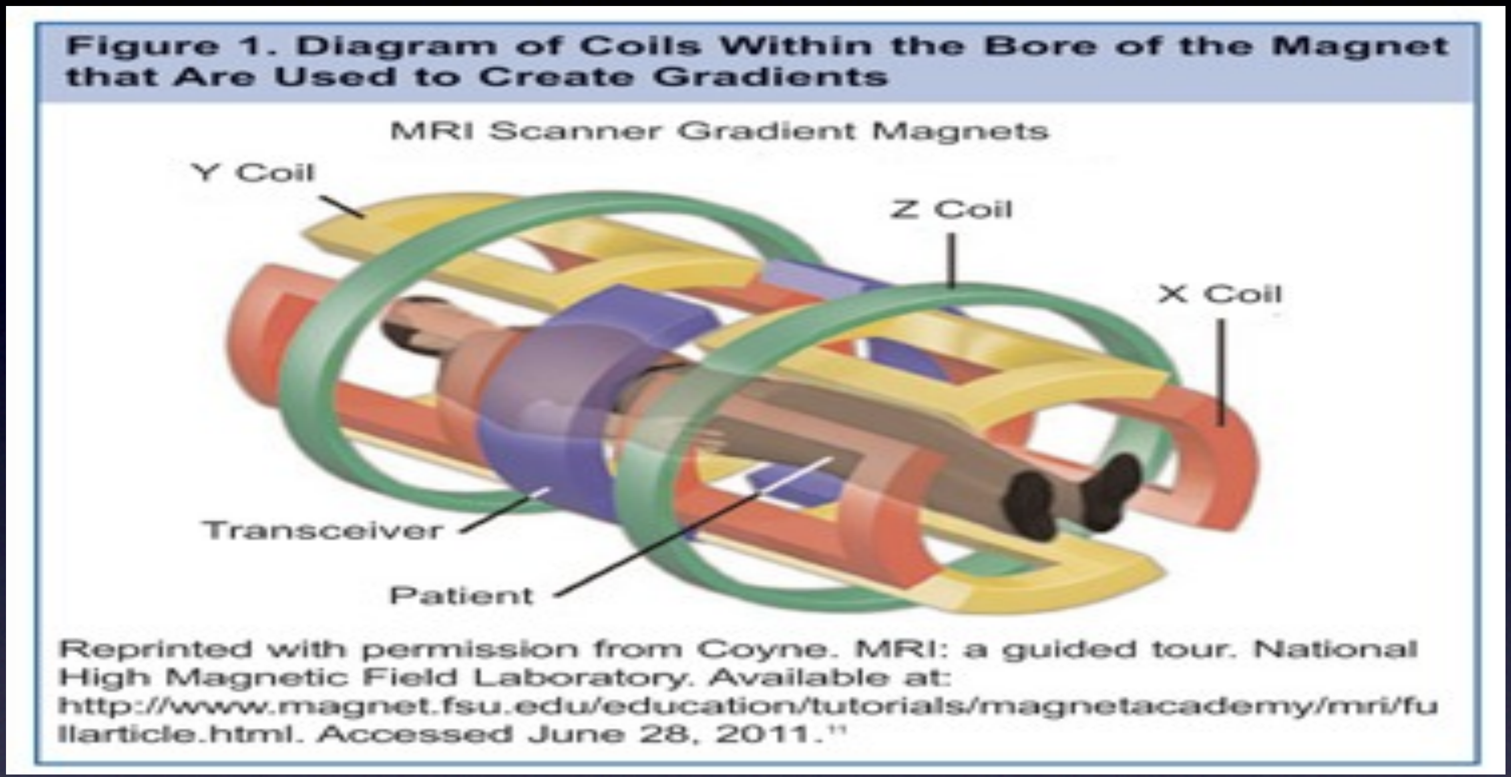


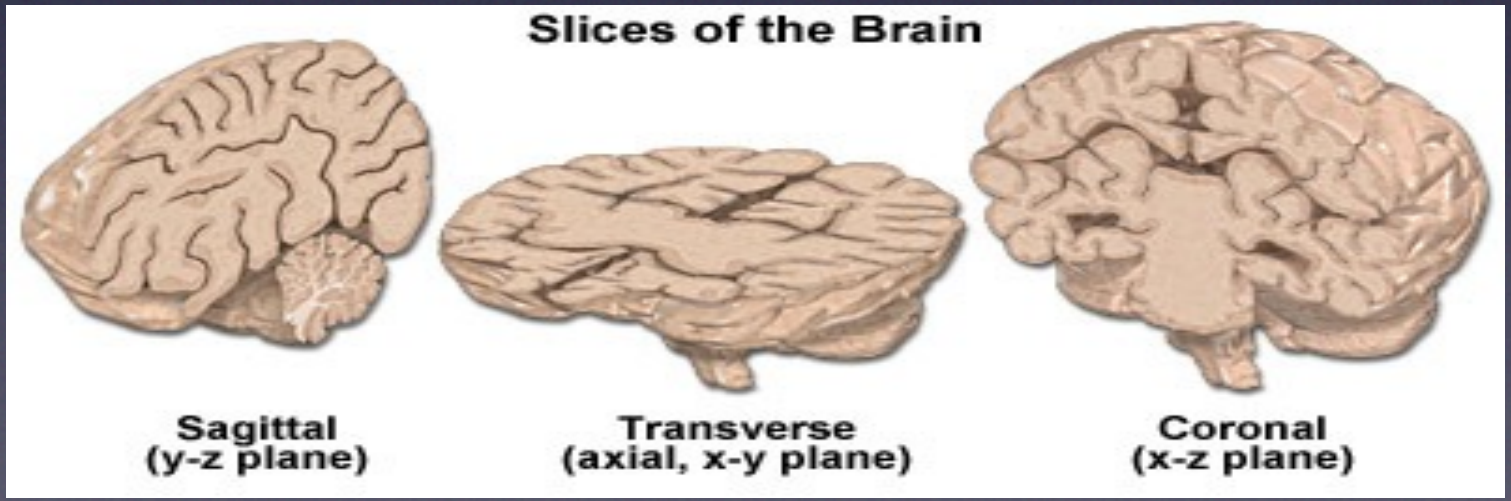


- MRI scanner is actually a long coil of superconducting wire (magnet). Superconducting means there is no resistance (R=0) when the free electrons (aka electrical current) are passing through the wire. Superconducting wire is obtained by keeping the temperature of the wire very low (e.g. by using liquid N2 or He). The result of using a superconducting wire is a strong MF, meaning 1T; 1.5 T or 3T.

- The patient is not allowed to wear any metal on him when he is scanned with an MRI scanner. If he has a pacemaker, metal valves or any metal implants, MRI is contraindicated since it can variates the intensity of the MF.

MRI scanner: gradient coils





- Gradient coils are small coils of wire attached to the long coil (magnet) used to variate the intensity of the MF. This variation is important to localize different parts of the brain (different parts of the brain will respond to different radio frequency waves and will emit different signals).
- There are 3 types of gradient coils corresponding to each axis X,Y and Z.
- They can localize any part of the brain, in sagittal, transverse (axial) or coronal plane.

MRI scanner today

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History of MRI

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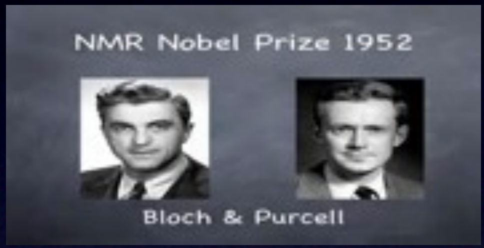
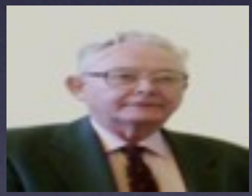
- 1947: NMR principle discovered by Felix Bloch and Edward Mills Purcell.



- 1977: first images taken by Paul Lauterbur (left) and Peter Mansfield (right). Lauterbur proposed in 1972 the use of gradient coils that allowed spatial localization of tissues on 2D images. Peter Mansfield developed a mathematical technique that allow scan to take seconds rather than hours.



- Raymond Damadian (big pic on the left) was the first to propose the use of NMR to diagnose disease in humans in an article published in "Science" in March 1971 called "Tumor detection by NMR". He also created the first MRI machine in 1972.

History of brain imaging

- X ray: skull absorb all X ray, brain=dark
- Pneumoencephalography: 50 y. ago used to dx. a tumor: injected air in the CF-> air goes in ventricles -> X ray -> air in the middle of the ventricles/not
- CT scan: 1979 Nobel Prize for Cormack & G. Hounsfield -> structure of brain
- PET scan: 1963 Glass & Harper -> breathed radioactive Xe to investigate brain function
- MRI: 1977 - Paul Lauterbur 1st image
- MRI : 1977 - Raymond Damadian 1st machine (left pic.)