Nuclear physics, radioactive decay

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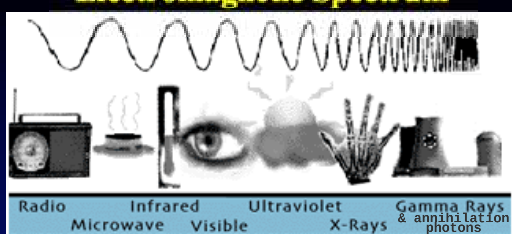
Electromagnetic Spectrum



The electromagnetic spectrum stretches from radio waves to gamma rays.

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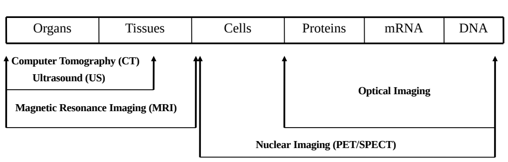

large availability of highly specific tracers

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highly sensitive measurement of a large variety of biological processes

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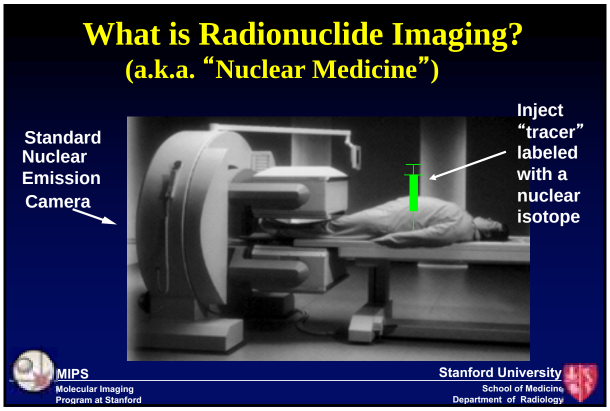
What is Radionuclide Imaging?
(a.k.a. “Nuclear Medicine”)
Standard Nuclear Emission Camera
Inject “tracer” labeled with a nuclear isotope
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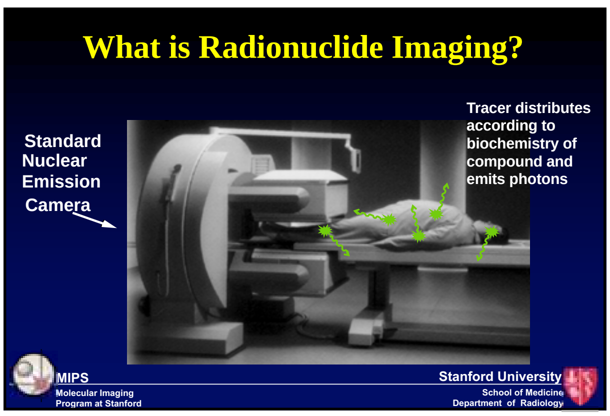
What is Radionuclide Imaging?
Standard Nuclear Emission Camera
Tracer distributes according to biochemistry of compound and emits photons
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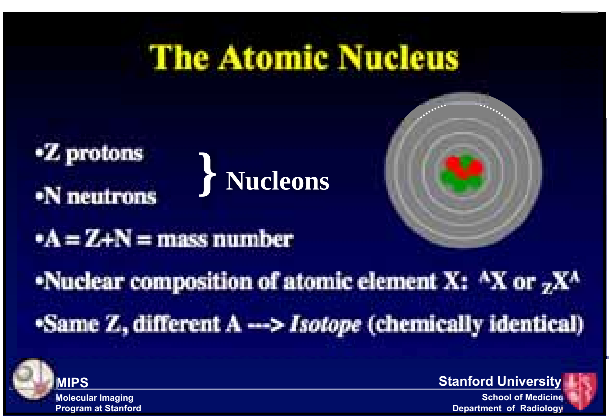
The Atomic Nucleus
•Z protons
•N neutrons
} Nucleons
•A = Z+N = mass number
•Nuclear composition of atomic element X: ^{A}X or $_{Z}X^{A}$
•Same Z, different A ---> *Isotope* (chemically identical)
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Forces Within the Nucleus

- *Strong* nuclear forces bind nucleons together
- *Weak* nuclear forces control certain nuclear decays
- *Electromagnetic* forces cause repulsion between protons
- *Binding energy* is the energy required to break apart nucleus into its individual constituents:

$$BE(A,Z)=[ZM_H+NM_N-M(A,Z)]c^2$$

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There are Tremendous Forces Within the Nucleus

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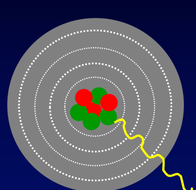
What is a radionuclide?

A nucleus in an energetic ("unstable") condition that relaxes ("decays") by emitting radiation in the form of energetic particles



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Nuclear Physicists

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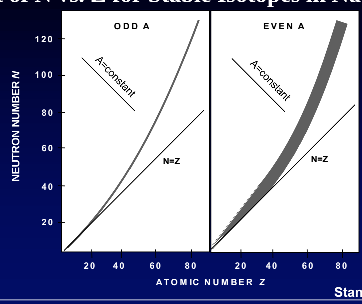
Nuclear Stability

Plot of N vs. Z for Stable Isotopes in Nature



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Relevant Modes of Nuclear Decay for Imaging

•**Gamma Ray Emission (Isomeric Transition)**:

Nucleons (protons and neutrons) rearrange themselves to a less energetic, more stable configuration, giving off electromagnetic energy $E_\gamma = E_i - E_f$ in the form of gamma (γ) rays. For imaging, need *metastable* parents. *Z* does not change.

$^{A}X_{Z}$ --> $^{A}X_{Z} + \gamma$ (or internal conversion electrons) (+ x-ray or Auger e^-)

Example nuclei that result in γ emission: ^{111}In, ^{123}I, ^{125}I, ^{99m}Tc, ^{201}Tl

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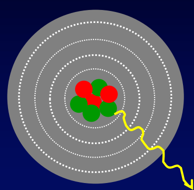
Gamma ray decay (isomeric transition)

A nucleus in an energetic ("unstable") condition that relaxes ("decays") by emitting gamma rays



Internal conversion competes with gamma ray decay

Excited nucleus relaxes by ejection an inner shell electron, which leaves an inner shell electron vacancy which is filled by outer shell electrons and the excess energy is either emitted as:

1. x-ray (Characteristic radiation) or
2. Transferred to an outer shell electron (Auger electron)

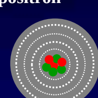
Relevant Modes of Nuclear Decay for Imaging

•Beta Decay (Isobaric Transition):

Nucleons transform into each other to obtain a more stable configuration. This involves the emission or absorption of a beta (β) particle.

Examples: $n \to p + e^- + \nu$ (electron emission); $p \to n + e^+ + \nu$ (positron emission); $e^- + p \to n + \nu$ (electron capture)

For Beta Emission, $E_\beta + E_\nu = M_N - M_P$. Z changes.

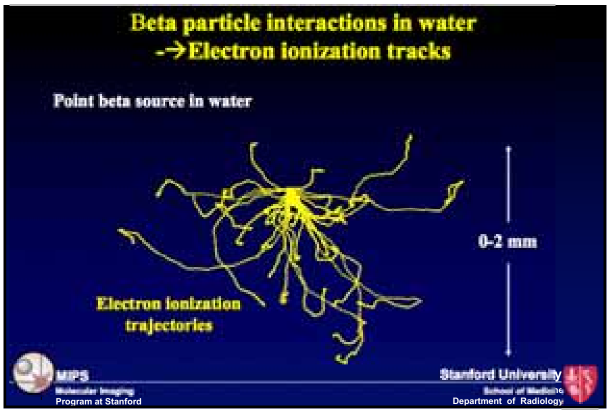


$${}^{A}X_{Z} \to {}^{A}Y_{Z\pm 1} + e^{\mp} + \nu$$

For electron capture: $e^- + {}^{A}X_{Z} \to {}^{A}Y_{Z-1} + \nu$ (+ x-ray or Auger e^-)

Example β-decaying nuclei: ^{3}H, ^{14}C, ^{32}P, ^{11}C, ^{13}N, ^{15}O, ^{18}F

Example electron capture decaying nuclei: ^{111}In, ^{201}Tl


Beta particle interactions in water
-→Electron ionization tracks
Point beta source in water
0-2 mm
Electron ionization trajectories
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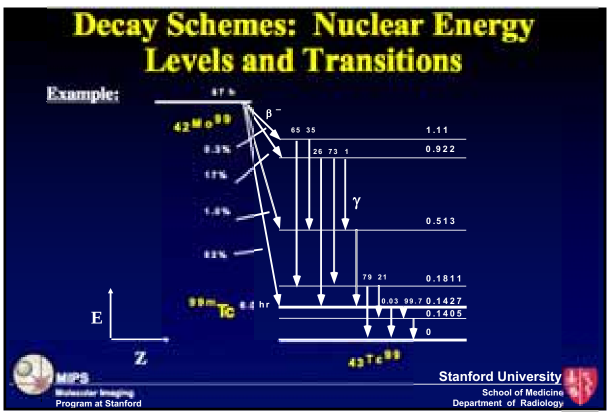
Decay Schemes: Nuclear Energy Levels and Transitions
Example:
42Mo99
β−
γ
1.11
0.922
0.513
0.1811
0.1427
0.1405
0
99mTc
43Tc99
E
Z
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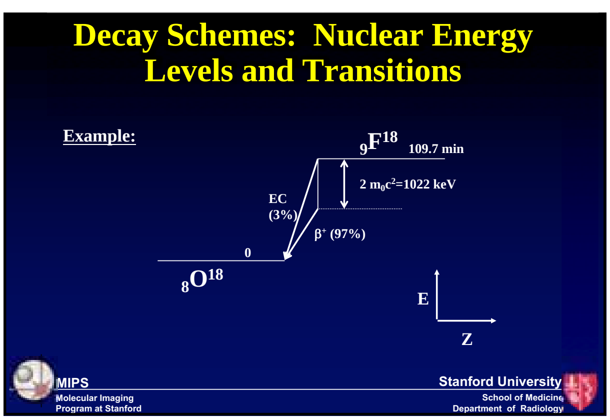
Decay Schemes: Nuclear Energy Levels and Transitions
Example:
9F18 109.7 min
2 m0c2=1022 keV
EC (3%)
β+ (97%)
0
8O18
E
Z
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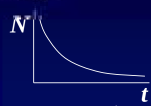
Nuclear Decay Probability

Radioactivity is a random process. If N_0 identical unstable parent nuclei were present initially, the most probable number N surviving after a time t is given by:

$$N = N_0 e^{-\lambda t}$$



λ = decay constant

Activity $\equiv -dN/dt = \lambda N_0 e^{-\lambda t} = \lambda N = (dN/dt)_0 e^{-\lambda t}$

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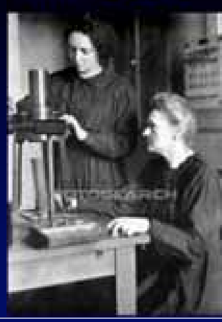
Marie Curie



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Radioactivity

<u>Exponential radioactive decay</u>

If $(dN/dt)_0$ is the initial activity of a radioactive source, then the activity after a time t will be given by:

$$dN/dt = (dN/dt)_0 e^{-\lambda t}$$

(Ci or Bq)
1Ci=3.7×10^{10} dis/sec
= 3.7×10^{10} Bq

λ=decay constant=ln2/$\tau_{1/2}$

$\tau_{1/2}$=half-life of radionuclide

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Some Common Radionuclides Used in "Nuclear Medicine"

Isotope	Energy (keV)	Half-life	Production
^{67}Ga	93, 185, 300	78 hours	Cyclotron
^{111}In	172, 247	67 hours	Cyclotron
^{113m}In	392	100 minutes	Cyclotron
^{123}I	159	13.2 hours	Cyclotron
^{131}I	364	8 days	Fission
^{99m}Tc	140	6 hours	Generator
^{201}Tl	80, 167	73 hours	Cyclotron
^{133}Xe	80	5 days	Fission
^{18}F	511 keV	110 min.	Cyclotron
^{11}C	511 keV	20.4 min.	Cyclotron

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