DEVIL PHYSICS
THE BADDEST CLASS ON CAMPUS
IB PHYSICS

TSOKOS LESSON 7-1B RADIOACTIVITY

Essential Idea:

- In the microscopic world energy is discrete.

Nature Of Science:

- Accidental discovery:
  - Radioactivity was discovered by accident when Becquerel developed photographic film that had accidentally been exposed to radiation from radioactive rocks.
  - The marks on the photographic film seen by Becquerel probably would not lead to anything further for most people.
  - What Becquerel did was to correlate the presence of the marks with the presence of the radioactive rocks and investigate the situation further.

International-Mindedness:

- The geopolitics of the past 60+ years have been greatly influenced by the existence of nuclear weapons

Understandings:

- Radioactive decay
- Alpha particles, beta particles and gamma rays
- Half-life
- Absorption characteristics of decay particles
- Background radiation

Applications And Skills:

- Completing decay equations for alpha and beta decay
- Determining the half-life of a nuclide from a decay curve
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Guidance:

- Students will be required to solve problems on radioactive decay involving only integral numbers of half-lives
- Students will be expected to include the neutrino and antineutrino in beta decay equations

Data Booklet Reference:

$$E = hf$$

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

Utilization:

- Knowledge of radioactivity, radioactive substances and the radioactive decay law are crucial in modern nuclear medicine
- How to deal with the radioactive output of nuclear decay is important in the debate over nuclear power stations (see Physics sub-topic 8.1)
- Carbon dating is used in providing evidence for evolution (see Biology sub-topic 5.1)
- Exponential functions (see Mathematical studies SL sub-topic 6.4; Mathematics HL sub-topic 2.4)

Aims:

- Aim 8: the use of radioactive materials poses environmental dangers that must be addressed at all stages of research
- Aim 9: the use of radioactive materials requires the development of safe experimental practices and methods for handling radioactive materials

Introductory Video

Segre Plots

- At low Z numbers, stable nuclides have N = Z
- At higher Z numbers, N > Z

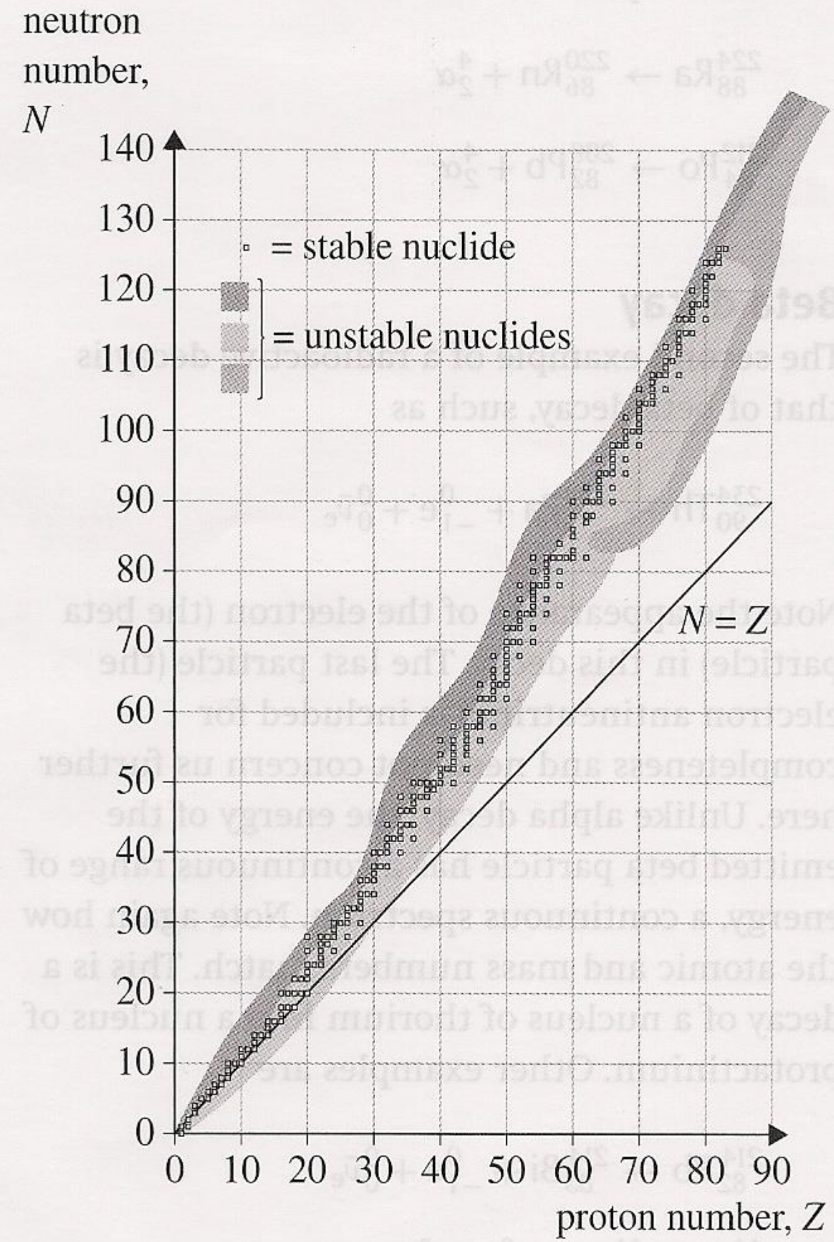
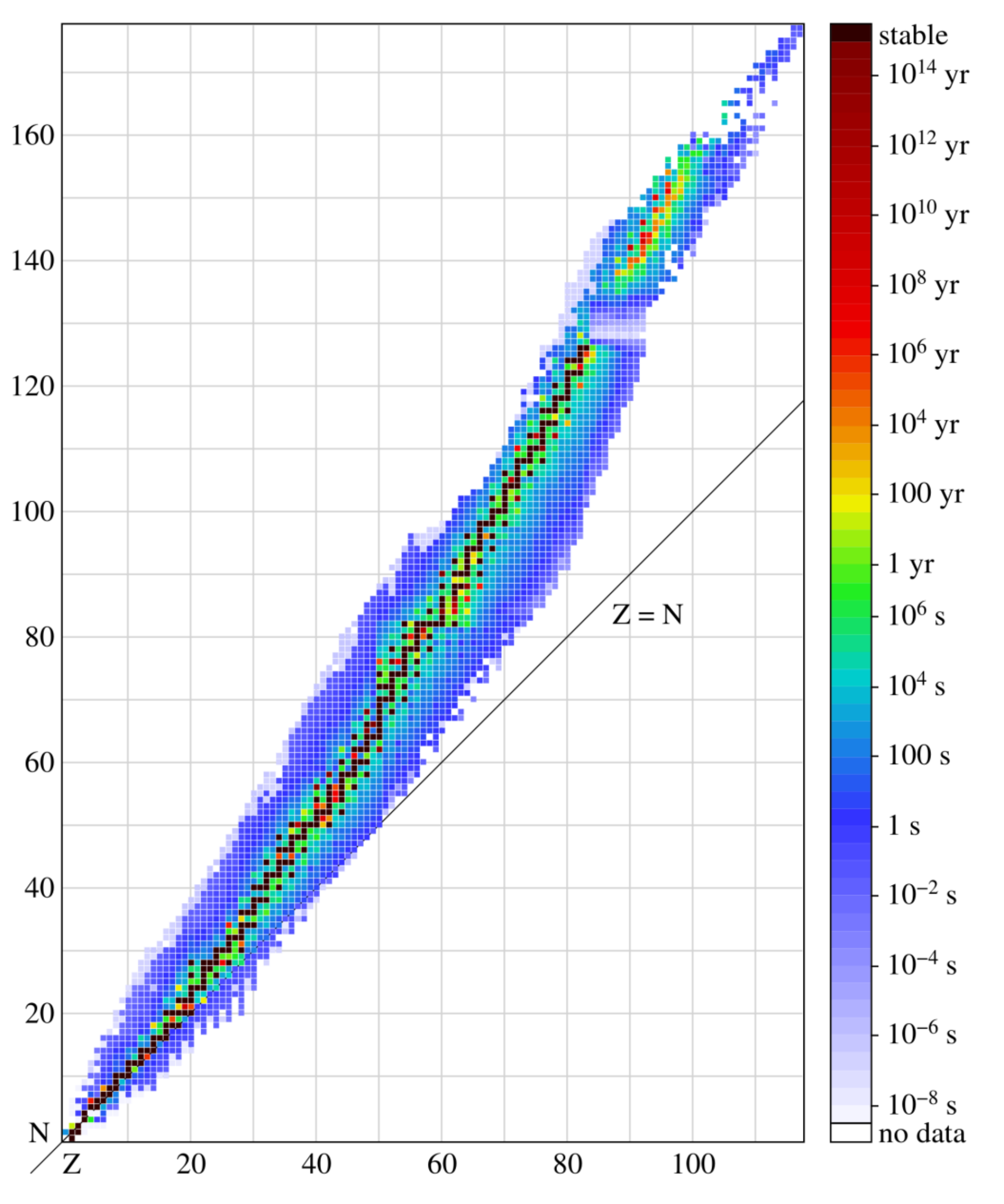


Figure 2.4 A Segre plot of stable nuclides.

Segre Plots

- Most nuclides are unstable
- Unstable nuclides emit particles that carry energy away from the nucleus
- This is called radioactivity



Alpha, Beta and Gamma Radiations

- Distinguished by their ionizing and penetrating power
  - These particles ionize the air they pass through, i.e. they knock electrons off atoms of the gases in the air
  - Alpha particle (α) of energy 2 MeV produces 10,000 ion pairs per mm
  - Beta particle (β) of energy 2 MeV produces 100 ion pairs per mm
  - Gamma particle (γ) of energy 2 MeV produces 1 ion pair per mm

Alpha, Beta and Gamma Radiations

- When passed through a magnetic field, one of the particles was found to be positively charged, one negatively charged, and one neutral.

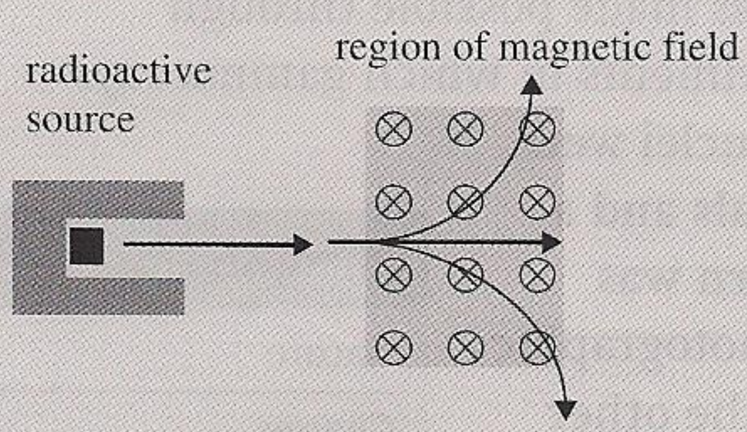


Figure 2.1 The existence of three distinct emissions is confirmed by letting these pass through a magnetic field and observing the three separate beams.

Which is which?

Alpha Particles

- Positively charged
- Identified by Rutherford and Royds as helium nuclei stripped of its electrons

$$^{4}_{2}He$$

- Charge is equal to *+2e*
- Easiest to absorb
- Stopped by a few cm of air

Alpha Particles

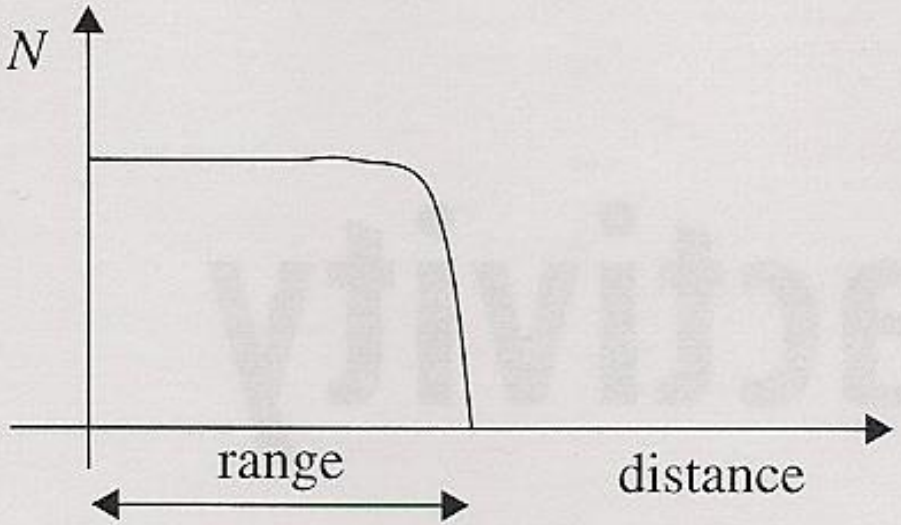


Figure 2.2 The penetration of matter by alpha particles of a fixed energy. The number of particles transmitted falls sharply to zero after a distance called the range. Particles of higher energy will have a larger range.

Alpha Decay

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}\alpha$$

$$^{224}_{88}Ra \rightarrow ^{220}_{86}Rn + ^{4}_{2}\alpha$$

$$^{212}_{84}Po \rightarrow ^{208}_{82}Pb + ^{4}_{2}\alpha$$

Beta Particles

- Negatively charged electrons ($_{-1}e$) or sometimes a positron ($_{+1}e$)
- Identified by Thompson's charge-to-mass experiments
  - Found that these ratios decreased as velocity increased
  - Consistent with theory of special relativity – mass increases as speed approaches speed of light
- Beta particles stopped by a few cm of paper or metal a few mm thick

Beta Minus Decay

- A neutron (larger mass) decays into a proton (smaller mass)
- Emits an electron ($_{-1}e$) and an anti-neutrino
- Mass difference translated into particle energy ($E = mc^2$)

$$^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e + {}^{0}_{0}\overline{\nu}_e$$

$$^{214}_{82}Pb \rightarrow {}^{214}_{83}Bi + {}^{0}_{-1}e + {}^{0}_{0}\overline{\nu}_e$$

$$^{40}_{19}K \rightarrow {}^{40}_{20}Ca + {}^{0}_{-1}e + {}^{0}_{0}\overline{\nu}_e$$

Beta Plus Decay

- A proton (smaller mass) decays into a neutron (larger mass)
- Emits an positron ($_{+1}e$) and a neutrino
- Increase in mass from proton to neutron indicates energy must be added to make this happen

$$^{22}_{11}Na \rightarrow ^{22}_{10}Ne + ^{0}_{+1}e + ^{0}_{0}\nu_e$$

$$^{13}_{7}N \rightarrow ^{13}_{6}C + ^{0}_{+1}e + ^{0}_{0}\nu_e$$

Gamma Rays

- Neutrally charged photons (same photons in electromagnetic radiation) with very small wavelengths
  - $\lambda \leq 10^{-12}$ m
  - Smaller than X-ray wavelengths
- Identified through measuring diffraction patterns of decaying nuclei passing through a crystal
- Stopped only by several centimeters of lead

Gamma Decay

- Nucleus emits a high frequency photon
- Nucleus does not change composition
- Nucleus moving from a higher to a lower energy level

$$^{238}_{92}U \rightarrow {}^{238}_{92}U + {}^{0}_{0}\gamma$$

$$^{60}_{28}Ni \rightarrow {}^{60}_{28}Ni + {}^{0}_{0}\gamma$$

$$^{24}_{12}Mg \rightarrow {}^{24}_{12}Mg + {}^{0}_{0}\gamma$$

$$E = hf$$

$$f = \frac{c}{\lambda}$$

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

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

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Energies

- Alpha particles have discrete energies
- Beta particles have a continuous range of energies
- Gamma rays from a particular nucleus have a few discrete energy levels with maximum energies of about 1 MeV

Speeds

- Alpha particles are slow (~ 6% of the speed of light)
- Beta particles are fast (~ 98% of the speed of light)
- Gamma rays, since they are photons, travel at the speed of light

Characteristic	Alpha particle	Beta particle	Gamma ray
Nature	Helium nucleus	(Fast) electron	Photon
Charge	$+2e$	$-e$	0
Mass	6.64×10^{-27} kg	9.1×10^{-31} kg	0
Penetrative power	A few cm of air	A few mm of metal	Many cm of lead
Ions per mm of air for 2 MeV particles	10 000	100	1
Detection	Causes strong fluorescence Affects photographic film Is affected by electric and magnetic fields	Causes fluorescence Affects photographic film Is affected by electric and magnetic fields	Causes weak fluorescence Affects photographic film Is not affected by electric and magnetic fields

Table 2.1 Properties of alpha, beta and gamma radiations.

Property	Type of particle emitted		
	α (alpha)	β (beta)	γ (gamma)
Relative charge	+2	-1	0
Relative mass	4	0.00055	0
Nature	2 protons + 2 neutrons (^{4}He nucleus)	Electron (emitted by a nucleon jumping down in energy)	Very high frequency electromagnetic radiation (photons)
Range in air	Few cm	Few metres	Very long
Stopped by	paper	Aluminium foil	Lead sheet
Deflection by electrical field	low	High (opposite direction to α)	nil
Symbol	α or $^{4}_{2}He$	β or e^{-} or $^{0}_{-1}e$	γ or $^{0}_{0}\gamma$

Detecting Radiation

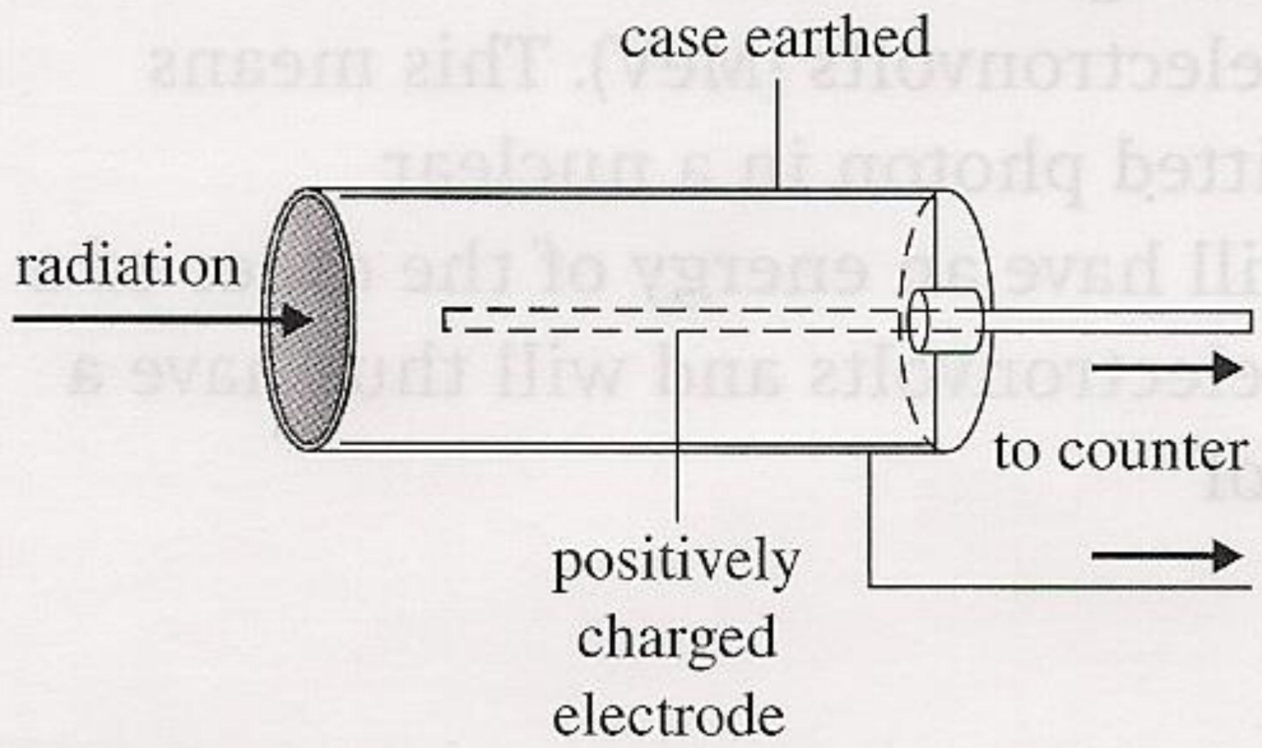
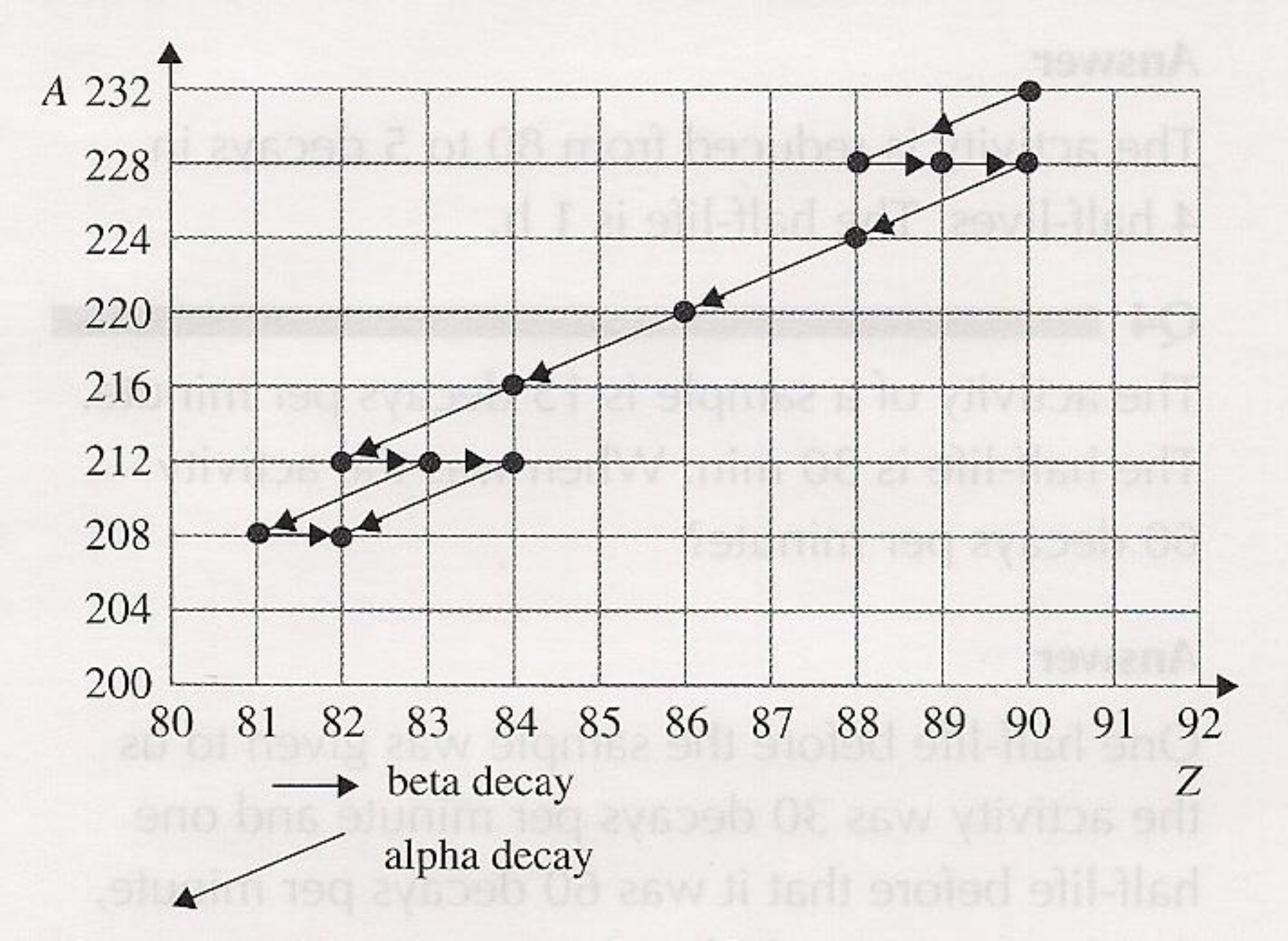


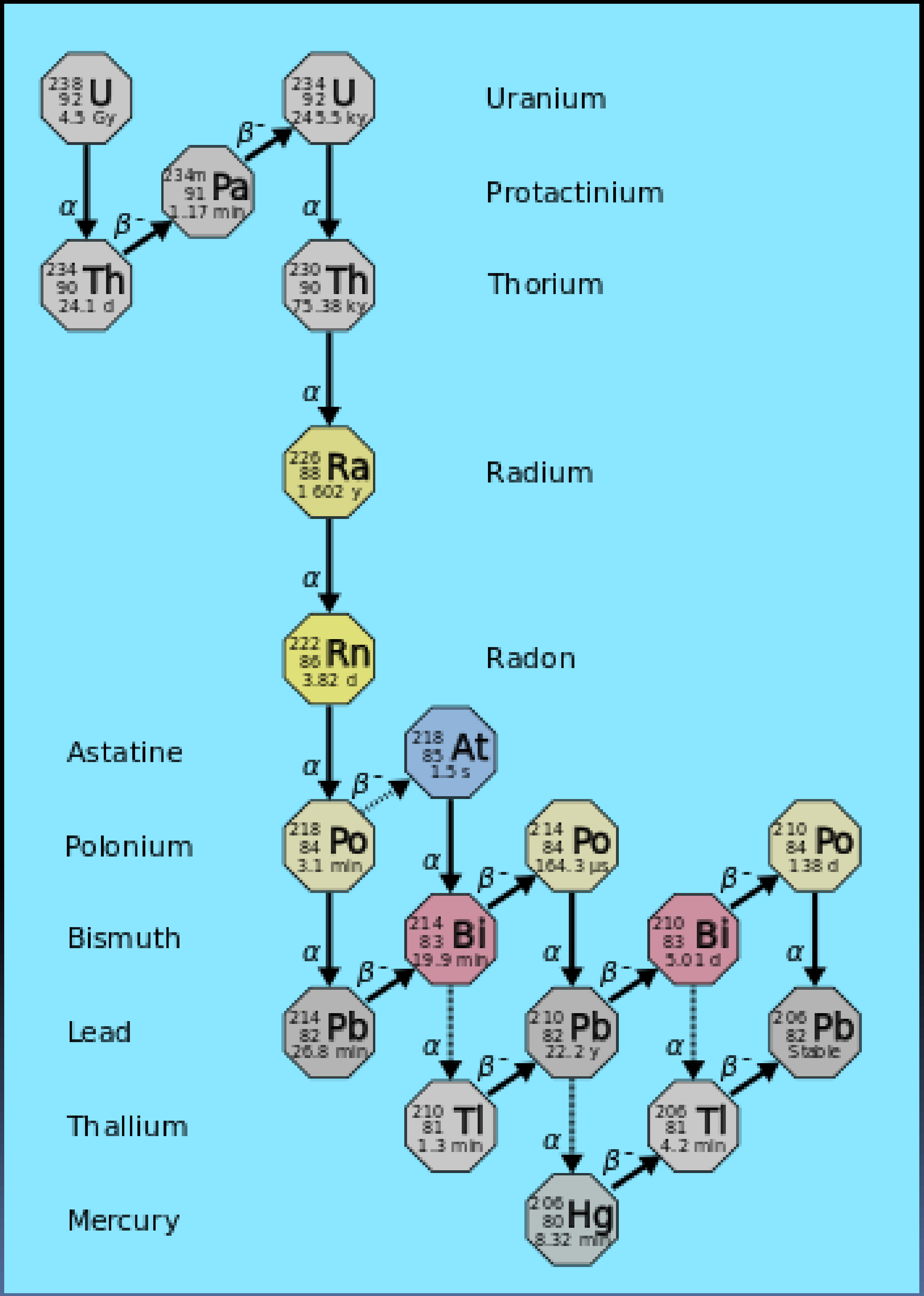
Figure 2.3 A Geiger–Müller tube for detecting ionizing radiation.

Decay Series

- Diagram of changes in atomic number and mass number as an element undergoes several decays
- Shows different possible decay paths
- Decays continue until all nuclei are stable

Thorium Decay




Uranium
Protactinium
Thorium
Radium
Radon
Astatine
Polonium
Bismuth
Lead
Thallium
Mercury
238 92 U 4.5 Gy
234 92 U 245.5 ky
234m 91 Pa 1.17 min
234 90 Th 24.1 d
230 90 Th 75.38 ky
226 88 Ra 1 602 y
222 86 Rn 3.82 d
218 85 At 1.5 s
218 84 Po 3.1 min
214 84 Po 164.3 µs
210 84 Po 138 d
214 83 Bi 19.9 min
210 83 Bi 5.01 d
214 82 Pb 26.8 min
210 82 Pb 22.2 y
206 82 Pb Stable
210 81 Tl 1.3 min
206 81 Tl 4.2 min
206 80 Hg 8.32 min

Law of Radioactive Decay

- The law of radioactive decay states that the number of nuclei that will decay per second (i.e. the rate of decay) is proportional to the number of atoms present that have not yet decayed.
- Decay of individual nuclei is random and spontaneous

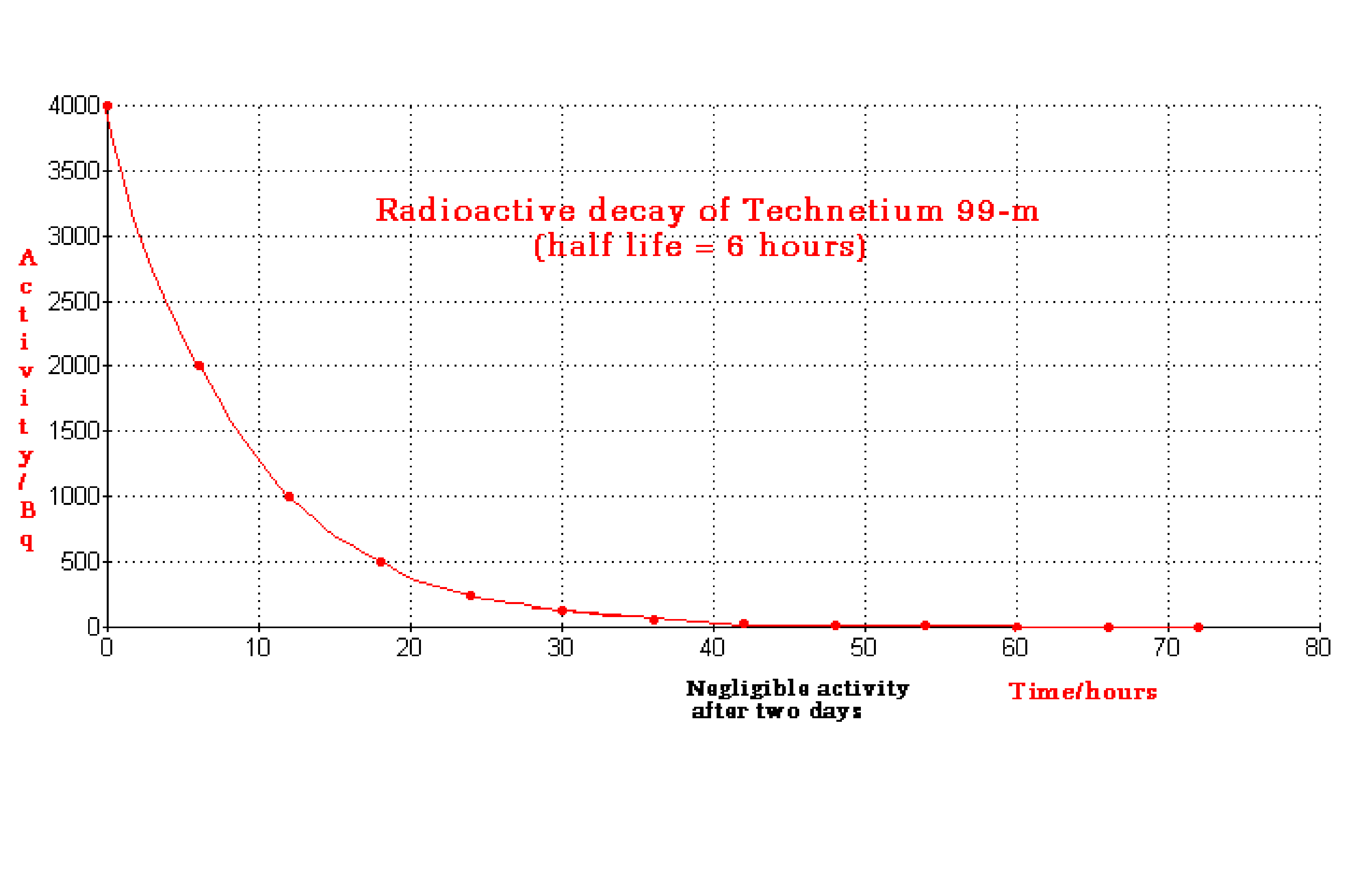
Law of Radioactive Decay

- But, the number of nuclei that will decay per second (rate of decay) is proportional to the number of undecayed nuclei

$$\frac{\Delta N}{\Delta t} \propto N$$

- This means that the number of radioactive nuclei decreases exponentially

Law of Radioactive Decay



Half-Life

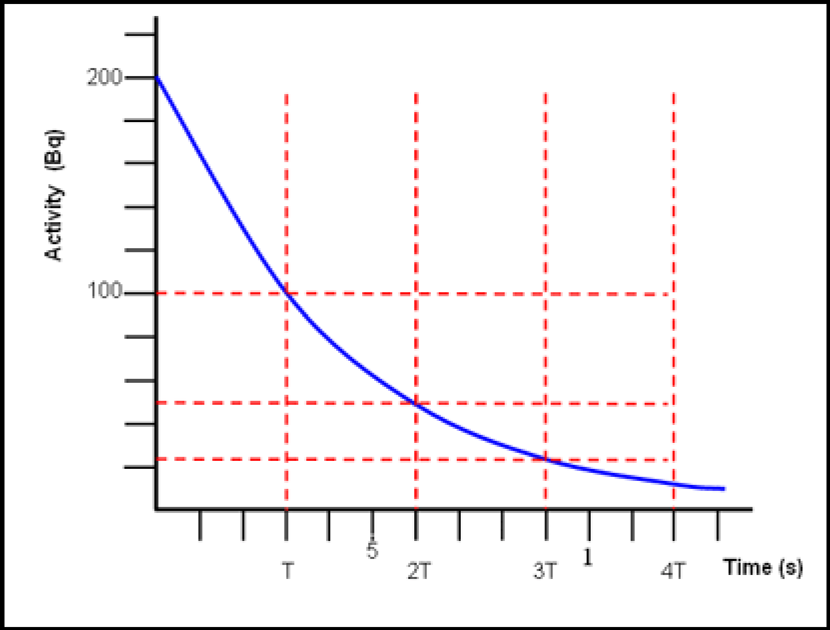
- There exists a certain interval of time, called the half-life, such that after each half-life the number of nuclei that have not yet decayed is reduced by a factor of 2.
- Activity (A) – the number of nuclei decaying per second
  - Becquerel (Bq) – 1Bq = 1 decay per second

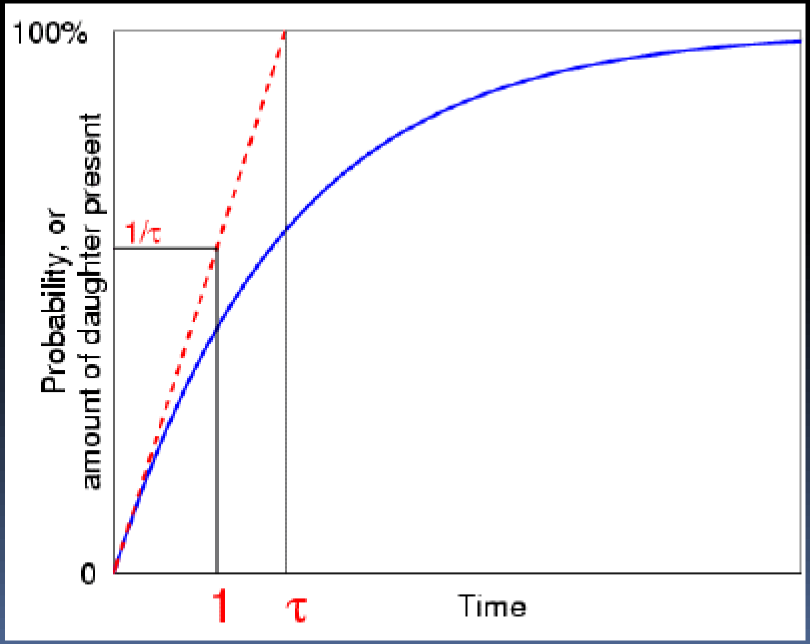
Half-Life and Probability

- After one half-life, the probability that a given nucleus will have decayed is 50%
- After two half-lives, the probability that a given nucleus will have decayed is the sum of the first and second half-life probabilities

$$\frac{1}{2}+\left(\frac{1}{2}x\frac{1}{2}\right)=\frac{3}{4}=75\%$$

Half-Life and Probability





Radioactive Decay

What is the half-life?

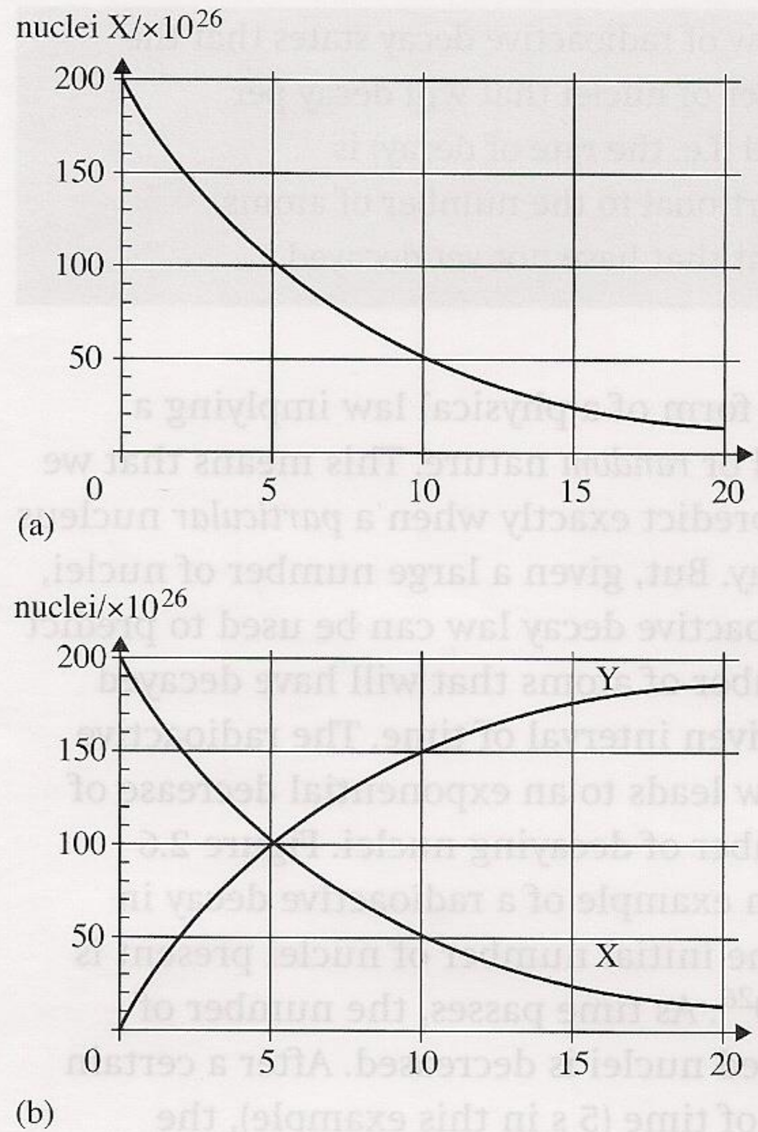
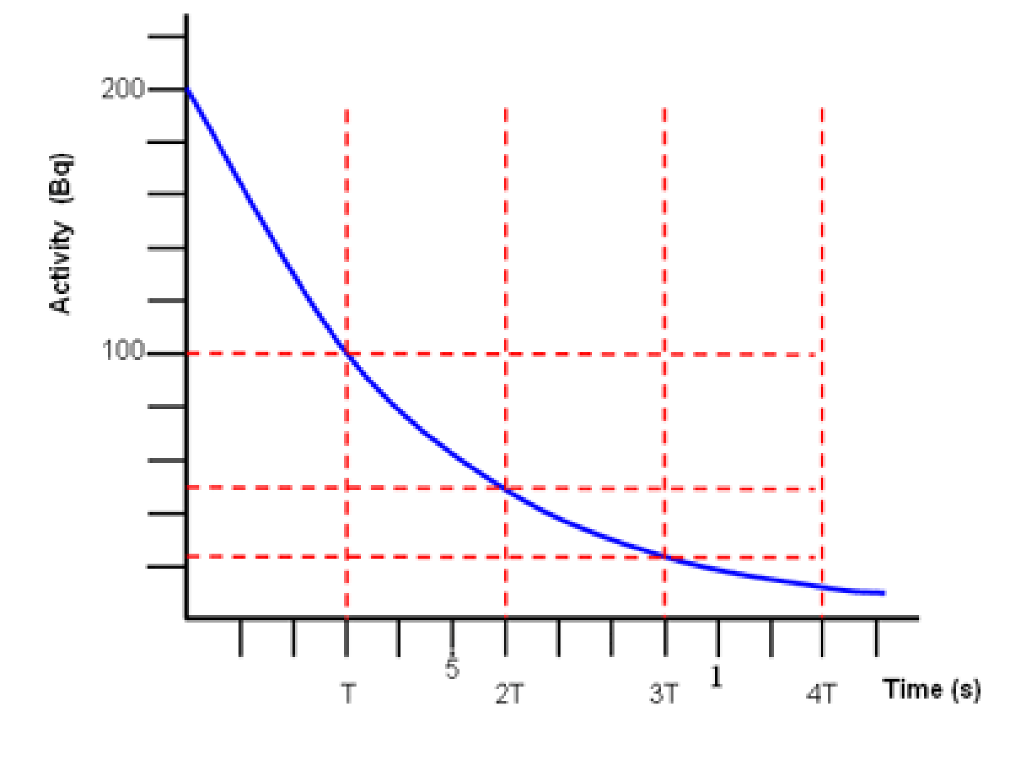


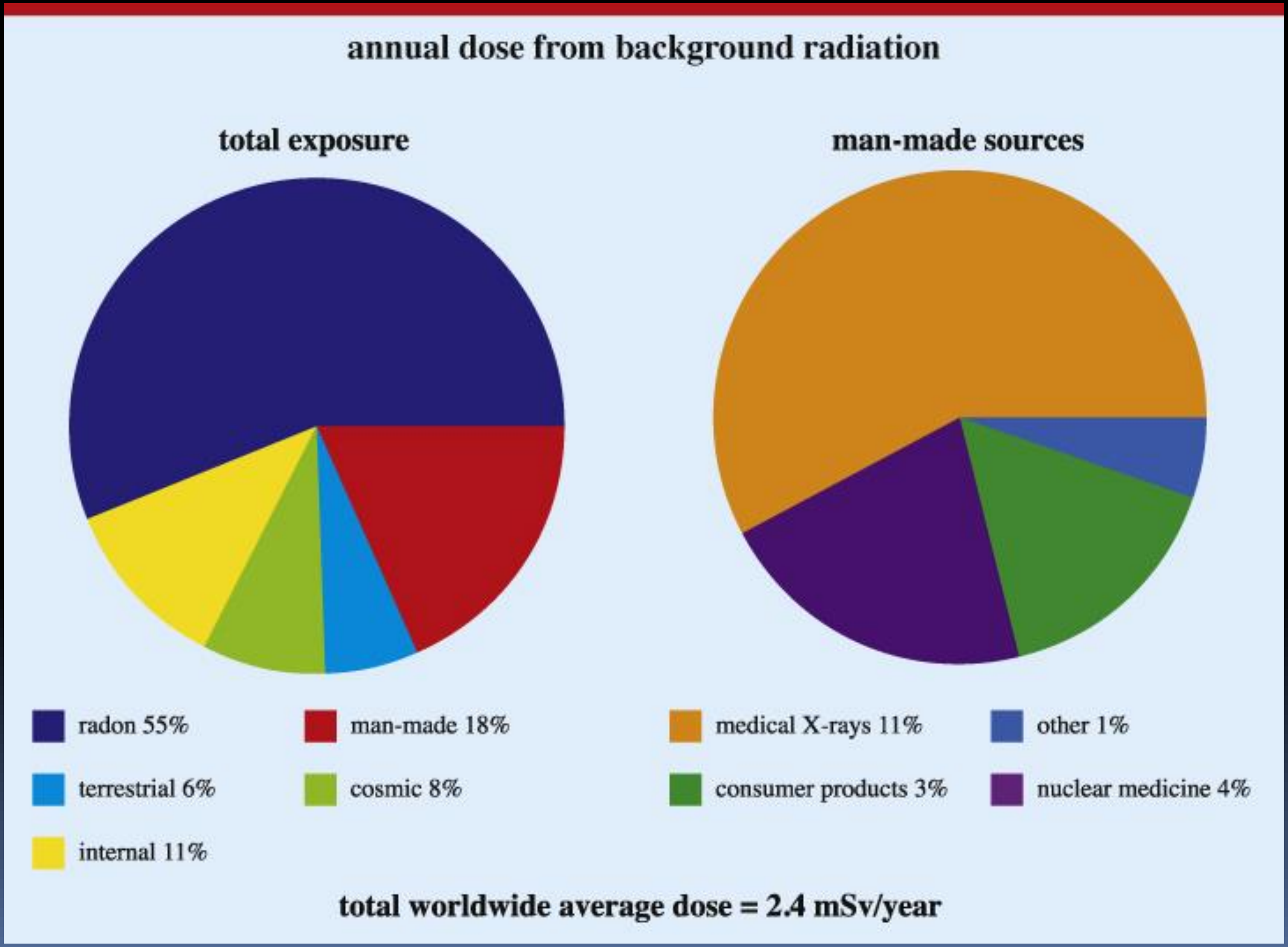
Figure 2.6 (a) The number of nuclei X that have not yet decayed as a function of time. This is an exponential decay curve. (b) The number of the daughter nuclei Y is increasing.

Activity

- Activity (A) – the number of nuclei decaying per second
  - Becquerel (Bq) – 1Bq = 1 decay per second
- Activity can also be used to determine half-life

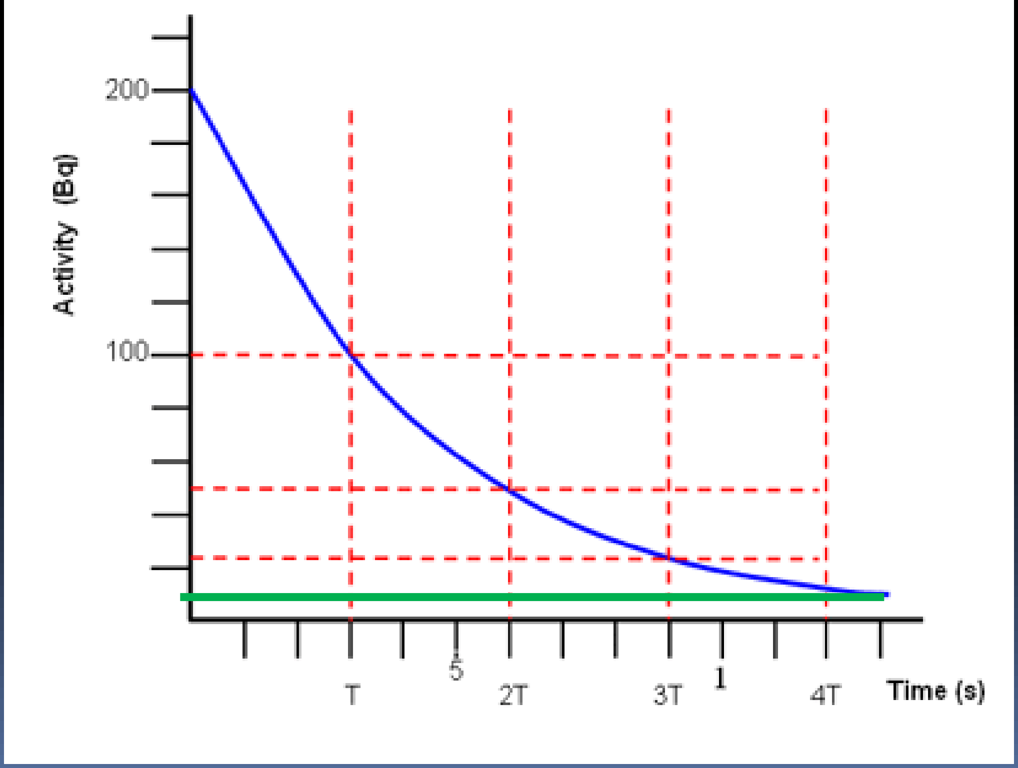


Background Radiation



Background Radiation

- To get an accurate measure of half-life, we must subtract background radiation (assuming a constant value) from all measurements



Fundamental Forces

- Electromagnetic Interaction:
  - Acts on any particle that has an electric charge
  - Force is given by Coulomb’s law
  - Infinite range

Fundamental Forces

- Weak Nuclear Interaction:
  - Acts on protons, neutrons, electrons, and neutrinos in order to bring about beta decay
  - Very short range (10^{-18} m)

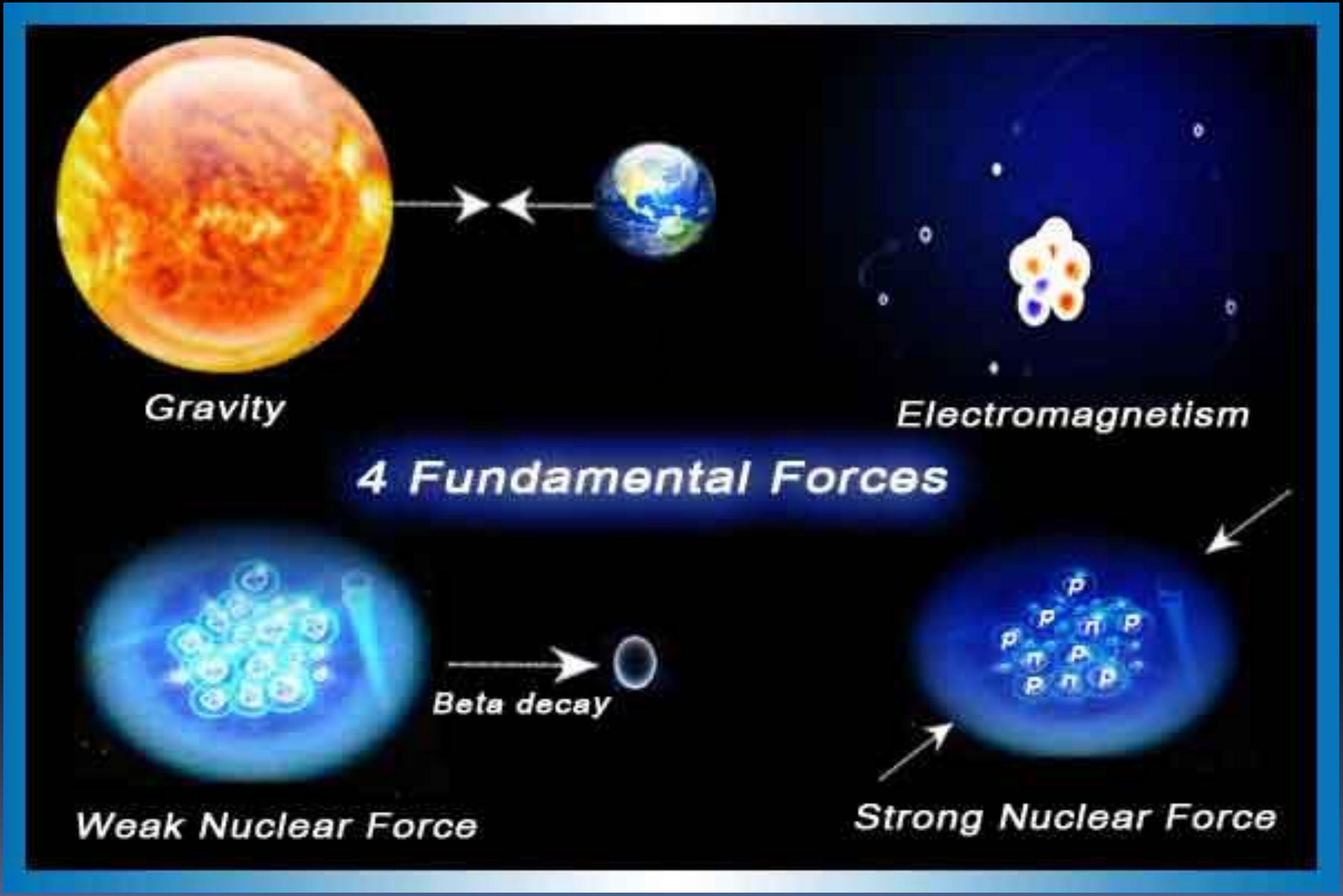
Fundamental Forces

- Strong Nuclear Interaction:
  - [Mainly] attractive force acts on protons and neutrons to keep them bound to each other inside nuclei
  - Short range (10^{-15} m)

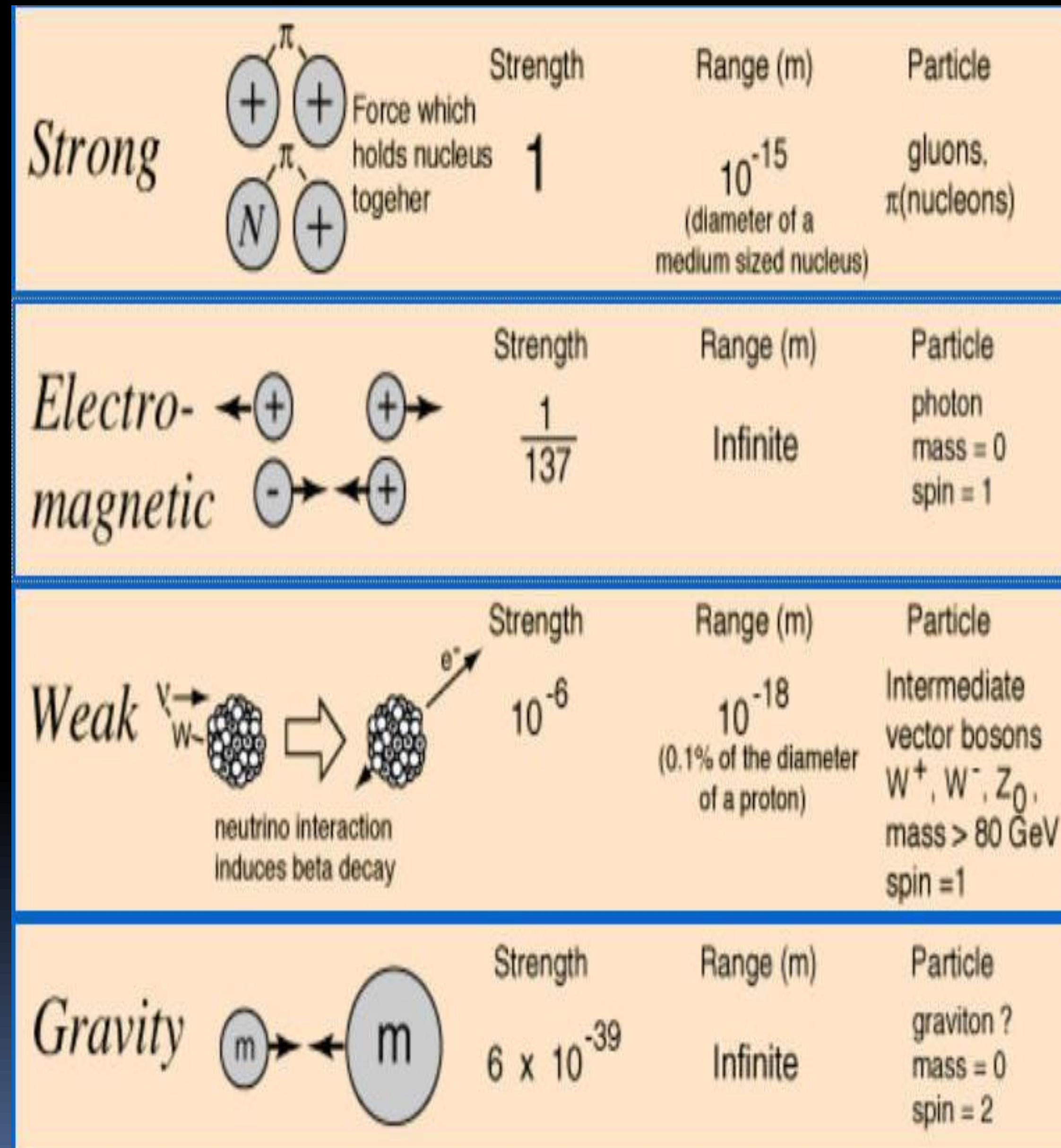
Fundamental Forces

- Gravitational Interaction:
  - Force of attraction between masses
  - Small mass of atomic particles makes this force irrelevant for atomic and nuclear physics
  - Infinite range

Fundamental Forces



Fundamental Forces



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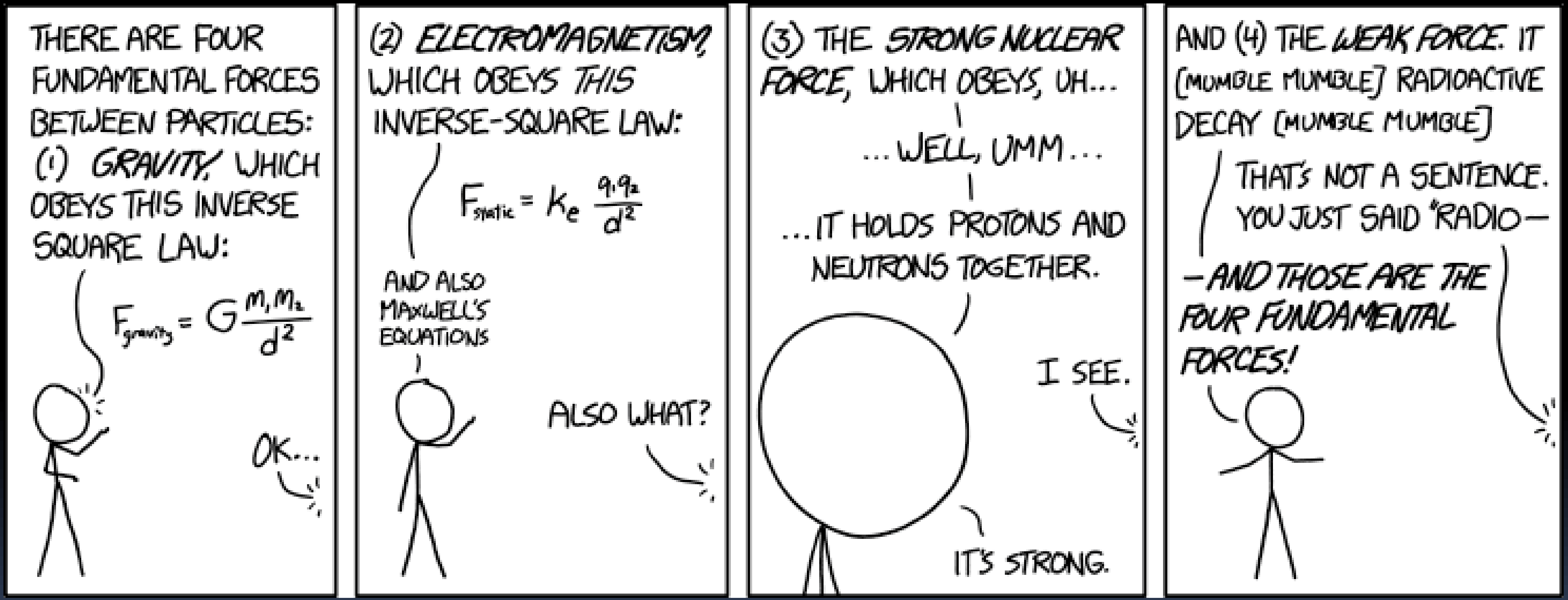

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- Aim 9: the use of radioactive materials requires the development of safe experimental practices and methods for handling radioactive materials

Essential Idea:

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QUESTIONS?

Homework

#8-15