

NE585
NUCLEAR FUEL CYCLES
Nuclear engineering basics
1

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Learning objectives

Demonstrating fundamental concepts in nuclear physics

Analyzing decay data to identify radionuclides

Summarizing different decay mechanisms

Book – Chapter 2

Learning nodes

Relativity

Atomic structure

Binding energy

Q-value

Radioactivity

Chart of the nuclides

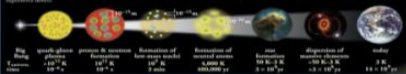
Decay chains

Half life

Nuclear Science

Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about 10^9 seconds, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. As time the temperature of the Universe cooled to about 10^8 K, this soup of quarks and gluons formed protons, neutrons, and electrons. As time passed, the temperature of the Universe cooled to about 10^4 K, and the electrons and protons combined to form neutral atoms. This is the point at which the universe became transparent and the light from the Big Bang was able to travel freely. The light from the Big Bang is still visible today as the cosmic microwave background radiation. The universe has been expanding ever since the Big Bang, and the expansion is accelerating.



Radioactivity

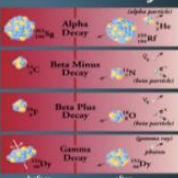
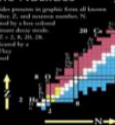
[illegible]

Chart of the Nuclides

The Chain of the Nucleides presents in graphic form all known nuclei with atomic number Z , and mass number, N . Each nucleide is represented by a box with color according to its predominant decay mode. Magic numbers (N or $Z = 2, 8, 20, 28, 50, 82$ and 126) are indicated by a triangle on the chart. They correspond to major shell gaps and show regions of greater nuclear stability.



Color Key

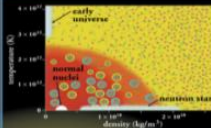
- Stable
- Spontaneous fission
- Alpha particle emission
- Beta minus emission
- Beta plus emission or electron capture

www.CPEPweb.org

Nuclear Science is the study of the structure, properties, and interactions of the atomic nucleus. Nuclear scientists calculate and measure the masses, shapes, spins, and decays of nuclei at rest and in collisions. They ask questions, such as: Why do nucleons stay in the nucleus? What combinations of protons and neutrons are good? What happens when nuclei are constructed or excited? What is the origin of the nuclei found on Earth?

Legend	electron (e^-)	quark	$A_{\text{strong}} = 14$
proton (p^+)	positron (e^+)	gluon field	$Z_{\text{strong}} = 6$
neutron	neutrino (ν)	gluon	
	antineutrino ($\bar{\nu}$)	photon (γ)	$Z_{\text{strong}} = A - 2$

Phases of Nuclear Matter



Nuclear matter can exist in several phases. When collisions create nuclei, individual protons and neutrons may evaporate from the nucleus itself. At sufficiently high temperatures or densities, a gas of nucleons (and background) forms. At even more extreme conditions, individual nucleons may cease to have meaningful identities, merging into the quark-gluon plasma (yellow background). Current data provide hints that physicists have glimpsed the quark-gluon plasma.

Unstable Nuclei

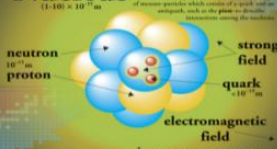
Stable nucleides form a narrow white band on the Chart of the Nuclides. Isotopes produce unstable nucleides far from this band and study their decay, thereby learning about the extremes of nuclear conditions. In its present form, this chart contains about 2500 different nucleides. Nuclear theory predicts that there are at least 4000 more to be discovered with $Z \leq 118$.



Schottium first synthesized
Thiomers 112 in a particle
acceleration experiment. They
did it by observing its charac-
teristic alpha particle decay chain.

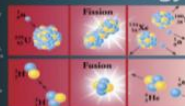
The Nucleus

As the corner of the story is a nucleus formed from nucleosome-protein and nucleosome. Each nucleosome is made from three *spools* held together by their strong interactions, which are mediated by glucose. In turn, the nucleosome is held together by the strong interaction between the glucose and nucleosome-protein. Nucleosome proteins often use the nucleosome-protein interactions, which consist of a nucleosome-protein, such as the nucleosome-protein.



In its most extensive range around the nucleus, its diameter typically up to 50,000 times the nuclear diameter. If the electron cloud were dense enough, this cloud would

Nuclear Energy



In the early stages of mitral evolution of cat, dog and other mammals, hydrolytic fission forms bulbars, releasing energy in the form of photons (light) and excitations. During the later stages of mitral evolution, more excitations reached up to and beyond excitations are accelerated by factors. By increasing the intensity of excitations that enter from the base, excitations rapidly become disseminated that excitations must have a mass greater than zero.

Applications



Radioactive Dating



Space Exploration
 Truncated and alpha particles, already observed elsewhere, are in Martian rocks. The Earth's structures are used to study ones from cylindrical arrangements in



Nuclear Reactors

Nuclear reactors use the fission of ^{235}U or ^{239}Pu nuclei to produce electric power. Reactors used most often today are pressurized water reactors (PWRs). In a PWR, the primary loop of water circulates around the reactor core, where it is heated by the fission reaction. The heated water then circulates through a steam generator, where it heats a secondary loop of water. The secondary loop of water then circulates through a turbine, which drives a generator to produce electricity. The turbine is then cooled by a third loop of water, which circulates through a condenser and back to the steam generator. This cycle is repeated continuously, as long as the reactor is operating.



Smoke Detectors

Many smoke detectors use a small amount of the alpha emitter ^{241}Am to ionize the air. Smoke entering the detector reduces the current and sets off the alarm.



Nuclear Medicine
Diagnostic images, such as ^{99m}Tc , ^{18}F , ^{131}I , are commonly used in the diagnosis of diseases of bones. Positron emitters, such as ^{18}F , are used in Positron Emission Tomography (PET) to generate images of the activities.



Magnetic Resonance Imaging
Magnetic Resonance Imaging (MRI) makes use of magnetic resonances involving the magnetic field of a nucleus in order to build chemical structures. This technique accurately maps the density of hydrogen to produce three-dimensional images of the human body.

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Relativity

We apply energy from nuclear reactions and radiation interactions with matter

$$E_{REST} = m_0 c^2 \quad (1)$$

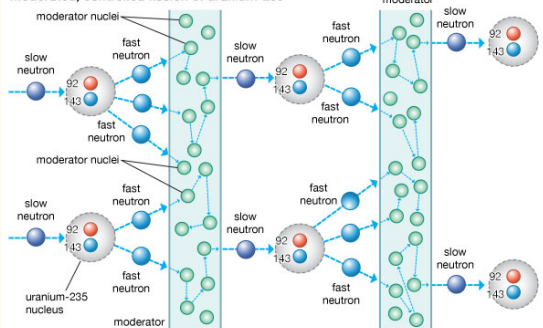
$$E = mc^2 \quad (2)$$

Rest mass energy for an electron – 0.511 *MeV*

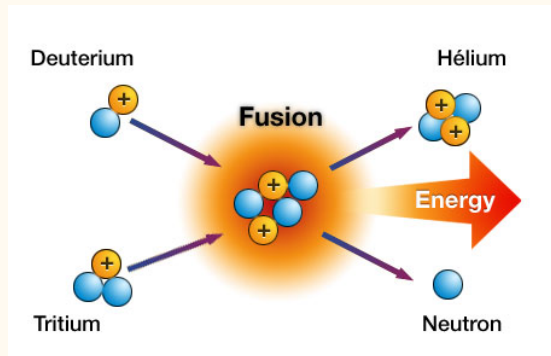
Save that for later

Energy released or energy injected

Moderated, controlled fission of uranium-235



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Determine the energy of a fusion neutron that is not at rest

$$m = \frac{m_0}{\sqrt{1 - \left(\frac{v^2}{c^2}\right)}} \rightarrow E = mc^2 \quad (3)$$

With $v = 5.2 \times 10^7 \text{ m/s}$, that is about $0.17c$; not negligible

So we have to compute the not rest mass

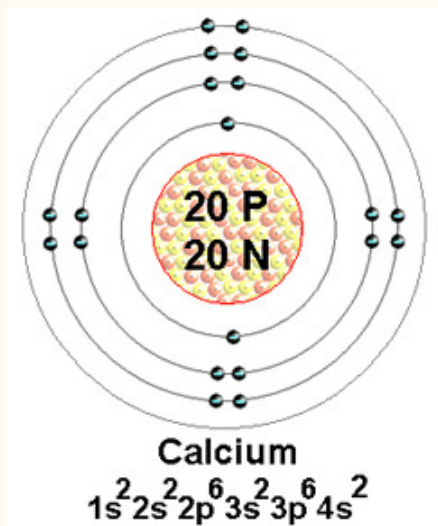
$$m_0(n) = 1.674927211 \times 10^{-27} \text{ kg}$$

Fusion neutron at that speed has $E = 14.5 \text{ MeV}$

For relativistic calculations use MeV

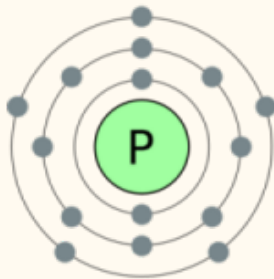
Atomic structure

The shell model describes how subatomic particles are arranged



15: Phosphorus

2,8,5



$${}^A_Z Q_{A-Z} = {}^{235}_{92} U_{143}$$

Binding energy

There are four fundamental forces of interaction

Gravity – Obvious

Strong nuclear – Holds the nucleus together

Electromagnetic – Basically electrons & magnetism

Weak nuclear – Changes the flavor of quarks

To blow out a nucleus, a lot of energy is needed

Would it be constant or variable per nucleus?

Why would you want to blow out the nucleus?

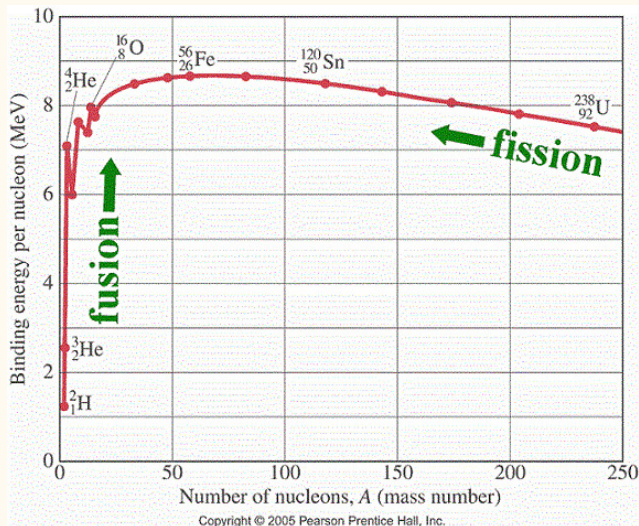
$$\Delta m = (A - Z)m_n - Zm_p - M \quad (4)$$

$$\Delta m({}_{94}^{239}\text{Pu}) = 1759 \text{ MeV} = 7.40 \frac{\text{MeV}}{\text{nucleon}} \quad (5)$$

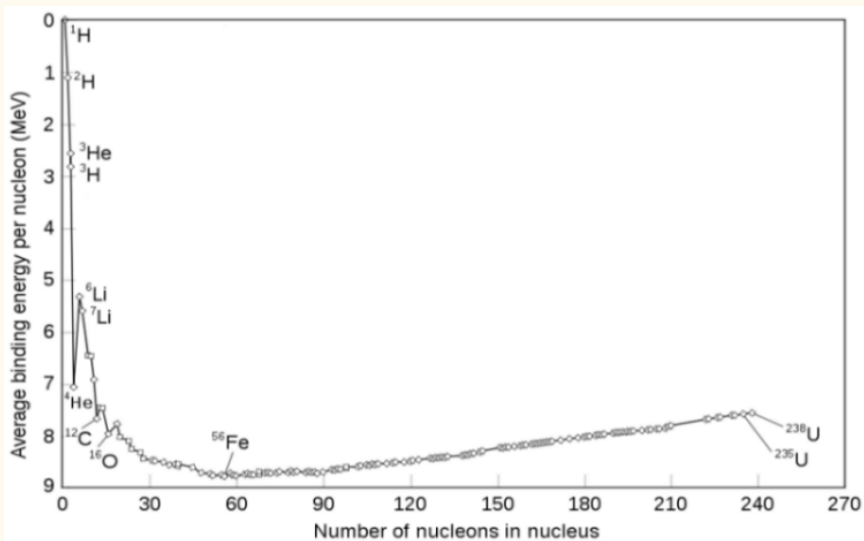
This energy corresponds to a velocity of 0.88c

$$931.5 \frac{\text{MeV}}{\text{amu}}$$

Binding energy is used to compare atomic stability, reaction energy, probability of fission/fusion

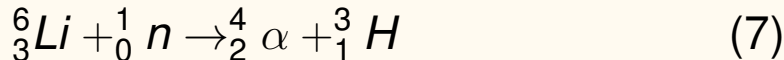


Light nuclei get more stable by fusion; heavy nuclei get more stable by fission



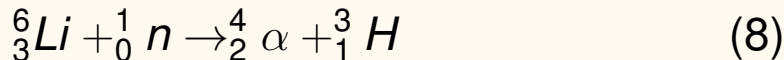
Q-value

The Q-value for a reaction indicates energy requirements



- (1) Conservation of nucleons
- (2) Conservation of charge
- (3) Conservation of momentum
- (4) Conservation of energy

Compute the Q value for this reaction



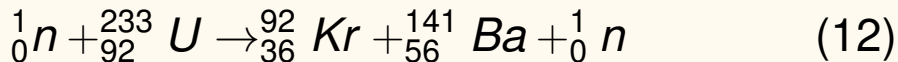
$$Q = [(M_{\text{Li}} + M_n) - (M_{\alpha} + M_H)]c^2 \quad (9)$$

$$Q = 4.78 \text{ MeV} \quad (10)$$

$$Q > 0 \rightarrow ?$$

$$Q < 0 \rightarrow ?$$

What is the energy of fission from thorium and uranium fuel cycles?



For comparison, burning a carbon atom releases 4 eV

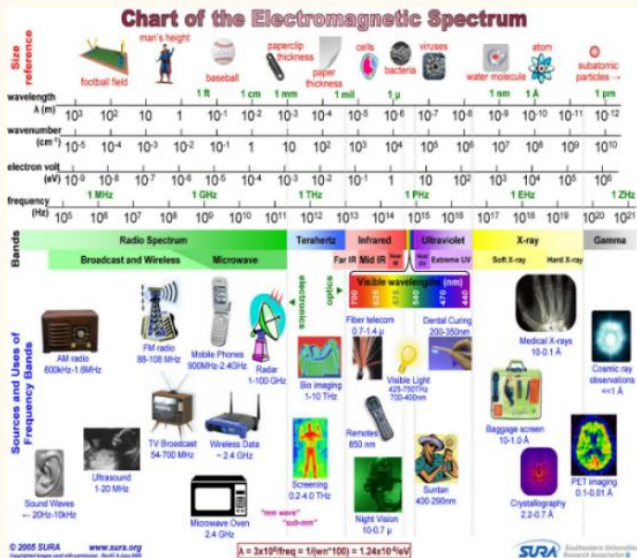
Radioactivity

Scientists in late 1800s made discoveries which would change the course of science, medicine, and history in the 20th Century

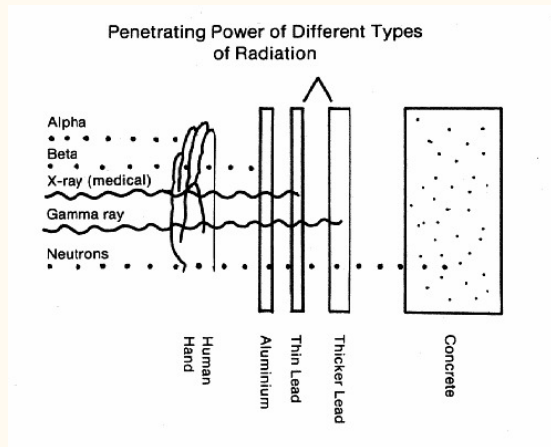
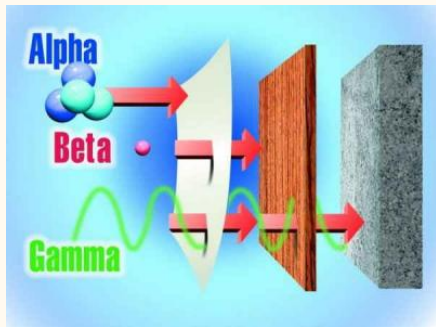


The Nobel Prize in Physics 1903 was divided, one half awarded to Antoine Henri Becquerel *"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity"* the other half jointly to Pierre Curie and Marie Curie, née Sklodowska *"in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel"*.

Radiation is energy as particles or electromagnetic waves, like sunshine



Radiation is energy as particles or electromagnetic waves



Radiation is energy as particles or electromagnetic waves

Charged particles are –

- protons (+)
- alpha (++)
- beta (+/-)
- heavy ions (varying)
- U,Pu (3+,4+,5+,6+)

Neutrons have no charge, but are also ionizing

Ionizing rays are x-rays, g-rays, cosmic rays

Ernest Rutherford discovered the three main kinds of radioactive decay (Chemistry Nobel 08)

Radioactivity

Alpha Decay

$^{263}_{106}\text{Sg} \rightarrow ^{259}_{104}\text{Rf} + ^4_2\text{He}$ (alpha particle)

Beta Minus Decay

$^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + e^- + \bar{\nu}_e$ (beta particle)

Beta Plus Decay

$^{18}_9\text{F} \rightarrow ^{18}_8\text{O} + e^+ + \nu_e$ (beta particle)

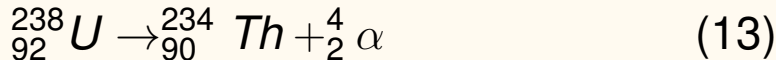
Gamma Decay

$^{152}_{66}\text{Dy} \rightarrow ^{152}_{66}\text{Dy} + \gamma$ (gamma ray)

before after

*Radioactive decay transforms a nucleus by emitting different particles. In **alpha** decay, the nucleus releases a ^4_2He nucleus—an alpha particle. In **beta** decay, the nucleus either emits an electron and antineutrino (or a positron and neutrino) or captures an atomic electron and emits a neutrino. A positron is the name for the antiparticle of the electron. Antimatter is composed of antiparticles. Both alpha and beta decays change the original nucleus into a nucleus of a different chemical element. In **gamma** decay, the nucleus lowers its internal energy by emitting a photon—a gamma ray. This decay does not modify the chemical properties of the atom.*

Alpha particle decay is the ejection of a helium atom from a heavy nucleus

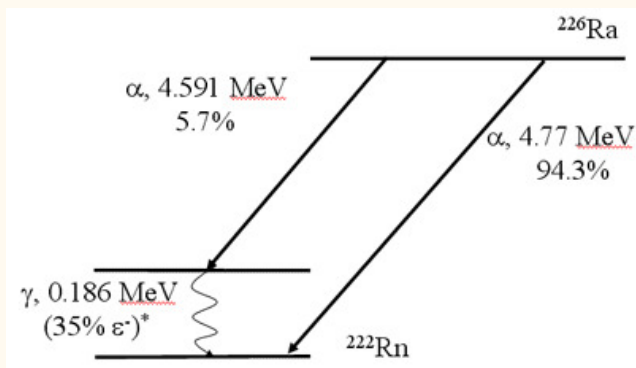


$$Q = 4.268 \text{ MeV} \quad (14)$$

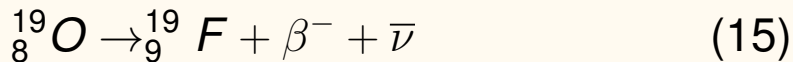
Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)

Discrete energy spectrum

Some % decay at certain energy

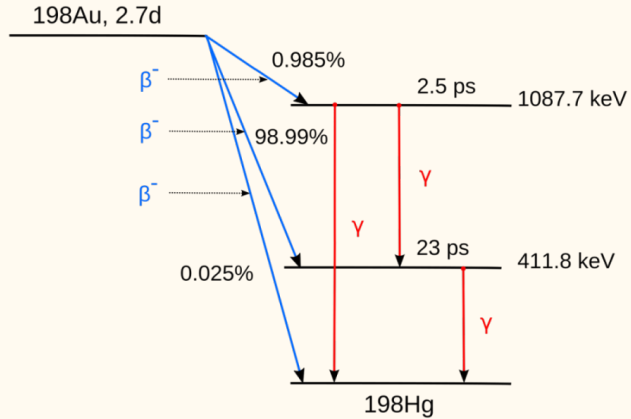


β^- particle decay occurs for unstable nuclei with excessive neutrons

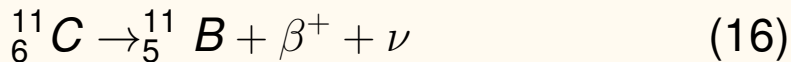


The neutron is converted to a proton and a beta negative (electron) and anti-neutrino (momentum) are ejected

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)

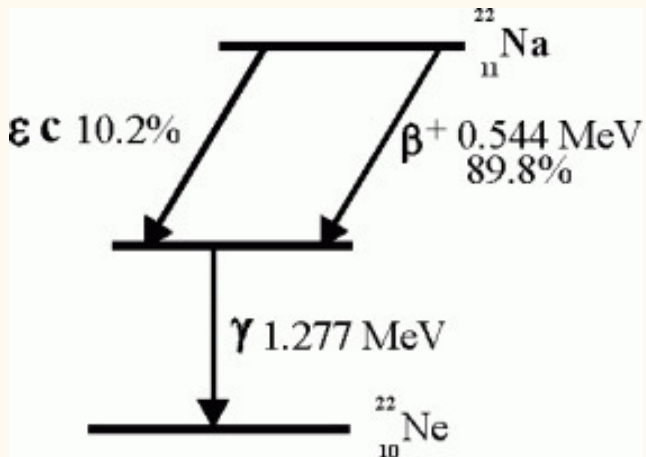


β^+ particle decay occurs for unstable nuclei with deficient neutrons

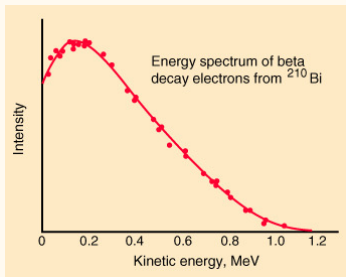


The proton is converted to a neutron and a beta positive (positron) and neutrino (momentum) are ejected

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)



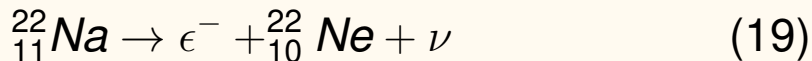
In both forms of beta decay, the energies are exhibited by a continuous energy spectrum



$$\overline{E}(\beta^-) = 0.3E_{MAX} \quad (17)$$

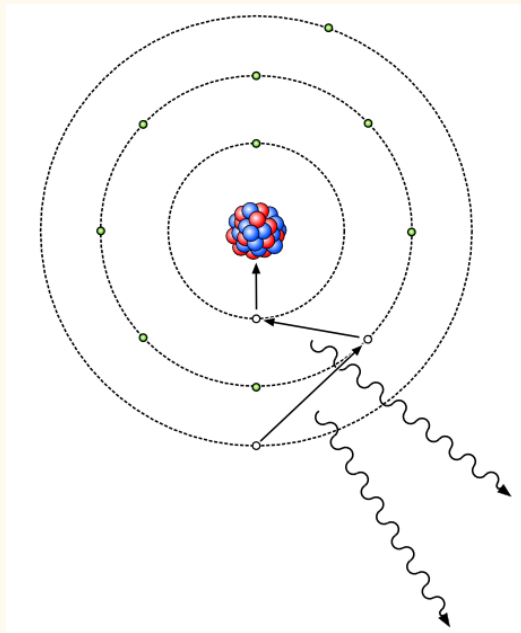
$$\overline{E}(\beta^+) = 0.4E_{MAX} \quad (18)$$

Electron capture also occurs for unstable nuclei with deficient neutrons

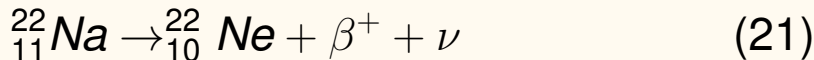
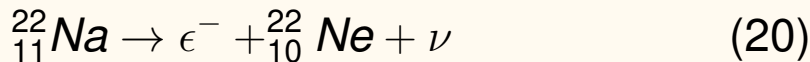


The K shell electron (not free) is absorbed by the nucleus to convert the proton to a neutron

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)



Electron capture and β^+ are competing processes



$$Q = 2.842 \text{ MeV} \quad (22)$$

$Q > 1.022 \text{ MeV}$ positron favored

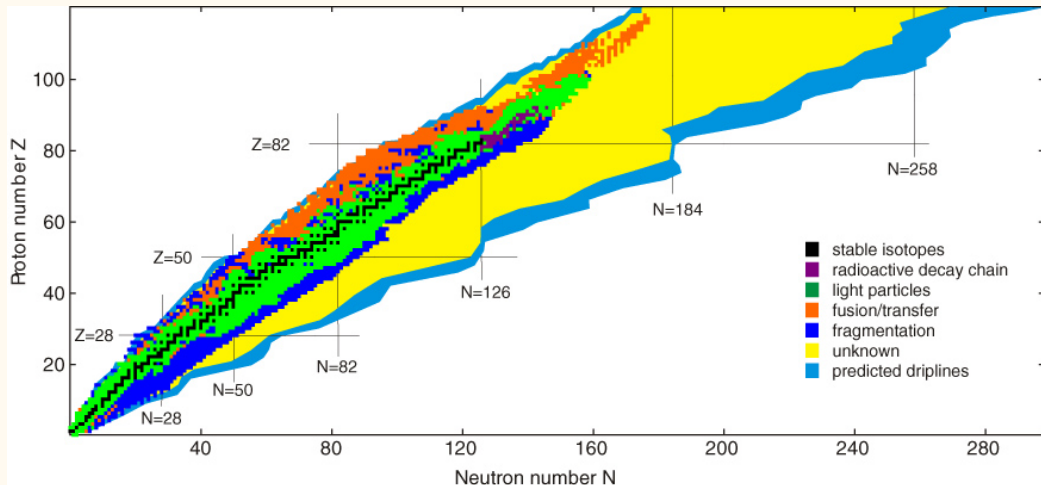
$Q < 1.022 \text{ MeV}$ electron capture favored

Why?

γ -ray emission is not a decay mode, but superfast de-excitation of the nucleus

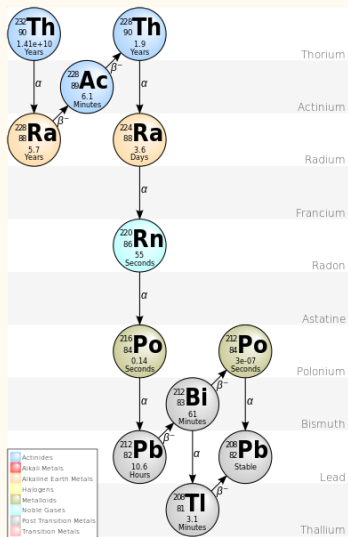
Interactions of gamma rays with matter is a very important branch of nuclear physics

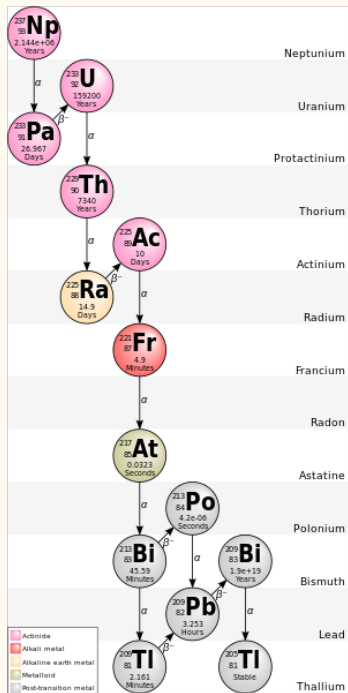
Chart of the nuclides

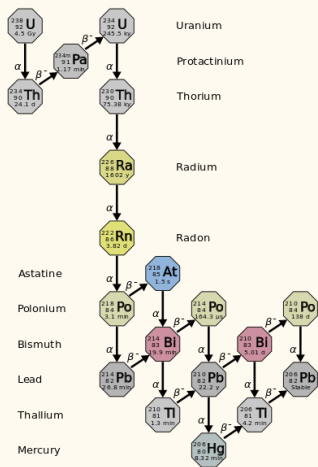


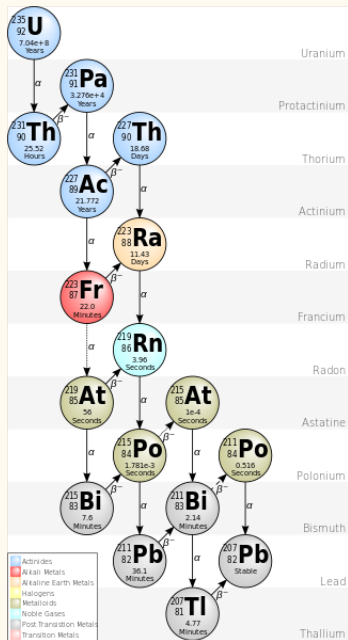
Ra 224 3.66 d α 5.6854 5.4486... γ 241..., C14 σ 12.0	Ra 225 14.8 d β^- 0.3, 0.4 γ 40 e^-	Ra 226 1600 a α 4.7843, 4.601... γ 186... C14 σ 12.8 $\sigma_f < 5E-5$
Fr 223 21.8 m β^- 1.1... α 5.34 γ 50, 80, 235...	Fr 224 3.3 m β^- 2.6, 2.8... γ 216, 132, 837 1341...	Fr 225 4.0 m β^- 1.6... γ 182, 32, 225 200...
Rn 222 3.825 d α 5.48948... γ (510) σ 0.74	Rn 223 23.2 m β^- γ 593, 417, 636 655...	Rn 224 1.78 h β^- γ 261, 266...

Decay chains









Half life

A radioactive isotope decays with a unique characteristic time

Decay is stochastic, characterized by Poisson distribution

So the decay of any one radionuclide cannot be predicted

The probability per time that a nucleus will decay is a constant

Decay is described by a Poisson process

Occurrences are randomly distributed in time

What is the 'occurrence' here?

Homogeneous, long term decay rate is constant

$$\mu \equiv \lambda \Delta t \quad (23)$$

$$P(n) = e^{-\mu} \cdot \frac{\mu^n}{n!} \quad (24)$$

What is the expected value and variance of the distribution?

A radioactive isotope decays with a unique characteristic time

$n(t)$ atoms at t have decayed in dt

$$\lambda n(t) dt \quad (25)$$

The number of atoms that decay on average in the interval $t, (t + dt)$ can be expressed as –

$$-dn(t) = \lambda n(t) dt \quad (26)$$

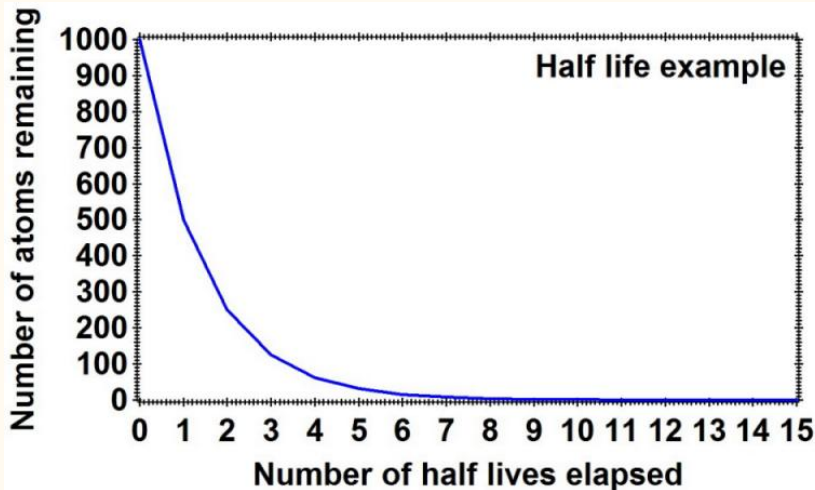
You should be able to solve this for $n(0) = n_0$

Radionuclides are characterized by half life

$$t_{\frac{1}{2}} = \frac{\ln 2}{\lambda} \quad (27)$$

Half life can be derived from the decay law

A radionuclide is 'negligible' after 10 half-lives have elapsed



Why would this be important?

How was half-life discovered?

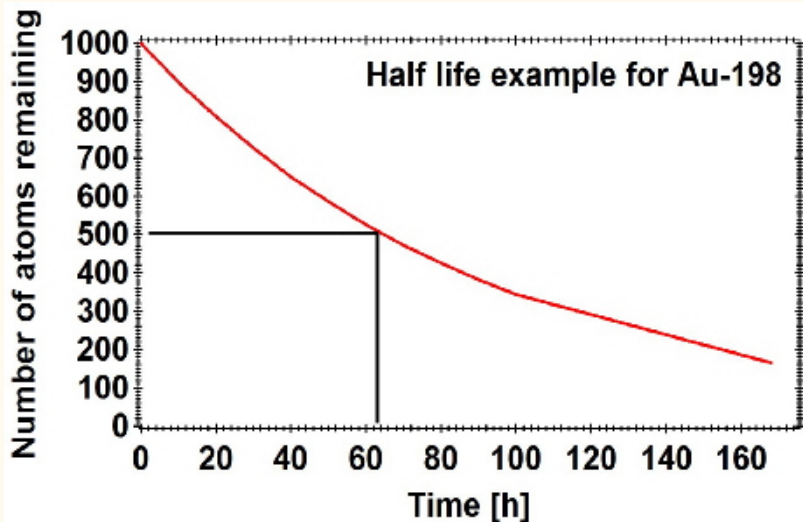
Rutherford discovered alpha and beta particle decay

In the course of, he noticed that there was a characteristic time

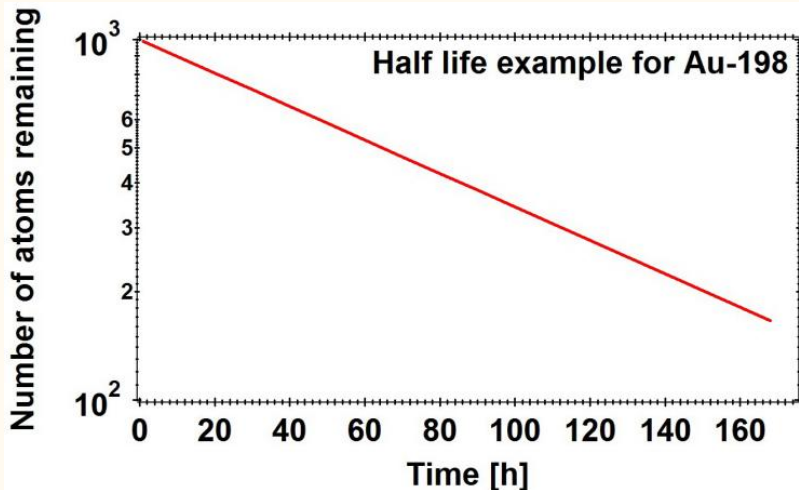
Basically observed decay time was the same for each atom

Experiments with thorium led to the discovery of radon

Then observing the radon gas led to the decay/half-life (65 s)



Engineers like straight lines



Slope of the line is the decay constant

