• Z counts the protons, N counts the neutrons, A is the atomic **mass number**: \( A = Z + N \)
  • The value of \( N \) for a particular element can vary
• Notation: \( \frac{A}{Z}X \) where
  • \( X \) is the symbol for the element
• Example:
  • The element is He \( \frac{4}{2}\text{He} \)
  • The mass number, \( A \), is 4
  • The atomic number, \( Z \), is 2
  • Therefore, there are 2 neutrons in the nucleus
Isotopes

• An element can have isotopes, with different numbers of neutrons, but of course, fixed Z
• All isotopes of a particular element will have the same number of protons and electrons
  • Same Z, but different N, therefore different mass
• The chemical properties are almost entirely determined by the bonding electrons, so the chemical properties of different isotopes of a given element are essentially identical
• Example: $^3\text{He}$, $^4\text{He}$, $^6\text{He}$, $^1\text{H} = \text{D, deuterium}$
• Beware, D$_2$O is POISONOUS. Deuterated or “Heavy” Water. Slight chemical difference but….
Isotopes and Atomic Mass

- The **atomic mass** of an atom is the mass of the nucleus plus the (small) masses of Z electrons.
- The atomic masses of different isotopes are different.
- The periodic table contains an *average* value of the atomic mass for each element based on the *natural abundance* of each isotope.
- The value listed in the periodic table is the mass in grams of 1 mole [Avogadro’s number] of *atoms*.
- Different elements but with the same Z+N value are called isobars, [bar means weight], because they are relatively close in atomic mass. Not exactly because of slightly different n and p masses. AND different binding energies due to structural details. And different numbers of electrons.

Section 30.1
Most nuclei have an approximately spherical shape.

The radius, \( r \), depends on the number of nucleons it contains:

\[
r = r_o A^{1/3} \quad \text{or} \quad A = \frac{r}{r_o^3}
\]

\( r_o \approx 1.2 \text{ fm} = 1.2 \times 10^{-15} \text{ m} \)

Volume goes as \( r^3 \) and billiard-ball nucleons are tightly packed in nuclei.
Potential Energy

- Since the protons in the nucleus are charged particles, they have a potential energy associated with them.

\[ PE = \frac{k(+e)(+e)}{r^1} = 2 \times 10^{-13} \text{ J} \approx 1 \text{ MeV} \]

- This is very large compared to the typical atomic-scale energy of around 10 eV.
- This is much larger than the energies associated with electrons, molecules, and chemical reactions.
- EACH pair of protons contributes independently. The number of pairs is \( Z(Z-1)/2 \), roughly proportional to \( Z^2 \).
Forces in the Nucleus

• The protons in the nucleus repel one another with a large electrostatic force
• To make the nucleus stable, there must be another even stronger force acting to attract them
• This force is called the **strong force**
• The strong force attracts any two nucleons to each other – *IF* they are close enough to each other
Pairs of protons, pairs of neutrons, and protons and neutrons all attract via the strong force.

If only two protons are involved, the electric force is greater in magnitude than the strong force. For example:

- A nucleus containing just two protons is not stable.
The strong force has an approximately constant magnitude when the nucleons are about 1 fm apart.

The force is negligible when the distance is greater.

The strong force does not play any role in binding electrons — 2 reasons: A) distance; B) electrons don’t feel the strong force at all.
Stability in the Nucleus

- Neutrons are essential for the stability of the nucleus.
- A neutron placed near two protons will add an attractive force that helps overcome the Coulomb repulsion.
  - *Three* strong-force pairwise binding energies are sufficient to bind $^3$He.
Stability in the Nucleus, cont.

• The number of neutrons generally increases as the atomic number increases
  • As more and more protons are added to the nucleus, proportionally more and more extra neutrons are needed to give enough strong binding energy to overcome the Coulomb un-binding (repulsion) energy

• Adding too many neutrons eventually results in an unstable nucleus

• This is explained by the quantum theory of the nucleus called the nuclear shell model
  • There are energy levels of nucleons inside a nucleus, similar to the energy levels of electrons within an atom
  • Excess neutrons must live in too-high energy levels (Pauli exclusion)
Radioactivity

- Some nuclei are unstable and decay spontaneously into two or more particles
- This process is called **radioactive decay**
  - The term **radioactivity** refers to the process in which a nucleus spontaneously emits particles or radiation
- The decay products were originally called **alpha, beta** and **gamma**
  - Generally all are called “radiation” even though only **gamma** (photons) is actually a form of electromagnetic radiation
  - Alpha particles are charged Helium nuclei, bound ppnn
  - Beta particles are electrons ($\beta^-$) or anti-electrons ($\beta^+$)
Alpha Decays

- Alpha decays follow patterns similar to chemical reactions
  - Parent nucleus $\rightarrow$ daughter nucleus + alpha particle
    - The daughter nucleus and the alpha particle are collectively known as *decay products*
- Example of a nuclear decay that produces an alpha particle:
  \[ ^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn} + ^{4}_2\text{He} \]
- The number of nucleons is conserved
- The numbers of protons and neutrons are separately conserved

Section 30.2
Beta Particles

- There are two varieties of beta particles
  - Beta- particle is just an electron
  - Beta+ particle is a **positron**
    - The antiparticle of the electron
    - Except for charge, identical to the electron
- Electrons and positrons have the same mass
- They are both point charges
- Beta decay can change $p$ into $n$, or vice versa
- A closely-related process is Electron Capture, where $e^-$ is absorbed by the nucleus (changing a proton into a neutron in the process)
Beta Particles, cont.

- Decays follow this pattern
  - Parent nucleus $\rightarrow$ daughter nucleus + beta particle + antineutrino

- The antineutrino is unseen, it has *almost* no interaction with matter
Beta Particles, final

- Example of a nuclear decay that produces a beta particle:
  \[ ^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + e^- \]

- The number of nucleons is conserved
  - A neutron is converted to a proton

- Electric charge is conserved

- A nucleus is “transmuted” into one of its neighboring isobars

- The neutrino *must* be present to conserve angular momentum, linear momentum, and energy. Also to conserve something called “electron number”
Gamma Decay

- Gamma decay produces photons
- Decays produce the following pattern
  - Parent nucleus $\rightarrow$ daughter nucleus + gamma ray
- Example of a nuclear decay that produces a gamma ray:
  \[ ^{14}_7\text{N}^* \rightarrow ^{14}_7\text{N} + \]
  - The asterisk denotes that the nucleus is in an energetically excited state

Section 30.2
Gamma Rays and Energy Levels

• The excited nucleus can emit gamma rays with many different energies
  • Depends on which excited and final states are involved
• Typical gamma rays have energies from about 10 keV to 10 MeV or higher

ENERGY LEVELS OF $^{60}_{28}$Ni

- $E = 1.18$ MeV
- $E = 2.16$ MeV
- $E = 1.33$ MeV

Section 30.2
Gamma Rays vs. X-rays

- Gamma rays and X-rays are both portions of the electromagnetic spectrum.
- Their energy ranges overlap.
- By convention, the distinction is based on the origin of the radiation:
  - Gamma rays are produced in nuclear reactions.
  - X-rays are generated by processes involving atomic electron transitions between energy levels.
Conservation Rules

- Conservation of mass-energy
  - The total energy (including mass-energy) at the start of the decay must equal the total at the end of the decay

- Conservation of momentum

- Conservation of electric charge
  - The total number of charged particles may change, but the total amount of charge will not, e.g. $\gamma \leftrightarrow e^+ e^-$

- Conservation of nucleon number

- Conservation of electron number

Section 30.2
Radioactive Decay Series

- When a nucleus undergoes alpha or beta decay, it is converted into another type nucleus.
- The decay reactions often continue through numerous steps.
- Eventually, a stable daughter nucleus is produced.
Decay Series, Example

- The original parent nucleus is $^{238}_{92}U$ and the final product is $^{206}_{82}Pb$
- Beta- decays are indicated by horizontal arrows to the right
  - One neutron changes into one proton
- Diagonal arrows represent alpha decays
  - Reduces the proton number by two and the neutron number by two

Section 30.2
Beta Decay and Life on Earth

- The sun converts four protons into He, changing two protons into two neutrons in a complicated series of steps involving other nuclei such as Carbon
- Beta decay is essential for this to happen.
- Beta decay is caused by the Weak Nuclear Force, one of the four known forces of nature (incl. also: EM, Strong-Nuclear, and Gravity)
- Without the Weak Force, the sun couldn’t shine.
Binding Energy of Alpha Particle

- The alpha particle consists of two protons and two neutrons
  - The total mass of the individual particles is 4.0320 u
- The mass of the actual alpha particle is 4.0015 u
- The difference is due to the binding energy of the alpha particle, $E_{\text{binding}} = (\Delta m)c^2$
- For the alpha particle, $\Delta m = -0.0305$ u, which is 28.4 MeV/$c^2$, $E_{\text{binding}} = -28.4$ MeV -- about 7 MeV per nucleon --- more tightly bound than in Deuterium or $^3$He
- The alpha particle has a lower energy than a collection of separated protons and neutrons and won’t spontaneously fall apart.

Section 30.2
Energy in a Nuclear Reaction

- Total mass before = 226.0234 u
- Total mass after = 226.0202 u
- $E_{\text{reaction}} = -4.8$ MeV (compare to BE of $^3\text{He}$)
- This energy is typically released as kinetic energy of the products
- To conserve momentum, the products are emitted in opposite directions

INITIAL (before decay)

$^{226}_{88}\text{Ra}$

88 p  
+ 138 n

FINAL (after decay)

$^{222}_{86}\text{Rn}$

86 p  
+ 136 n

$^4_2\text{He}$
Half-life

• Individual nuclei decay one at a time, at random times
  • It is not possible to predict when a particular nucleus will decay – randomness, quantum probabilities
• The decay probability of a particular nuclear species is fixed (well, maybe – Prof. E. Fischbach and I are checking just this question in a series of experiments)
• This decay probability is determined within the nucleus, which is so tiny that it is hardly influenced by pressure, temperature, chemical reactions, and other Atomic-level influences.
• Possible exception: electron capture [pressure]
Half-life

- The decay probability is usually specified in terms of the *half-life* of the nucleus, $T_{1/2}$
- Assume an initial number of nuclei, $N_0$, are present in a sample at $t = 0$
- At time $t = T_{1/2}$, half of the nuclei will have decayed
- Leaving half as many nuclei, with the same decay probability,
- Number will be cut in half again, after one more half-life.
- Etc. etc.
Half-life, cont.

- At time \( t = 2 \frac{T}{1/2} \), there will be \( N_0 / 4 \) nuclei remaining, etc.
- This decay curve is described by an exponential function
- The decay constant, \( \lambda \), is defined so that
  \[
  N = N_0 e^{-\lambda t}
  \]
- \( N = N_0 2^{-t/T_{1/2}} \)
Half-life, final

- A large decay constant means a short half-life and a small decay constant means a long half-life
- Values for half-life vary widely

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>n (a free neutron)</td>
<td>10.4 min</td>
</tr>
<tr>
<td>(^1)H (a proton)</td>
<td>Stable</td>
</tr>
<tr>
<td>(^2)H (deuterium)</td>
<td>Stable</td>
</tr>
<tr>
<td>(^3)H (tritium)</td>
<td>12.33 yr</td>
</tr>
<tr>
<td>(^{14})C</td>
<td>5730 yr</td>
</tr>
<tr>
<td>(^{60})Co</td>
<td>5.27 yr</td>
</tr>
<tr>
<td>(^{123})I</td>
<td>13.2 h</td>
</tr>
<tr>
<td>(^{222})Rn</td>
<td>3.82 days</td>
</tr>
<tr>
<td>(^{226})Ra</td>
<td>1600 yr</td>
</tr>
<tr>
<td>(^{235})U</td>
<td>(7.04 \times 10^8) yr</td>
</tr>
<tr>
<td>(^{238})U</td>
<td>(4.47 \times 10^9) yr</td>
</tr>
</tbody>
</table>
• The “strength” of a radioactive sample is measured using a property called its activity
• This can be measured with a Geiger counter, for example
• The activity is proportional to the number of nuclei that decay in one second
Geiger Counter

- Invented by Hans Geiger
  - Student of Rutherford
- Detects the passage of a fast-moving particle through a gas
- The particle ionizes the gas and a current flows between the central wire and the walls
- Current comes as short pulses, giving the “clicks”
Measuring Radioactivity – Units of Decay Rate

- A common unit of “activity” is the Curie (Ci)
  - 1 Ci = $3.7 \times 10^{10}$ decays / s
  - In practice, a sample with this activity would be very dangerous
  - Most studies or medical uses involve activities of millicuries or microcuries
- The official SI unit of activity is the Becquerel (Bq)
  - 1 Bq = 1 decay / s
  - 1 Ci = $3.7 \times 10^{10}$ Bq
Nuclear Stability

- To be stable, a nucleus containing two or more protons must contain neutrons.
- The dashed line in the plot indicates $N = Z$.
- Low-mass nuclei tend to have equal numbers of protons and neutrons.
- Heavy nuclei contain more neutrons than protons.
Nuclear Stability

- There are of order 300 stable isotopes, and thousands of unstable ones.
- Plot shows more and more extra neutrons added as $Z$ increases.
- There are also artificial isotopes of larger $Z$ beyond 92, with rather short half-lives, created at Berkeley, Dubna (Russia), and Darmstadt (Germany).

- Yellow and brown = excess protons
- Green = excess neutrons

Section 30.3
**Nuclear Stability, cont.**

Section 30.3

Blue=stable, with abundance % shown.

Unstable nuclide lifetimes range from ms to billions of years.

---

**Table:**

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Number</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag93</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>Ag94</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>Ag95</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>Ag96</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Ag97</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>Ag98</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>Ag99</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>Ag100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Ag101</td>
<td>101</td>
<td></td>
</tr>
<tr>
<td>Ag102</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>Ag103</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td>Ag104</td>
<td>104</td>
<td></td>
</tr>
<tr>
<td>Ag105</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>Ag106</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>Ag107</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td>Ag108</td>
<td>108</td>
<td></td>
</tr>
</tbody>
</table>

---

**Diagram:**

- Blue indicates stable nuclides with abundance percentage shown.
- Unstable nuclides have lifetimes ranging from milliseconds to billions of years.
Nuclear Power Plants

• Nuclear fission is used in a controlled way in nuclear power plants
• Nuclear fission is typically the splitting of a $^{235}\text{U}$ nucleus into two (unequal-mass) fragments called “fission products”
• An important example occurs when a (slow) neutron collides with $^{235}\text{U}$

$$^1\text{n} + ^{235}\text{U} \rightarrow ^{130}\text{Ba} + ^{94}\text{Kr} + 3\,^0\text{n}$$

• There are a variety of ways the split can divide, this is just one of them
Features of Fission Reactions

- The reaction produces more free neutrons than the one neutron needed to cause it.
- These free neutrons can then induce fission in other nearby uranium nuclei, creating a *chain reaction*.
- But the neutrons must be slowed down first, by repeatedly bouncing off the nuclei of a “moderator”, such as water or graphite.
- The reaction releases energy:
  - The extra binding energy is released in the form of gamma rays and through the kinetic energies of the particles produced.
Chain Reaction, Example
Factors Influencing the Reaction

- Natural uranium is more than 99% $^{238}\text{U}_{92}$ which does not readily undergo fission
  - Natural uranium is enriched to increase the concentration of $^{235}\text{U}_{92}$
  - This is a difficult engineering process – centrifuges now
  - Heavy water, $\text{D}_2\text{O}$ moderating works w. natural uranium
- If the stack of uranium is small, many of the nuclei are close enough to the surface that many of the released neutrons escape before inducing another fission event (an example of surface to volume ratio effects)
  - The **critical mass** is the minimum amount of nuclear fuel material needed to sustain a chain reaction
  - Several kg for bomb w. good n reflectors around the U
Energy from Fission

- The binding energy per nucleon of $^{235}_{92}U$ is about -7.6 MeV
- For many of the fission products, the binding energy is about -8.5 MeV per nucleon
- The decay products are MORE tightly bound by -0.9 MeV per nucleon
- Since there are 235 nucleons, the total energy release per nuclear fission is about 210 MeV
- For one gram of pure $^{235}_{92}U$, this would correspond to a total energy of about $9 \times 10^{10}$ J
  - For comparison, one gram of TNT releases about 4200 J; 1 kg, 4.2 E6 J; 1 T, 4.1 E9 J, 20 Tons give
Nuclear Power Plants

- Nuclear fission is used in a controlled way in nuclear power plants
- Safety is always a major concern at a nuclear fission reactor
  - All reactors are now designed with extensive safety features
  - The latest designs include passive safety features that do not require operator action or electronic feedback to deal with emergency situations
  - Water reactors shut down if the moderating water is lost
  - But the “afterglow” of radioactive fission products releases troublesome amounts of heat (viz Fukushima)
Nuclear Power Plants

• Chernobyl (in the Ukraine, coincidentally) was graphite moderated and was thermally UNSTABLE: As it heats up, the fission reaction INCREASES.
• Not safe. A dumb and now never used design. Meltdown and release of radioactives was pretty messy. Water reactors are much much safer.
• There are options using Thorium that are even cleaner, do not produce Plutonium (another fissionable bomb material), and there’s four or five times more Thorium than Uranium on Earth.
• But the technology is much less advanced
• The “sailing ship syndrome”: fast sailing clippers outcompeted steam ships for a number of years.
Power Plant Components

- **Fuel rods** contain $^{235}\text{U}$ that can be added or removed from the core while the reactor is operating.
- **Control rods** contain materials that absorb neutrons:
  - They can be inserted or removed from the core to control the number of free neutrons and adjust the fission rate.
Power Plant Components, cont.

- Moderator circulates through the core
  - Often water
  - One function is to slow down the neutrons to greatly increase the probability they will induce a fission event
  - It also carries away heat to a separate steam engine where a generator converts it to electrical energy
- This heat engine operates according to the laws of thermodynamics
  - Including needing a cold reservoir to dispose of waste heat
  - Considerable energy inefficiency (Carnot cycle, laws of Thermodynamics)

Section 30.3
Fusion Reactions

- In **nuclear fusion**, two nuclei join together to produce one new particle.
- An example reaction:
  \[
  ^{6}_{3}\text{Li} + ^{6}_{3}\text{Li} \rightarrow ^{12}_{6}\text{C} + \text{energy}
  \]
- This energy is in the form of gamma rays plus the kinetic energy of the carbon nucleus.
- The energy released is about 2.5 MeV / nucleon.
  - This is more energy per nucleon than fission.
Fusion and the Sun

• Nuclear fusion is the process that powers stars
• Hydrogen nuclei are fused to form helium nuclei
  • Heavier elements can also be formed by fusion
• Fusion reactions can take place in the Sun due to the high temperatures and pressures in the core. The reactions also take millions of years (but lots of nuclei acting)
  • To produce fusion on Earth, you have to give the nuclei high speeds and keep them close together
  • Experimental designs for fusion power plants are being built
Biological Effects

- The biological effects of radioactivity result from the way the decay or reaction products interact with atoms and molecules.
- The typical binding energy of an electron in an atom is on the order of 10 eV.
- The energy released in a nuclear reaction is typically several MeV.
- If one of the particles collides with an atomic electron, there is enough energy to eject the electron from the atom or break a chemical bond in molecules.
Amount of Damage

- The amount of damage that a particular particle is capable of doing is complicated to predict.
- Alpha and beta emitters must be ingested to do harm (easily stopped by skin).
- Gamma emitters are penetrating.
- Need Pb other high-Z shielding,
- And/or DISTANCE \((1/r^2\) helps a lot)
- And/or TIME -- less is less.

- ALARA is the motto
Measuring Damage

- **Radiation absorbed dose** – rad
  - 1 rad is the amount of radiation that deposits $10^{-2}$ J of energy into 1 kg of absorbing material
    - The unit accounts for both the amount of energy carried by the particle and the efficiency with which the energy is absorbed
    - SI unit is the Sievert, 1 Sievert = 100 rad
    - LD 50 is about 6 Sievert = 600 rad. Extremities a lot more tolerant.

- **Relative biological effectiveness** – RBE
  - This measures how efficiently a particular type of particle damages tissue
  - This accounts for the fact that different types of particles can do different amounts of damage even if they deposit the same amount of energy.
Measuring Damage, cont.

- RBE value tends to increase as the mass of the particle increases

- *Röntgen Equivalent in Man – rem*
  - Dose in rem = (dose in rad) x RBE
  - This combines the amount and effectiveness of the radiation absorbed

### Table 30.3 Relative Biological Effectiveness (*RBE*) for Different Types of Radiation

<table>
<thead>
<tr>
<th>Radiation</th>
<th>RBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha particles</td>
<td>10–20</td>
</tr>
<tr>
<td>Beta particles</td>
<td>1.0–1.7</td>
</tr>
<tr>
<td>Gamma rays and X-rays</td>
<td>1.0</td>
</tr>
<tr>
<td>Slow neutrons</td>
<td>4–5</td>
</tr>
<tr>
<td>Protons</td>
<td>5</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>10</td>
</tr>
<tr>
<td>Heavy ions</td>
<td>20</td>
</tr>
</tbody>
</table>
Radiation Damage

- When the radiation dose is low, cells are sometimes able to repair the damage
  - Especially if the dose is absorbed over long periods of time
  - Generally, small amounts of radiation do not cause significant harm to living cells – may even help
- If the radiation dose is very large, cells can be completely destroyed
- At intermediate doses, cells survive but often malfunction as a result of the damage
  - A typical result is that the affected cells reproduce in an uncontrolled fashion, leading to cancer
Radiation damage is usually most severe for quickly dividing cells
  • Many types of blood and bone marrow cells fall into the category
  • Cancerous cells are also quickly dividing, so radiation can be used as a tool to selectively destroy cancer cells

The amount of damage can depend strongly on where the radiation source is located
  • For example, an alpha particle outside the body will be stopped in the outer layer of skin and do relatively little damage
  • If a person ingests an alpha particle it can do a great deal of damage to nearby cells
TABLE 30.4  Radiation Doses in Perspective (Typical Values)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Dose (mrem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airline flight from New York City to Los Angeles</td>
<td>3</td>
</tr>
<tr>
<td>Dental X-ray</td>
<td>10</td>
</tr>
<tr>
<td>Chest X-ray</td>
<td>5–10</td>
</tr>
<tr>
<td>Mammogram</td>
<td>50–100</td>
</tr>
<tr>
<td>Approximate annual dose from natural background sources</td>
<td>300</td>
</tr>
<tr>
<td>Recommended maximum annual dose in addition to background dose</td>
<td>500</td>
</tr>
<tr>
<td><em>Apollo XVI</em> astronauts</td>
<td>500</td>
</tr>
<tr>
<td>1-in-30 risk of cancer</td>
<td>10,000</td>
</tr>
<tr>
<td>Radiation sickness possible</td>
<td>60,000</td>
</tr>
</tbody>
</table>

CAT scans now give over 1000 mRem, more than the natural dose accumulated over 3 years

Section 30.4
Radiation in Everyday Life

• For common medical procedures, the benefits may outweigh the risk of exposure – but beware of unnecessary CAT scans (and never ask a barber if you need a haircut!)

• Natural exposure occurs from many sources
  • Cosmic rays – a collection of many different types of particles from outer space
  • Radon – produced by the decay of $^{238}U$ in rocks and soil
  • In Lafayette, about 180 mRem per year from EACH of these two sources
Radioactive Tracers

• A *radioactive tracer* is a chemical that contains radioactive nuclei
• The movements of the tracer nuclei can be monitored by observing the radiation they emit through decay
• Tracers are widely used in medicine and many other fields
• Examples include
  • Nuclear stress testing
  • PET scanning
  • Thyroid cancer fighting
Radiation and Cancer Treatment

- Radiation treatments are effective in treating many types of cancer
- Radioactive materials emit high energy electrons or gamma rays that kill nearby cancer cells
- Examples include
  - Breast cancer (my wife received 6000 Rem, cumulative over a 35 day period, after a breast lumpectomy. The breast is an extremity, for radiation purposes! They took great pains to avoid the chest and ribs.)
  - Prostate cancer
Carbon Dating

- Cosmic rays interacting with atmospheric nitrogen produce $^{14}\text{C}$
- $^{14}\text{C}$ is radioactive with a $T_{1/2} = 5730$ years
- Carbon dating is done by measuring the ratio of C-14 to C-12 and observing the decrease due to the decay of the $^{14}\text{C}$

![Graph showing the decay of carbon-14 over time](image)
MRI

- **Magnetic resonance imaging (MRI)** makes use of the magnetic properties of nuclei.
- Protons can have spin up or spin down states.
  - In a magnetic field, each state has a different energy.
The presence of a photon can be detected by observing the absorption of a photon that induces a transition to the higher energy state

- The absorption occurs only if the separation between the energy levels matches the photon energy

An MRI magnet is designed so the energies match only at a particular spot within the body

- The MRI signal gives the density of protons at that spot

By scanning this spot around the body, a three-dimensional image can be constructed
New Conservation Law

- Nuclear physics reveals a new conservation law – conservation of nucleon number
  - All known nuclear reactions conserve the number of nucleons
  - Physicists don’t know why nucleon number is conserved
  - Number conservation rules do not apply to all particles
    - For example, electron number is not conserved by neutrinos as they travel in space. They oscillate among three “flavors” associated with electrons and their heavy cousins, muons and tau leptons
Quarks

- Nucleons are composed of particles called **quarks**
  - Determined by scattering experiments
- There are several different types of quarks
- All carry electric charge of $\pm \frac{e}{3}$ or $\pm \frac{2e}{3}$
- Protons and neutrons are each composed of three quarks