Classroom notes for: Radiation and Life

98.101.201

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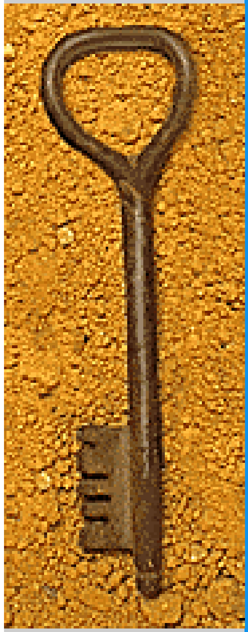
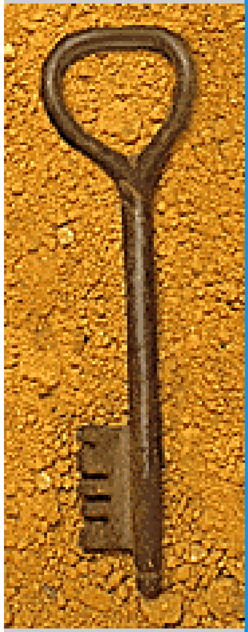


Sources of Ionizing Radiation / Ionizing Radiation Interactions with Matter

- **Definition of Radiation**

Radiation is the emission or transmission of energy in the form of waves (or particles) through space or through a material medium; the term also applies to the radiated energy itself; i.e., the term radiation describes both the act of emitting energy or particles and the waves or particles themselves. The term includes electromagnetic, acoustic, and particle radiation (electrons, protons, neutrons, etc…), and all forms of ionizing radiation. (http://www.encyclopedia.com)

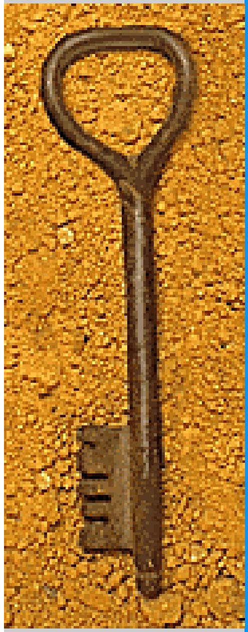
Our primary interest is with ***ionizing radiation***, that is, radiation with enough energy to eject electrons from atoms.



There are many types of radiation- remember our discussion of the electromagnetic spectrum? However, our focus for the rest of the class will be exclusively on ionizing radiation.

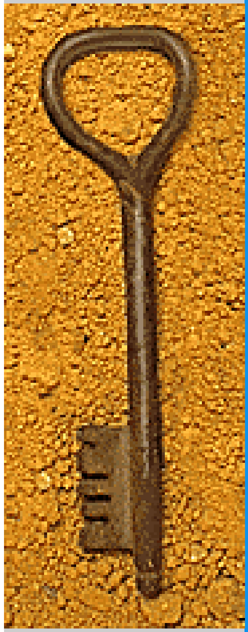
- UV radiation receives much attention, because it is a known carcinogen. However, the methods by which UV radiation interacts with matter (and potentially induces cancer) are different than those of ionizing radiation, so we won't consider it further.

- That particular transformation occurred because the electromagnetic properties of ultraviolet radiation cause a highly specific warping and cracking of the DNA molecule, said Dr. Brash, and in attempting to repair the wreckage, the enzymes of the cell ended up inserting the wrong bases into the disrupted site. As a result of the erroneous repair job, he said, the p53 gene could no longer perform its task as tumor suppressor. (http://www.sroa.org/_onconews/Vol3No1/Ultraviolet_Radiation.htm



The radiations emitted by such diverse items as cellular phones, microwave ovens, state-police radar guns, and electrical power distribution lines have also been implicated as potential carcinogens. However, if they do cause cancer, the mechanisms by which this occurs are fundamentally different from the way in which ionizing radiation can induce cancer; so will not consider these radiations, either

- We will characterize ionizing radiation in two broad ways: it's source (i.e., how it's created), and the manner in which it interacts with matter. Please understand these two concepts are separate and distinct.

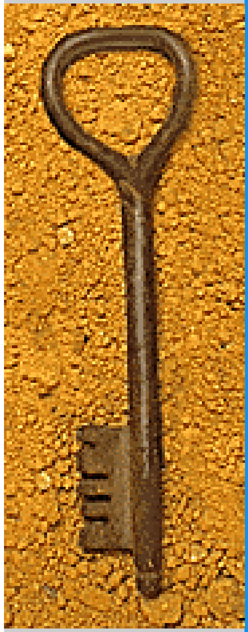


Sources of Ionizing Radiation

Ionizing radiation is generated in several ways:

- by the decay of a radioactive nucleus; or
- by the de-excitation of a nucleus in a higher energy state; or
- by nuclear reactions; or
- by the emission of x-rays by electrons; or
- by annihilation events; or
- by ionization events.

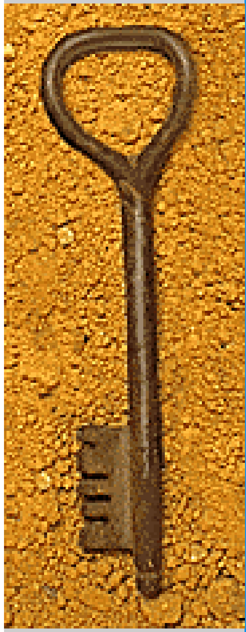
We will consider each category in turn. Understand that in only one of the six cases discussed is radiation emitted by the decay of a radioactive nucleus; i.e., there are many other sources of radiation beyond radioactive nuclei.



Decay of a Radioactive Nucleus

Consider alpha particle emission.

Recall that protons in the nucleus repel each other by virtue of their positive charges; however, protons and neutrons experience a strong force attraction that balances the Coulombic repulsion. This doesn't guarantee that the nucleus is stable. Imagine a group of two protons and two neutrons bundled together, and imagine that this bundle is "bouncing" back and forth inside the nucleus with a staggering frequency (~10^{21} 1/s). Even though it is "trapped" in the nucleus, the rules of quantum mechanics dictate that for certain nuclei (particularly more massive ones) that there is a very small chance that each time the bundle "bounces" off of the barrier, it will suddenly appear on the other side (barrier tunneling). Once outside the nucleus, it is no longer bound by the strong force attraction and Coulombic repulsion pushes the bundle away. This is an overly simplistic analogy, but it gives a feel for what occurs during alpha emission.

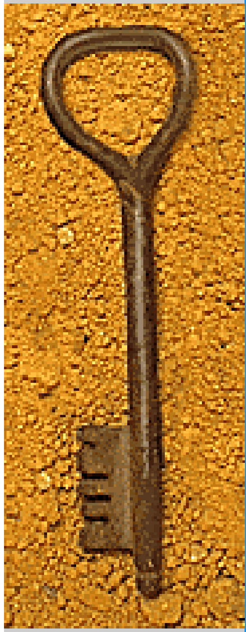


Alpha Particle continued

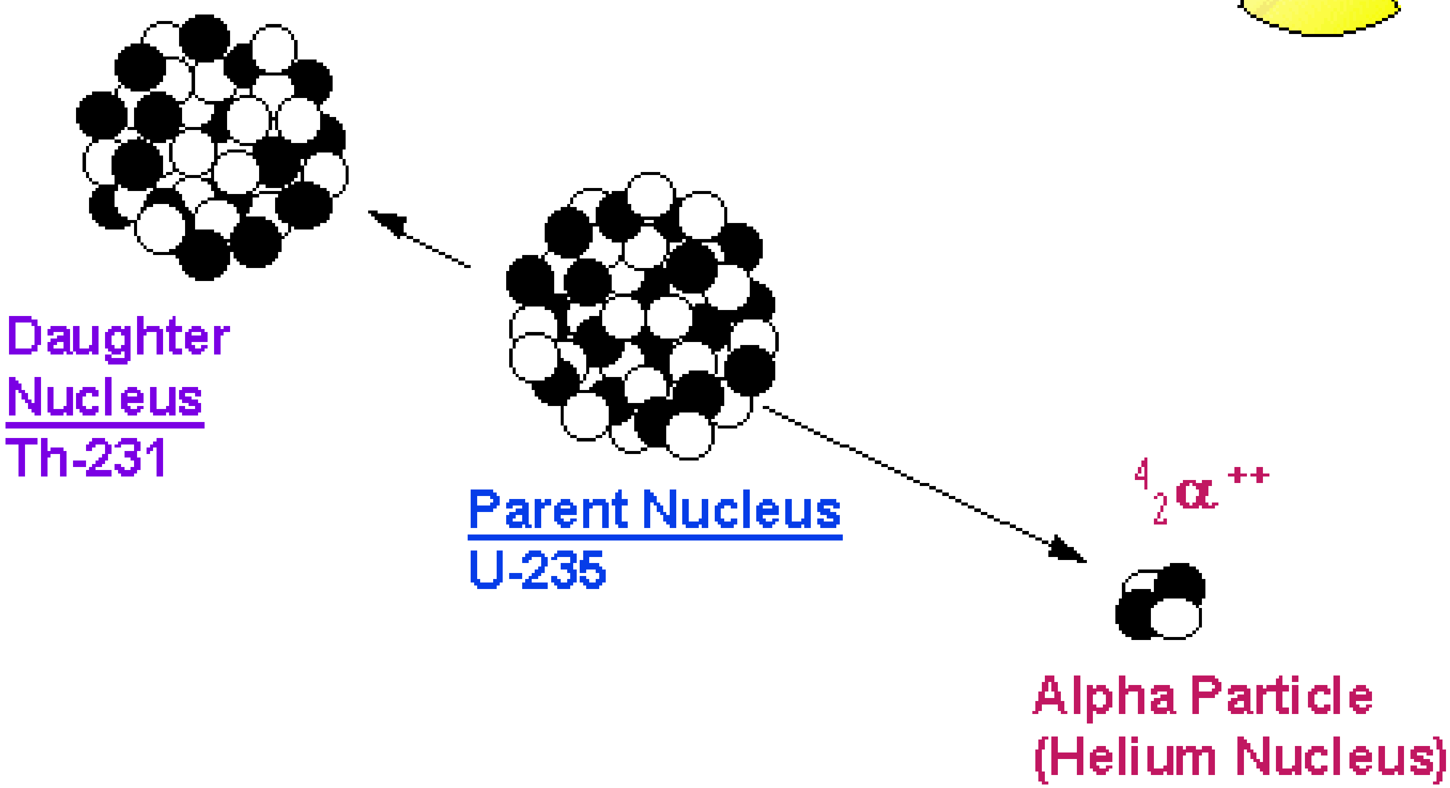
- As a result of this “imbalance” between the strong nuclear and electromagnetic forces, certain nuclei are considered radioactive and will emit an alpha (α) particle. (*Radiation and Health*, Luetzelschwab, p. A3)
- An alpha particle is simply a “bundle” of two protons and two neutrons- essentially the nucleus of a helium atom.

Before After

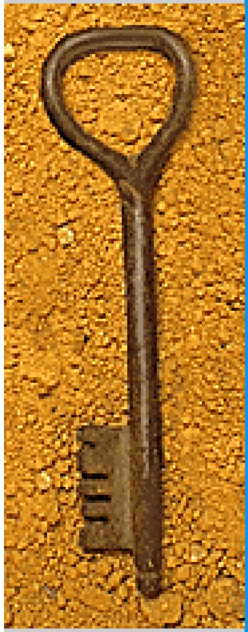
- ${}_{92}$U-235 ---> ${}_{90}$Th-231 + ${}_{2}\alpha$-4 + Q



Alpha Particle Radiation



(diagram courtesy of the University of Michigan Student Chapter of the Health Physics Society)



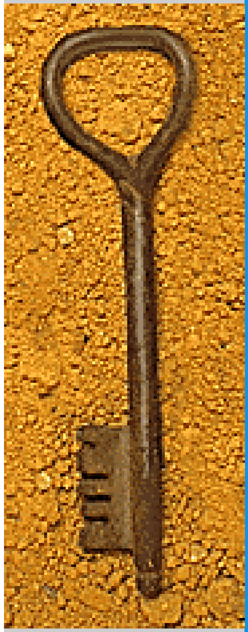
- The arrow indicates that an event occurred; in this case the uranium nucleus underwent radioactive decay. You can also think of it as an "equals" sign for balancing the values for A and Z on each side.
- $_{90}$Th-231 (thorium) is the "daughter" nucleus, or the progeny.

Because the alpha particle has two protons and two neutrons, the Z-value of the daughter is two less, and the A-value of the daughter is four less.

- α is the alpha particle; and
- Q is the excess energy of the reaction in eV or MeV (that is carried away by the speeding alpha particle and the recoiling "daughter" nucleus).

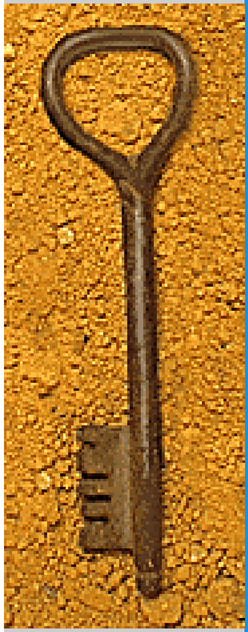
Q is calculated using Einstein's formula $E = mc^2$. Add up the masses of everything on the right side of the arrow, and the value will be less than the value obtained by adding everything on the left side; mass disappeared and was converted to energy.

Uranium, thorium, radium, radon, and polonium all have radioactive isotopes that emit alpha particles



Beta Particle Emission.

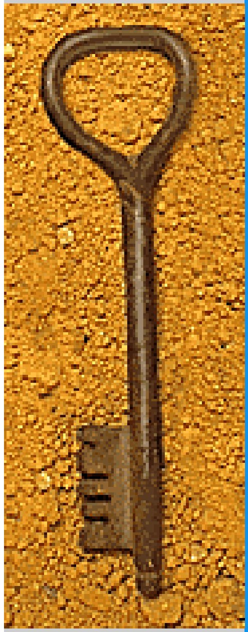
- The weak force plays a role in beta particle emission, during which the nucleus ejects an electron with a "-" or "+" charge.
  (http://www.phy.cuhk.edu.hk/cpep/weak.html)
- The negatively charged electron is no different than orbital electrons about which we've learned; in this instance it is called a beta particle because it originated in the nucleus.
- An electron with positive charge is known as a positron and is considered antimatter. It is in all respects identical to an electron, except that it has a positive charge.
- In either case, the beta particle is emitted by the nucleus, not because an electron was inside the nucleus, but by virtue of either of the following reactions:



- β^-: $n^0 \rightarrow p^+ + e^-$

- β^+: $p^+ \rightarrow n^0 + e^+$

- Whenever there is an imbalance between the number of neutrons and protons in the nucleus (more of one type or the other), one of these two reactions may occur; the greater the imbalance, the more likely the reaction. So even though the strong force acts as a glue, it is impossible to build a nucleus out or protons or neutrons only, because the weak force will motivate a beta particle emission.
- In essence, to build a nucleus entirely of neutrons, for instance, would require filling many neutron energy states, while leaving the proton shells unfilled. To achieve the state of lowest possible energy for the nucleus, neutrons would undergo beta decay to populate the unfilled proton states



- Before After
- $_{29}$Cu-64-- -> $_{30}$Zn-64 + $_{-1}\beta$ + ν + Q

Where:

The arrow indicates that an event occurred; in this case the copper nucleus underwent radioactive decay.

$_{30}$Zn-64 (zinc) is the “daughter” nucleus, or the progeny.

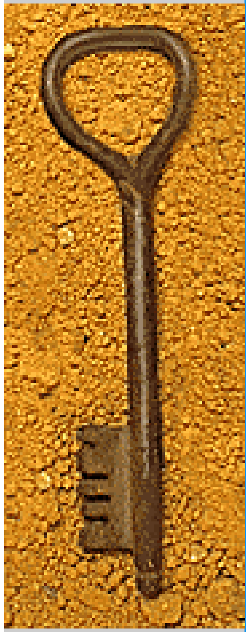
In this example of “beta-minus” decay, the Z-value of the daughter is one higher, because a neutron turned into a proton (A remains unchanged).

$_{-1}\beta$ the beta particle; and

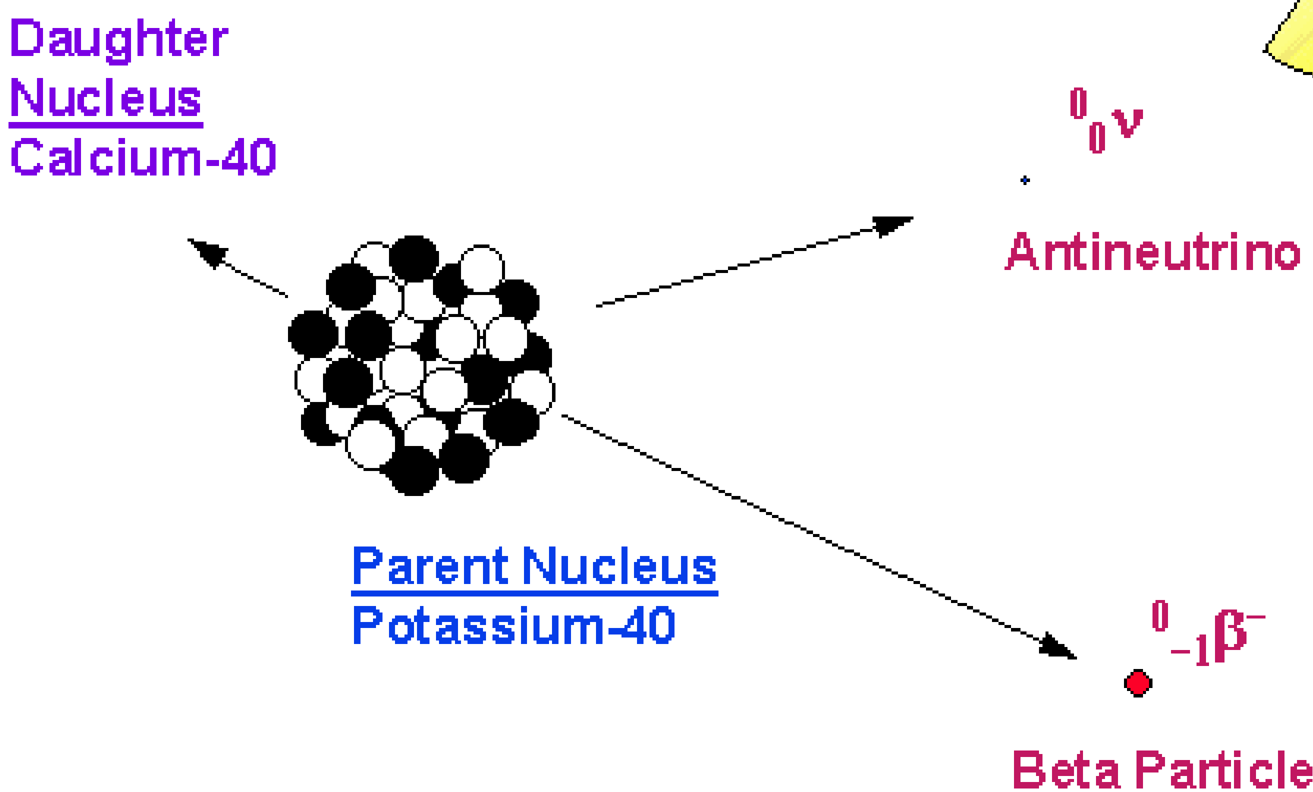
ν is an antineutrino; and

The antineutrino is of no concern to health physicists, because a low-energy neutrino will travel through many light-years of normal matter before interacting with anything.

(http://www.sciam.com/askexpert/physics/physics55/physics55.html)



Beta Particle Radiation



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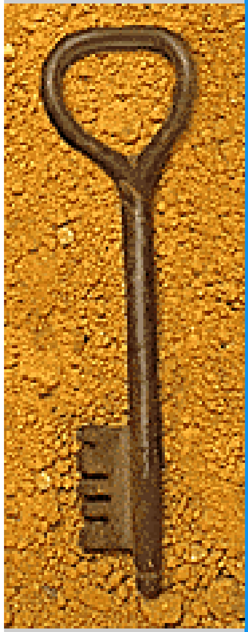


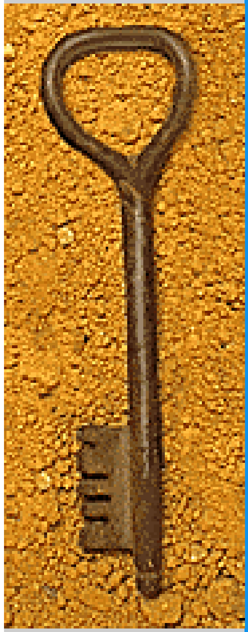
- *More About Neutrinos*
- Wolfgang Pauli first postulated the existence of neutrinos in 1930. At that time, a problem arose because it seemed that neither energy nor angular momentum were conserved in beta-decay.

(http://www.sciam.com/askexpert/physics/physics55/physics55.html)

- Nuclear forces treat electrons and neutrinos identically; neither participates in the strong nuclear force, but both participate equally in the weak nuclear force. Particles with this property are termed leptons.

(http://www.sciam.com/askexpert/physics/physics55/physics55.html)

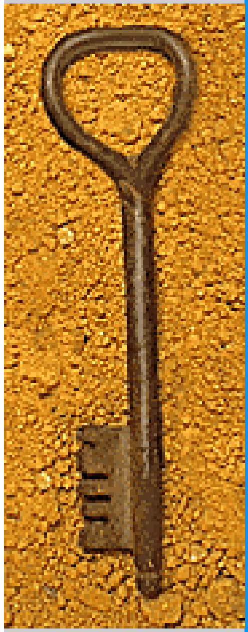
- The Sudbury Neutrino Observatory detects only 30 neutrinos per day. The neutrinos interact in a 1000-ton container of heavy water that is 6800 feet below ground, in Creighton mine near Sudbury, Ontario.
  (http://www.sno.phy.queensu.ca/)



De-excitation of a Nucleus

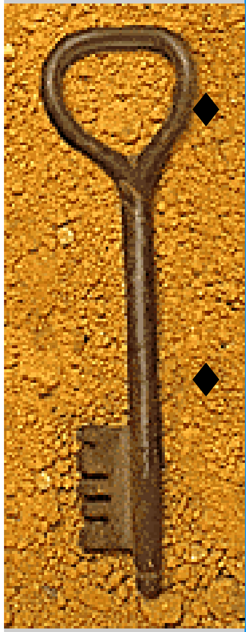
If the nucleus has excess energy, it is said to be an excited state; at some time later it can return to its original energy state (analogous to the behavior of excited electrons).

- The difference between the two energy states is an energy (E). When the nucleus de-excites, it emits a gamma-ray (γ) photon with an energy equal to the difference between the excited and original energy states ($E = h\nu$).
- In this instance, the nucleus need not be radioactive to emit a gamma ray; it simply needs to have had energy imparted to it, giving it excess.
- Often, following alpha or beta particle, the newly formed “daughter” nucleus is “born” in an excited state and will emit a gamma-ray photon within a very short time (roughly on the order of nanoseconds or less- essentially instantaneously for our purposes).
- There are some pure beta emitters, however, such as H-3, C-14, and P-32; and many alpha decays proceed directly to the ground state of the “daughter” nucleus without the emission of a gamma ray.



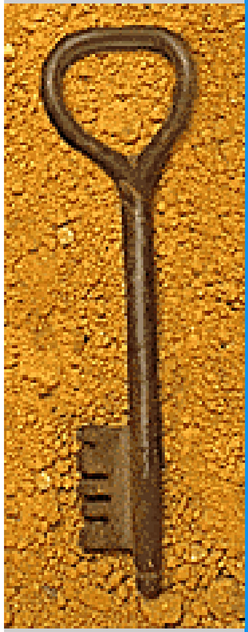
Nuclear Reactions

- The nucleus can be induced to emit radiation via nuclear reactions. Many types of particles can be emitted through these reactions, some of which are very exotic.
- Protons and neutrons are of interest for this course. For example:
- ${}_{8}O\text{-}16 + {}_{0}n\text{-}1 \rightarrow {}_{7}N\text{-}16 + {}_{1}p\text{-}1 + Q$
- In this reaction, the oxygen nucleus absorbs a neutron and is induced to emit a proton.
- Nuclear fission and nuclear fusion are both nuclear reactions that serve as sources of neutrons, and will be discussed later in the class.

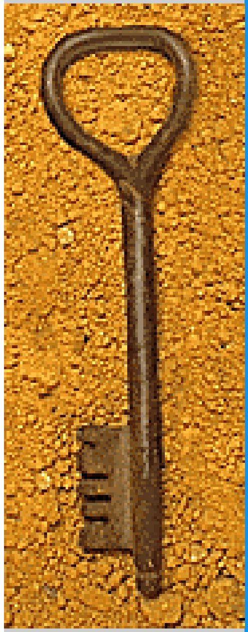


X-Ray Emission

- Consider the orbital transition of electrons.
  - When an orbital electron transitions from a higher to a lower energy state, a photon is emitted with an energy equal to the difference between the two energy states.
- If the photon's energy is large enough, it is an x-ray.
  - These are known as characteristic x-rays, because their exact energies depend upon the transitions between the energy states that are unique to the atoms of a particular element (remember spectroscopy?).
  - Note: both x- and gamma rays are photons; the only difference between them is that γs originate in the nucleus, while x-rays originate from electrons.
  - Consider free electrons (those that are not bound in an atom's electron shells).
  - An accelerating charge, when not bound in a shell, radiates energy (remember Maxwell?)
  - This radiation is known as Bremsstrahlung ("breaking radiation"), and the x-ray photons emitted have a range of energies.
  - Bremsstrahlung was the radiation Roentgen observed in 1895 (this information allows us to understand the final question left unanswered concerning Roentgen's observations).

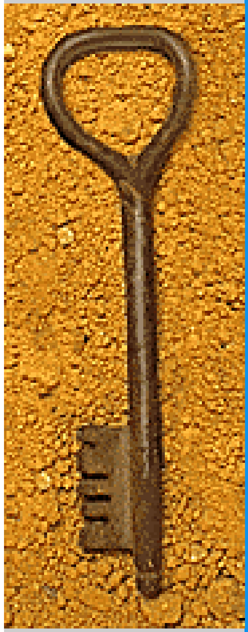


- **Annihilation Events**
  - When matter and antimatter come in contact, the mass vanishes completely and in its place appear high-energy photons (oftentimes called gamma-rays).
  - Antimatter is found only in minute quantities on the earth, and it is believed that in general, antimatter is comparatively rare throughout the universe. (http://www.encarta.msn.com)
- **Ionization Events**
  - When an orbital electron is ejected from an atom during an ionization event, it often has enough energy to itself be considered ionizing radiation (and known as a secondary charged particle).



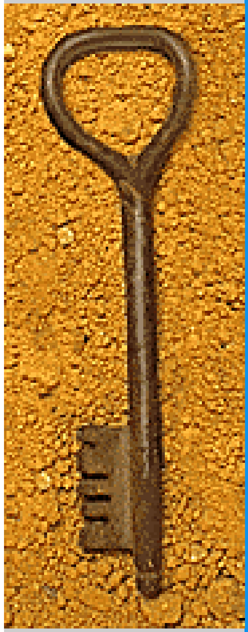
Ionizing Radiation Interactions with Matter

- Depending upon the exact interaction mechanisms, ionizing radiation can be categorized as either directly ionizing or indirectly ionizing (again, keep these two modes of interaction separate and distinct in your mind from the origins of the particles).
- **Directly Ionizing Radiation**
- Directly ionizing radiation has charge.
- The particles that meet this criterion are grouped as follows.
  - Light charged particles are: β^-, β^+, e^-, and e^+ (remember, all four of these are electrons; the symbol "β" is used simply to indicate that the electron originated in the nucleus).
  - Heavy charged particles are α, p^+, and recoil "daughter" nuclei (or nuclei that have been accelerated to high speeds by man or in stellar processes).
  - Directly ionizing radiation interacts with matter via two primary mechanisms.

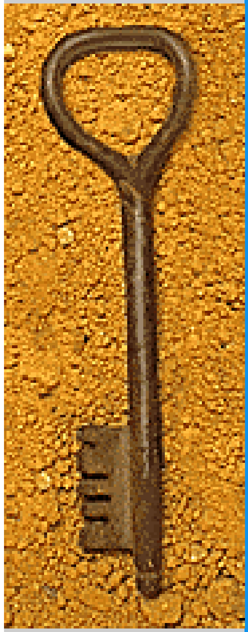


Interaction via Collision

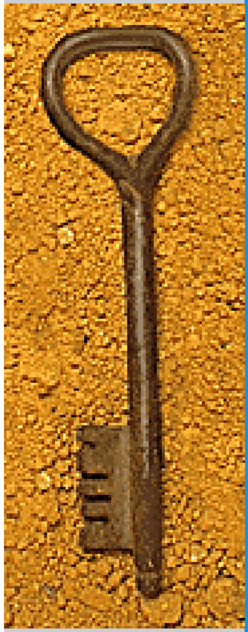
- By virtue of having charge, directly ionizing radiation interacts directly with the orbital electrons in the atoms of the "target" material.
- The particles have charge, and the orbital e^- in the target have charge, so all have electric fields that surround them. These electric fields extend away from the particles (remember the $1/r^2$ law?).
- The electric field of a directly ionizing particle can "bump" an orbital electron during a collision event (or conversely, the electric field of an orbital electron can "bump" the directly ionizing particle).
- Because there are so many orbital electrons in the target, the particle's electric field continuously interacts with the orbital electrons- there is no point during the particle's trip through the target that it is not being "bumping" or being "bumped".



- During each collision event, the directly ionizing particle loses energy; since it undergoes a continuous series of collisions, it continuously loses energy while traveling through the target matter.
- If the particle is continuously losing energy, it is continuously imparting energy to the target material (remember the principle of Conservation of Energy?).
- The energy absorbed either excites the orbital e^- or completely ejects it from the atom (this absorbed energy is known as the *absorbed dose*).
- Heavy charged particles will lose their energy very quickly, while the light charged particles (β^+, β^-) will lose their energy more slowly.
- Thus, the light charged particles will travel farther in matter.



- By the Bethe-Block formula for heavy charged particles, collisional stopping power [$(-dE/dx)_{coll}$] is proportional to z^2, where z is the charge of the directly ionizing radiation. (*Radiation Safety and Control, Volume 2*, French and Skrable, p. 10)
- The collisional stopping power [$(-dE/dx)_{coll}$] for electrons does not exhibit this dependence, so an electron with an identical energy and traveling through an identical medium will tend to have a smaller stopping power than a heavy charged particle. (*Radiation Safety and Control, Volume 2*, French and Skrable, p. 10)
- In general, however, neither type tends to penetrate very deeply in matter; for instance, heavy charged particles such as alphas will only travel cm in air and less than mm in water or tissue (*Radiation Safety and Control HW #2*, French)
- Also note that both heavy and light charged particles tend to lose their energy much more rapidly towards the end, so for both types, the greatest energy loss occurs at the end of the path.



The Bethe Formula for Stopping Power

$$-\frac{dE}{dx} = \frac{4\pi k_0^2 z^2 e^4 n}{mc^2 \beta^2} \left[\ln \frac{2mc^2\beta^2}{I(1-\beta^2)} - \beta^2 \right].$$

Using relativistic quantum mechanics, Bethe derived the following expression for the stopping power of a uniform medium for a heavy charged particle:

k_o = 8.99 x 109 N m2 C-2 , (the Boltzman constant)

z = atomic number of the heavy particle,

e = magnitude of the electron charge,

n = number of electrons per unit volume in the medium,

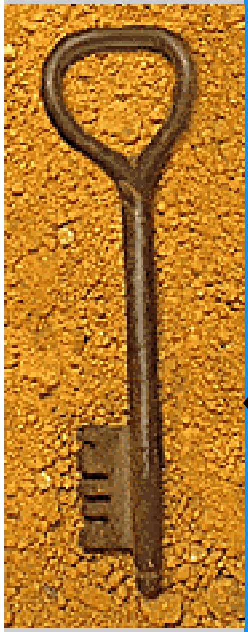
m = electron rest mass,

c = speed of light in vacuum,

â = *V*/*c* = speed of the particle relative to c,

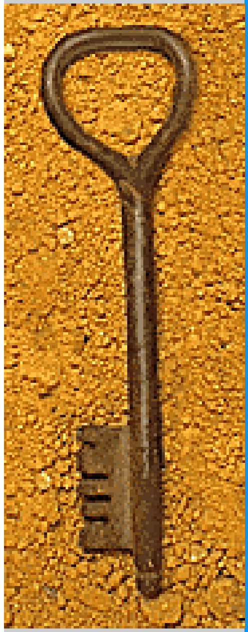
I = mean excitation energy of the medium.

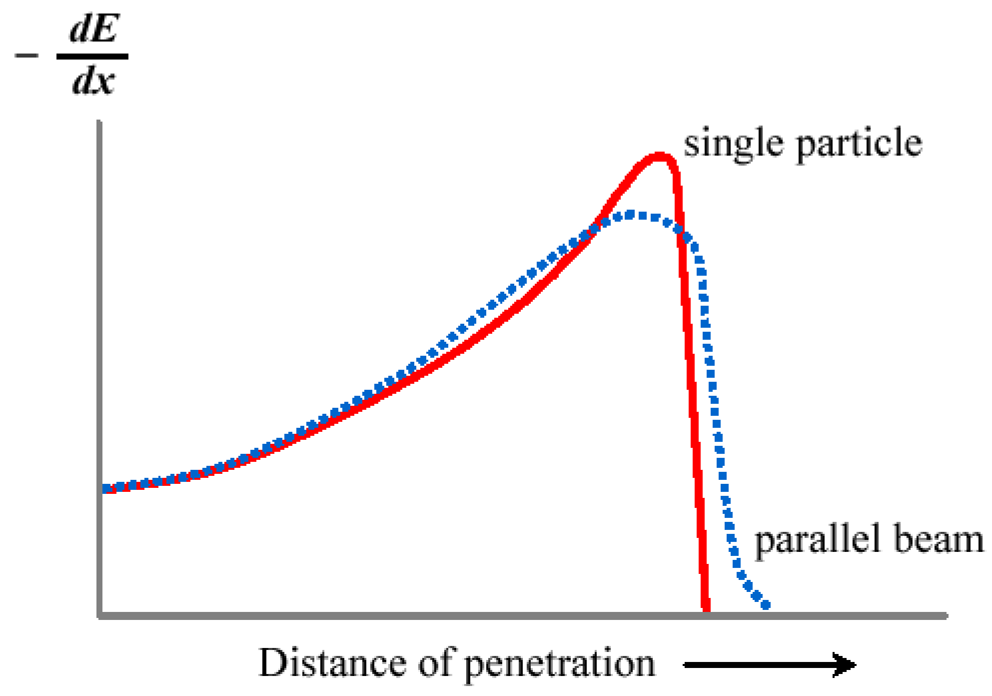
Stopping power versus distance: the Bragg Peak



$$-\frac{dE}{dx}=\frac{5.08 x 10^{-31} z^2 n}{\beta^2}[F(\beta)-\ln I_{ev}] \quad \text{MeV cm}^{-1}$$

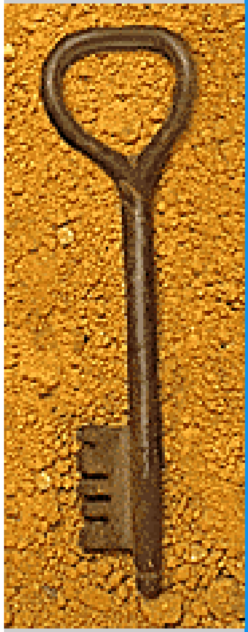
- At low energies, the factor in front of the bracket increases as ß   0, causing a peak (called the Bragg peak) to occur.
- The linear rate of energy loss is a maximum as the particle energy approaches 0.





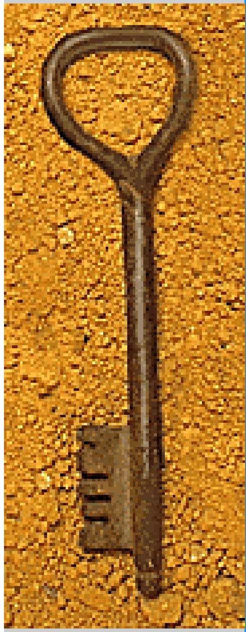
Rate of energy loss along an alpha particle track.

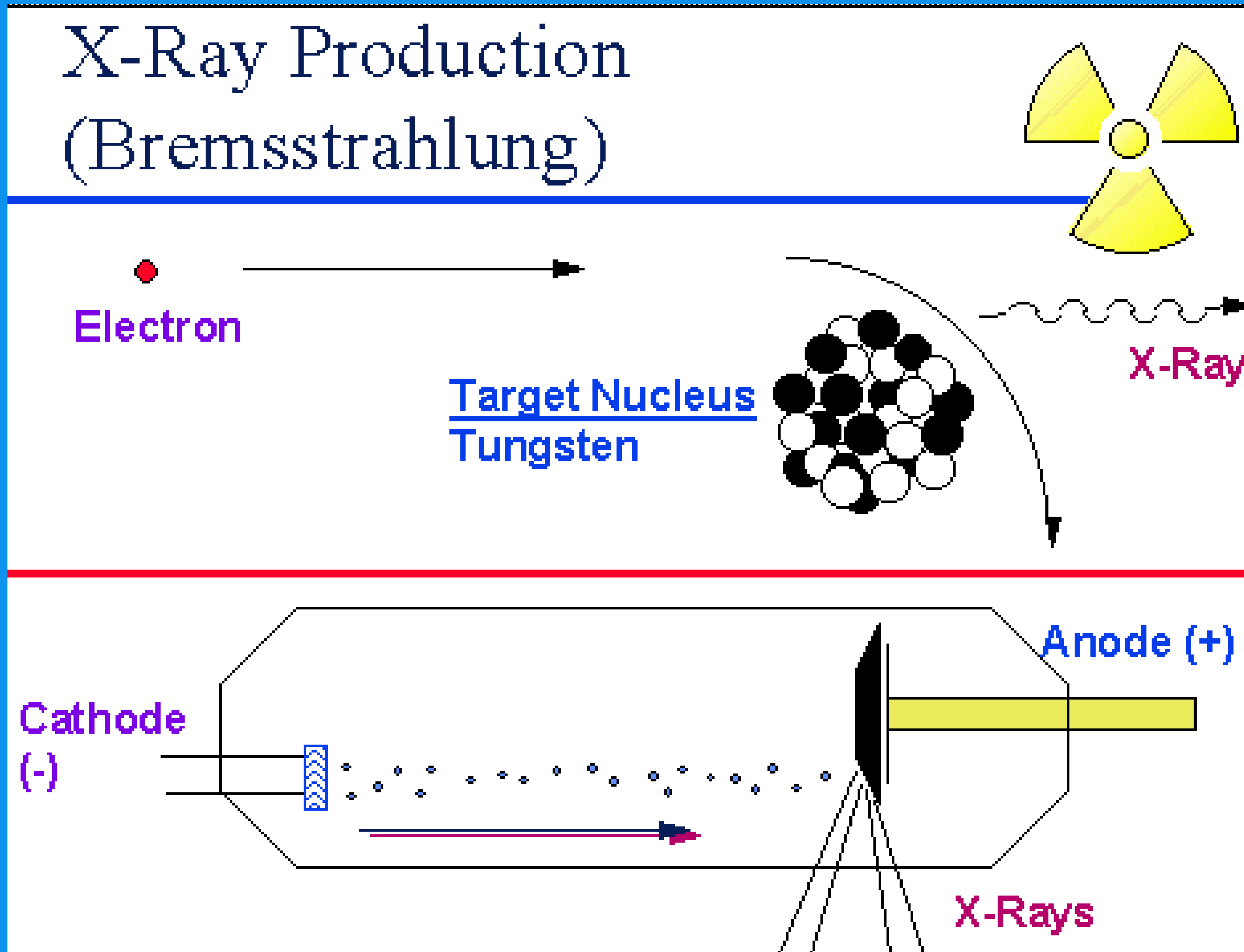
- The peak in energy loss at low energies is exemplified in the Figure, above, which plots -dE/dx of an alpha particle as a function of distance in a material.
- For most of the alpha particle track, the charge on the alpha is two electron charges, and the rate of energy loss increases roughly as 1/E as predicted by the equation for stopping power.
- Near the end of the track, the charge is reduced through electron pickup and the curve falls off.



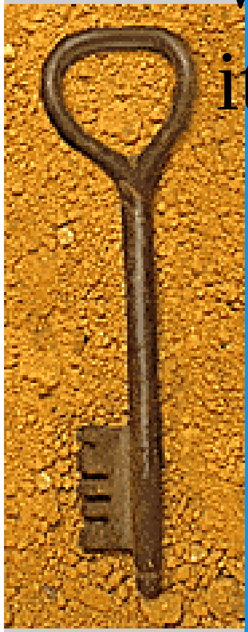
Interaction via Radiation Emission

- Charged particles can also lose their energy through the emission of radiation (vs. energy loss through collision, as just described).
- An accelerating charge, when not bound in a shell, radiates energy (remember Maxwell?).
- This radiation is known as Bremsstrahlung ("breaking radiation"), and the x-ray photons emitted have a range of energies.
- Thus, this *interaction* mechanism is also a *source* of ionizing radiation.
- Bremsstrahlung energy losses typically represent only a very small fraction of the overall energy lost while the charged particle is traveling through matter.
- For example, a .25 MeV electron that is completely stopped in tungsten (Z=74) will lose about 1.1% of its energy via Bremsstrahlung emission. (*Radiation Safety and Control, Volume 2,* French and Skrable, p. 16)
- Bremsstrahlung losses are negligible in a heavy-charged particle unless the particle energy is on the order of the particle's rest-mass energy (~938 MeV for a proton). (*Radiation Safety and Control, Volume 2,* French and Skrable, p. 9)



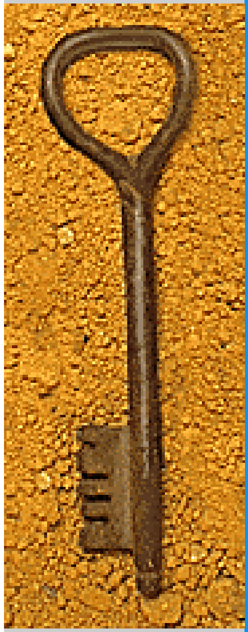


(diagram courtesy of the University of Michigan Student Chapter of the Health Physics Society)



What happens to directly ionizing radiation after it has impinged on a target and delivered energy?

- Eventually, the particle has lost all of its energy and is no more energetic then the particles making up the target.
- Beta particles and electrons eventually slow down to the point that they will be captured by an atom without a full shell, simply becoming part of the atom.
- Alpha particles and protons will slow down to the point that they will simply capture free electrons and become atoms of helium or hydrogen, respectively.



- Thus, after the directly ionizing radiation has lost its energy, it is no longer radiation; it simply becomes part of an atom (beta particles and electrons) or becomes a whole atom (alpha particles and protons) no different from other atoms in the target.

- Bear in mind that we have discussed interactions with the orbital electrons, not the nucleus. Thus, chemical bonds can be broken, and chemical properties altered as a result of exciting the orbital electrons or knocking them from the atom, but nothing is made radioactive. The nucleus is the source of radioactivity, so if it is unaffected by the passage of directly ionizing radiation, then it is not made radioactive, period.