Lecture 22

Fundamentals of Physics

Phys 120, Fall 2015

Nuclear Physics II

A. J. Wagner
North Dakota State University, Fargo, ND 58102

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Overview

- Radioactive decay review
- Half life
- Radioactive dating
- Human exposure to radiation

Nuclear Physics review

Atoms consist of electron clouds ($\approx 10^{-10}m$) surrounding a small nucleus ($\approx 10^{-15}m$).

Each nucleus consists of positively charged protons and electrically neutral neutrons, held together by an attractive proton-proton and proton-neutron force, called the strong force. *There is no strong force between neutrons.*

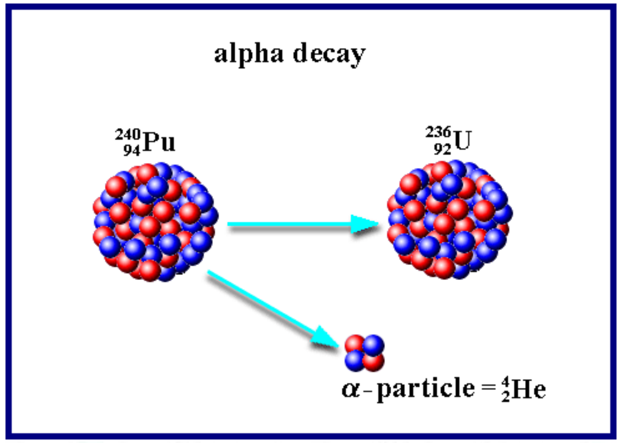
Since the electrical interaction between protons is very repulsive at such short distances, there are no nuclei consisting purely of protons (except ^{1}H) and neutrons are needed to stabilize the nucleus. But only some such combinations of protons and neutrons are stable, others will undergo radioactive decay.

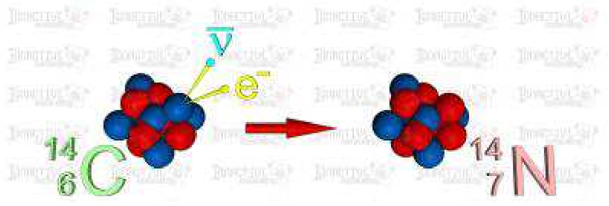
Radioactive decay path

alpha decay: a nucleus emits a particle consisting of two protons and two neutrons. Such an alpha particle will collide with molecules in the air, pick up two electrons and become a Helium atom.

beta decay: here a nucleus emits an electron. This is strange, since there are no electrons in the nucleus. Instead due to the weak force a neutron is transformed into a proton and an electron.

gamma rays: both decay forms above transform a nucleus to a nucleus of lower energy. The excess energy is emitted in form of a high energy **gamma ray photon**, similar to the emission of radiation when electrons take on a different quantum state.





Examples

$$^{14}_{6}C \rightarrow\ ^{14}_{7}N + \text{beta}$$

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

Energy:

nuclear energy → thermal energy + **radiant energy**

Concept check

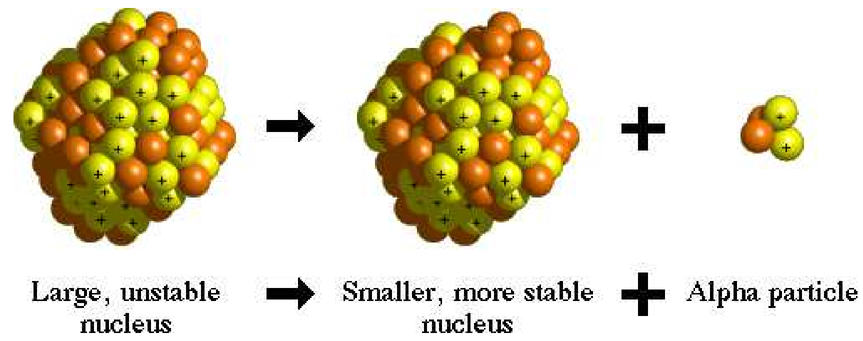
When radioactive iodine ($^{131}_{53}I$) beta-decays, the daughter nucleus is
a) $^{127}_{51}Sb$; b) $^{132}_{53}I$; c) $^{132}_{54}Xe$; d) $^{131}_{54}Cs$; e) $^{131}_{54}Xe$;

Half-life: when does a nucleus decay?

Nuclei are quantum mechanical objects, and their decay is a quantum process. As we have seen, such events are fundamentally unpredictable, but their overall statistics is predictable.

Compare this to flipping a coin: You don't know what the outcome is, but you know that the probability of getting heads up is 50%. Except that in a coin-flip the result is in principle predictable from Newtonian mechanics if you know exactly how you threw the coin. The decay of a nucleus is inherently unpredictable, and it is the prime example of a truly random process.

Alpha decay of uranium



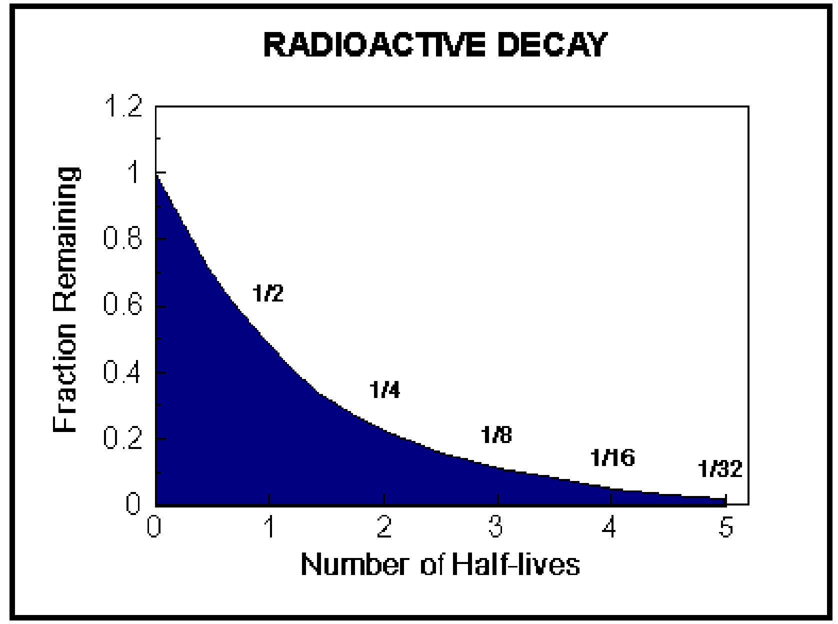
Think of a larger nucleus as a collection of alpha-particles moving near the surface. Each alpha particle is a matter wave with an uncertain position. So there is a chance that an alpha particle will find itself outside of the nucleus. When that happens it will be outside the reach of the strong nuclear force and electric forces will repel the positively charged alpha-particle from the positively charged nucleus.

Because of the quantum uncertainties nature knows about the chances that an alpha particle will be ejected, but not when it will be ejected. It may decay in 1s, 10 years or 100 billion years! Only for a large selection of atoms can we make statements about how many will have decayed in a certain amount of time.

Half-life

The most important feature of a nucleus is its **half-life**, that is the time after which half of a large collection of nuclei have decayed. Because some nuclei are much more stable than others different isotopes have widely different half-lives.

Example: The radioactive carbon isotope ^{14}C has a half-live of 6000 years. Assume you have one gram of ^{14}C. After 6000 years half of the carbon atoms will have beta-decayed to ^{14}N, the stable form of Nitrogen, so you will have half a gram left. After another 6000 years half of those atoms will have decayed so that you are left with 1/4 gram of ^{14}C.



Radioactive decay curve for any radioactive nucleus expressed in half-lives. For ^{14}C one half-live would be 6000 years, two half-lives would be 12,000 years, three half-lives would be 18,000 years and so on.

Half-life table

TABLE 22.2 Half-lives of Some Useful Radioisotopes

Radioisotope	Symbol	Radiation	Half-life	Use
Tritium	$^{3}_{1}H$	β^-	12.33 years	Biochemical tracer
Carbon-14	$^{14}_{6}C$	β^-	5730 years	Archaeological dating
Phosphorus-32	$^{32}_{15}P$	β^-	14.26 days	Leukemia therapy
Potassium-40	$^{40}_{19}K$	β^-	1.28×10^9 years	Geological dating
Cobalt-60	$^{60}_{27}Co$	β^-, γ	5.27 years	Cancer therapy
Technetium-99*m**	$^{99m}_{43}Tc$	γ	6.01 hours	Brain scans
Iodine-123	$^{123}_{53}I$	γ	13.27 hours	Thyroid therapy
Uranium-235	$^{235}_{92}U$	α, γ	7.04×10^8 years	Nuclear reactors

*The m in technetium-99m stands for metastable, meaning that it undergoes gamma emission but does not change its mass number or atomic number.

Making estimates

Starting with 100 pennies, suppose you toss all of them and remove the ones that come up tail. You toss the remaining coins and again remove the tails. If you continue the process, about how many tosses must you make before you get down to a single penny?

What is the half-life of pennies in this game?

Concept check

Suppose that a radioactive substance has decayed until only 1/64th of it remains. For how many half-lives has it been decaying?

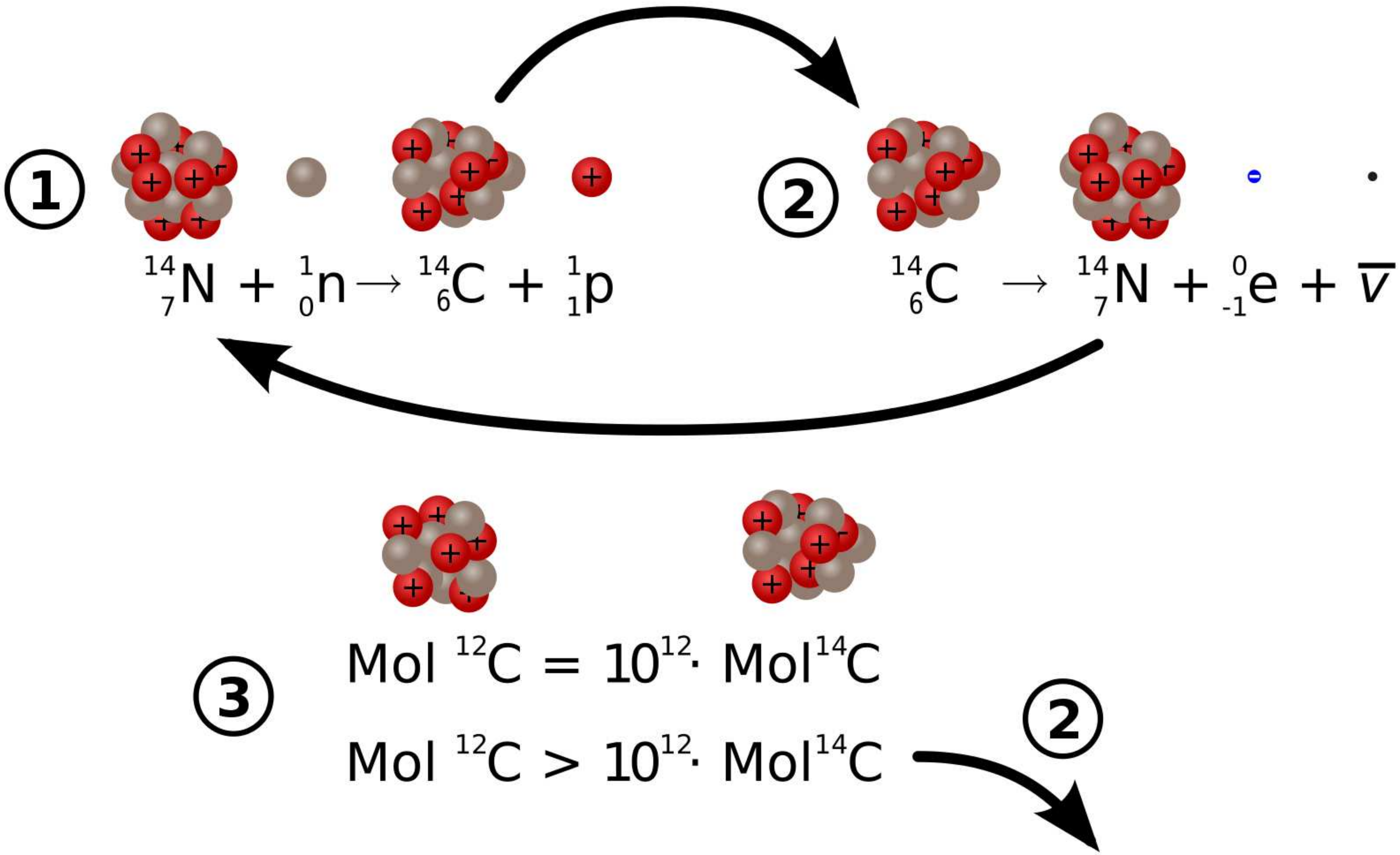
a) 2
b) 3
c) 4
d) 5
e) 6
f) 7

Radioactive dating: how old are things?

Almost all of the worlds carbon is in the form of ^{12}C and ^{13}C, the stable isotopes, but about one in a trillion (10^{12}) is ^{14}C.

Since the half-live of ^{14}C is about 6000 years and the earth is $4.5 \cdot 10^9$ years old you may wonder why there is still any radioactive carbon left in the atmosphere. The answer is: it is continually replenished through **cosmic rays**.

Creation of ^{14}C through cosmic rays



Concept Check

If there was no creation of ^{14}C, what would have been the original composition of the carbon isotopes when the earth was formed?

(a) 1% of the carbon would have been ^{14}C.
(b) 50% of the carbon would have been ^{14}C.
(c) 99% of the carbon would have been ^{14}C.
(e) There would have to have been more ^{14}C than there are atoms in the universe.

Answer

Today there are

$$\frac{{}^{14}C}{{}^{12}C + {}^{13}C} = 10^{-12} \tag{1}$$

How many half lives ago was the earth formed?

$$\frac{4.5 \cdot 10^9}{6 \cdot 10^3} \approx 7.5 \cdot 10^5 \tag{2}$$

So how much more ${}^{14}C$ would have existed $7.5 \cdot 10^5$ half-lives ago?

$$2^{750000} \approx 10^{226000} \tag{3}$$

and then there would have been

$$10^{-12} \times 7.5 \cdot 10^{226000} = 7.5 \cdot 10^{225988} \tag{4}$$

${}^{14}C$ atoms which makes no sense...

How big is this number? What weight would this correspond to?

Answer: how big is that number?

Let us try to express this in fractions of the mass of the earth. The total mass is

$$7.5 \cdot 10^{225988} \times 14 \times 1.66 \cdot 10^{-27} kg \approx 1.74 \cdot 10^{225963} \quad (5)$$

Compared to the mass of the earth this is

$$\frac{1.74 \cdot 10^{225963} kg}{6 \cdot 10^{24} kg} = 2.9 \cdot 10^{225938} \quad (6)$$

How about compared to the mass in our galaxy? Our galaxy is estimated to contain a mass of about $6 \cdot 10^{11}$ solar masses.

$$\frac{1.74 \cdot 10^{225963} kg}{6 \cdot 10^{11} \times 2 \cdot 10^{30} kg} = 1.4 \cdot 10^{225921} \quad (7)$$

How about compared to the mass of the universe (which is estimated at $3 \cdot 10^{52} kg$)?

^{14}C in biological tissue

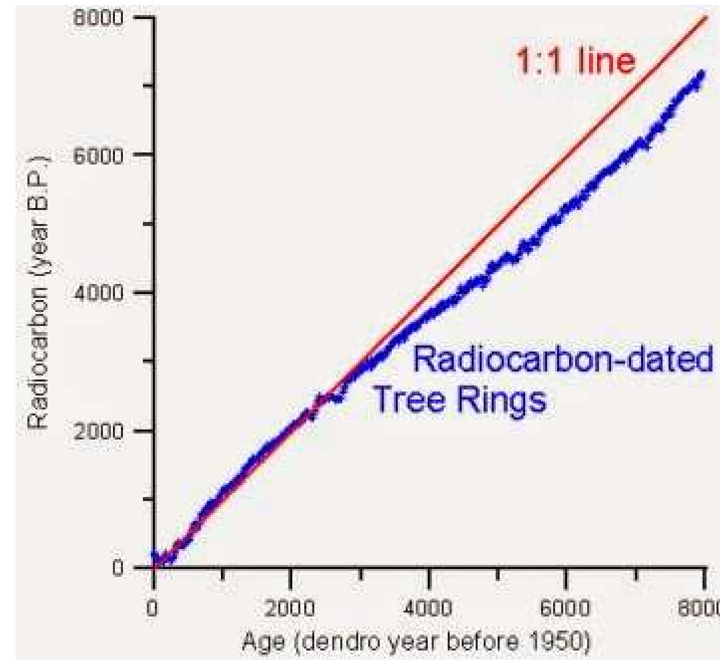
Biological tissue consists of bio-molecules, all of which have a high carbon content. All of this carbon comes originally from the atmosphere. In the atmosphere ^{14}C continuously decays and is replenished so that the ratio of carbon 14 to stable carbon remains 1 in 1 trillion.

Once a living organism dies the carbon is no longer exchanged and the decaying ^{14}C is no longer replenished. So the proportion of radioactive carbon contained in dead bio-matter decrease over time. This decrease can be used to date objects.

C14 versus tree ring dating

The assumption underlying C14 dating is that the concentration of C14 has remained constant over time. How do we know that this is right? The trick is to compare different dating methods and to see if the results are consistent. If all the dating methods give the same answer we will be likely to trust them, and the difference that the different methods have give us an idea of the potential error in these methods.

One very exact measurement technique is counting tree rings. Some of the oldest trees are 5000 years old, and because the width of a tree ring is very similar for different trees growing in the same region this set of data can be brought back to about 10,000 years.



Concept check

In a living person, the ratio of ^{14}C to total carbon is 1 to one trillion. The $^{14}C/C$ ratio 6000 years (one half-life of ^{14}C) after a person has died is

a) 2 to one trillion;

b) 1 to one trillion;

c) 1 to two trillion;

d) 1 to four trillion;

Concept check

An archaeologist digs up a bone and measures and average of one ^{14}C decay per minute in 1 gram of the bone's carbon. This is about 10% of the decay rate in living organisms. The animal has been dead about

a) 6000 years;
b) 13,000 years;
c) 19,000 years;
d) 60,000 years;
e) 600 years.

Age of the Earth

I earlier quoted the age of the earth as 4.5 billion years. But how do we know that?

William Thomson (Lord Kelvin) estimated the age of the earth by looking at the rate of cooling of the earth. The earth is constantly radiating heat from its hot core to the atmosphere, and assuming that it started as a ball of molten lava, and given the current temperature, he estimated the age of the earth to be somewhere between 20 and 400 million years.

This sat poorly with Charles Darvin, because this scarcely left enough time for evolution, but how could the calculation have been wrong?

After the Curies discovered radioactivity they noticed that nuclear decay events will release a significant amount of heat, and this heat release causes the earth to cool much more slowly.

Age of the earth: new measurements

There is a measurement technique that relies on a similar idea to carbon dating: once a uranium containing rock solidifies the stable product of the decay of uranium which is lead will accumulate. And if you assume that there was no lead initially the ratio of lead to uranium will give you an estimate for the age of the rock, and you know that the earth has to be older than the oldest rock you can find. That brings you into the billions of year range for the age of the earth.

There are more detailed measurements today which use meteors to calibrate the original composition of the earth, and these measurements arrive at

$$Age\ of\ earth \approx 4.5\ 10^9 years \tag{8}$$

Radioactivity and humans

Radioactivity can affect humans. This is because atoms that undergo nuclear reactions will typically destroy any chemical compounds that they are a part of.

This can happen when an atom is hit by radiation. Most dangerous is γ-radiation, because it can penetrate more deeply into tissue.

Another danger occurs if radioactive isotopes are ingested and metabolized into chemical compounds instead of their non-radioactive cousins.

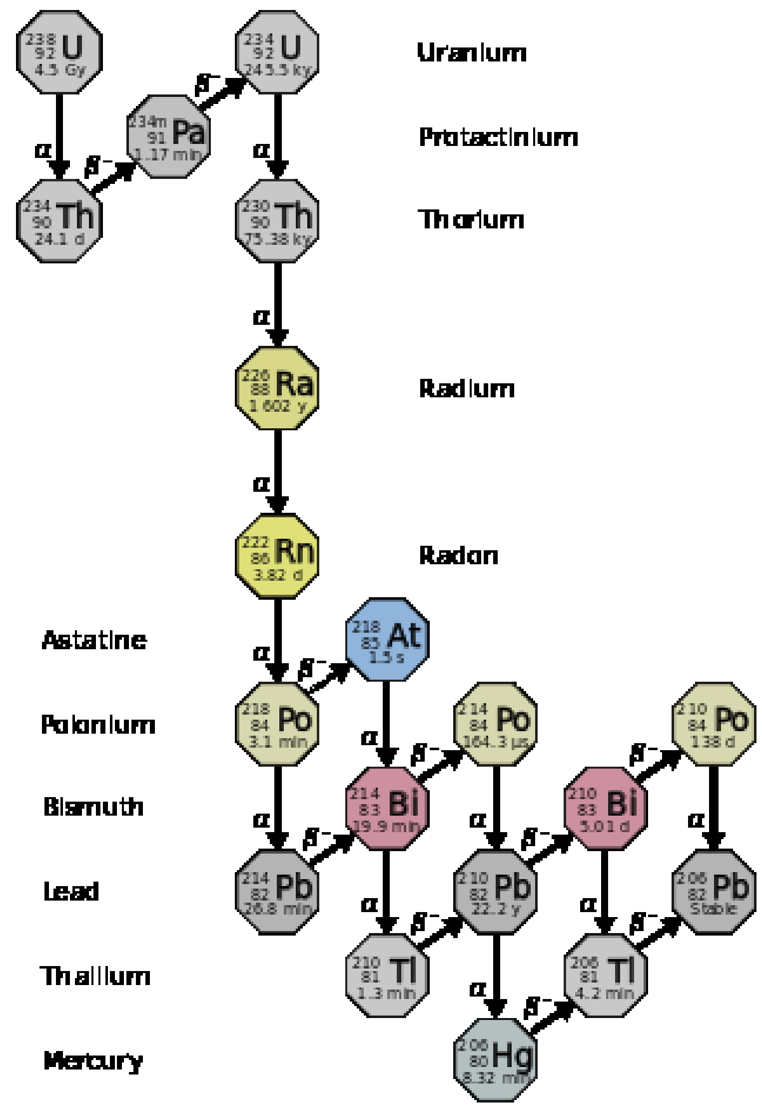
Human exposure to Radioactivity

- Radon in your basement
- Exposure to radiation (x-rays, radiation treatment)
- Cosmic rays (particularly when you are flying).
- Nuclear fallout

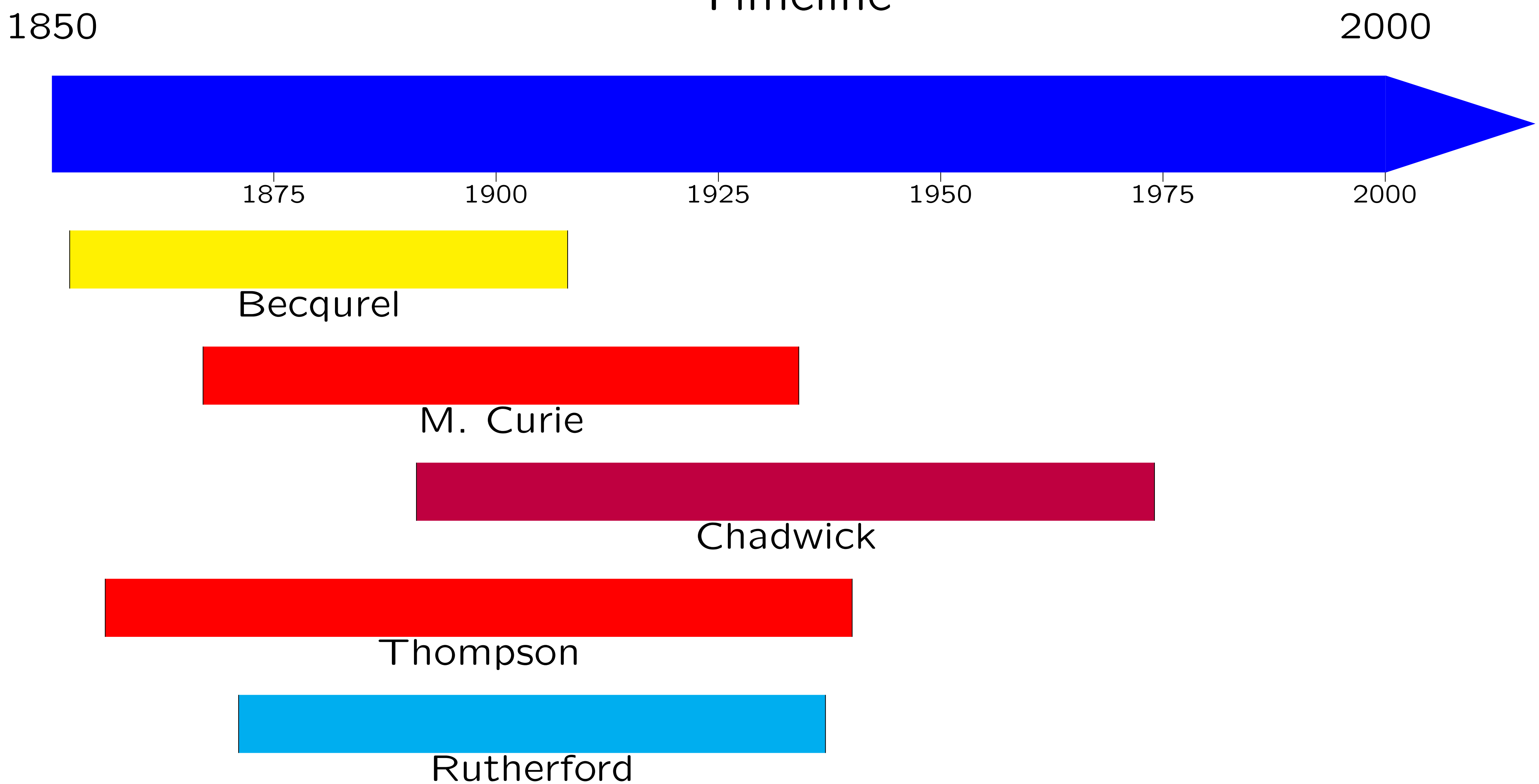
Radon

Source

The great majority of the radiation dose is not from radon itself, but from the short-lived alpha particle-emitting radon daughters, most notably ^{218}Po (radioactive $T^{1/2}$ =3 minutes), and ^{214}Po (radioactive $T^{1/2}$ =0.164 milliseconds), along with beta particles from ^{214}Bi ($T^{1/2}$ =19.7 minutes). [$T^{1/2}$ is physical half-life].



Timeline


1850
2000
1875
1900
1925
1950
1975
2000
Becqurel
M. Curie
Chadwick
Thompson
Rutherford

Summary

- Alpha, beta, and gamma decay
- Half-life of unstable nuclei
- Carbon dating
- Age of the Earth