

# **Radiation / Radioactivity / Radioactive Decay**

## **Radioactive Particles / Common Isotopes**

### **Counting**

---

**History – Discovery of X-rays / Radioactivity / Nuclear atom**

**Radioactive Decay – particles, half-life and equations**

**Radioactivity – the Nuclear atom / trip to the “Particle Zoo”**

**Counting: Film / Geiger Counter / LSC / PI**

**Common Radio isotopes / C Isotopes – C-12 / C-13 / C-14**

**C-14 and radiocarbon dating**

---

**Nuclear Energy - fission and fusion**

**Terms: Radioactivity / Exposure / Dose**



## The Nobel Prize in Physics 1901

"in recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him"



**Wilhelm Conrad Röntgen**

Germany

Munich University  
Munich, Germany

b. 1845  
d. 1923

Sept. 1895 - Marconi (radio waves / wireless)

Nov. 8, 1895 - Rontgen (discovery of X-rays)

Feb. 24, 1896 – Becquerel (U luminesce")

(Feb. 26, 27 - cloudy days)

(Mar. 1 - "radioactivity")

1897 - JJ Thomson (discovery of electrons)

1898 – Pierre & Marie Curie (Po, Ra)

1898 – Rutherford ( $\alpha$  and  $\beta$  radiation)

1902 – Rutherford (disintegration of elements)

1911 – Rutherford (Au foil exp. / nuclear atom)

1912 – von Laue (X-rays as waves)

**1913 Braggs – 1<sup>st</sup> crystal structure**

1920 – Rutherford (predicts neutron)



## The Nobel Prize in Physics 1903

"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity"

"in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel"

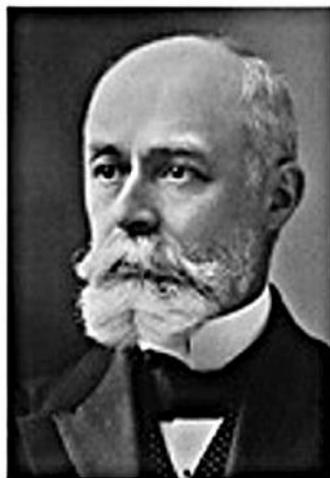
Marie and Pierre Curie



Marie Skłodowska-Curie  
1867-1934



Pierre Curie  
1859-1906



**Antoine Henri Becquerel**

🕒 1/2 of the prize  
France



**Pierre Curie**

🕒 1/4 of the prize  
France

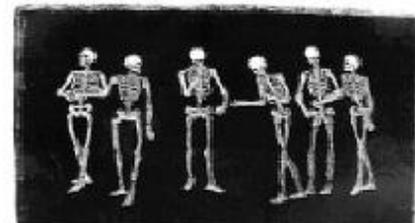


**Marie Curie, née Skłodowska**

🕒 1/4 of the prize  
France



Reproduction of an X-ray.  
The white color indicates the bones, which are the most dense parts of the body. The black color indicates the soft parts of the body, which are the least dense.



See "Women in Chemistry" in our S 2000 "Chemical Compositions" newsletter, p.4)



## The Nobel Prize in Physics 1906

"in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases"



**Joseph John Thomson**

United Kingdom

University of Cambridge  
Cambridge, United Kingdom

b. 1856

d. 1940

Sept. 1895 - Marconi (radio waves / wireless)

Nov. 8, 1895 - Rontgen (discovery of X-rays)

Feb. 24, 1896 – Becquerel (U luminesce”)

(Feb. 26, 27 - cloudy days)

(Mar. 1 - “radioactivity”)

1897 - JJ Thomson (discovery of electrons)

1898 – Pierre & Marie Curie (Po, Ra)

1898 – Rutherford ( $\alpha$  and  $\beta$  radiation)

1902 – Rutherford (disintegration of elements)

1911 – Rutherford (Au foil exp. / nuclear atom)

1912 – von Laue (X-rays as waves)

**1913 Braggs – 1<sup>st</sup> crystal structure**

1920 – Rutherford (predicts neutron)



## The Nobel Prize in Chemistry 1908

"for his investigations into the disintegration of the elements, and the chemistry of radioactive substances"



**Ernest Rutherford**

United Kingdom and New Zealand

Victoria University  
Manchester, United Kingdom

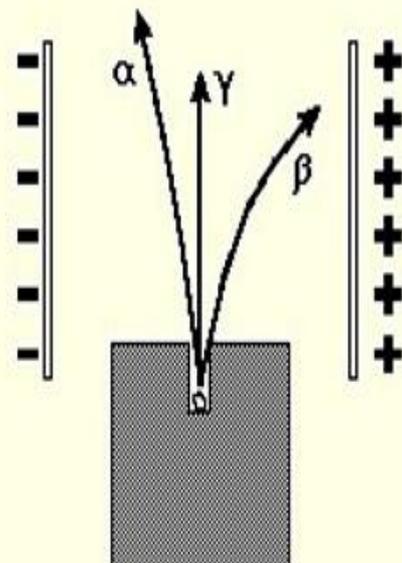
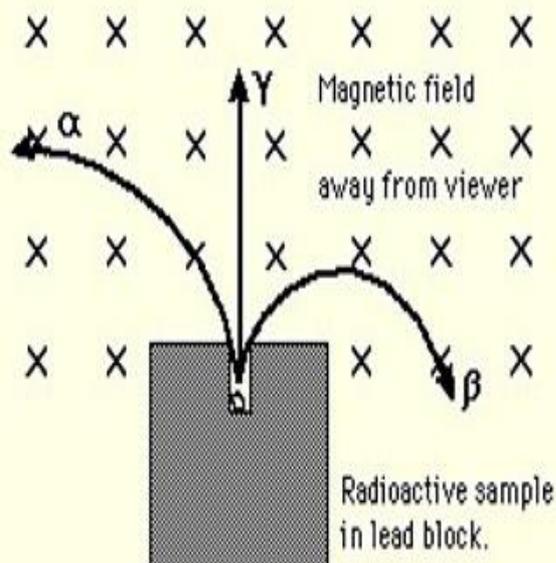
b. 1871

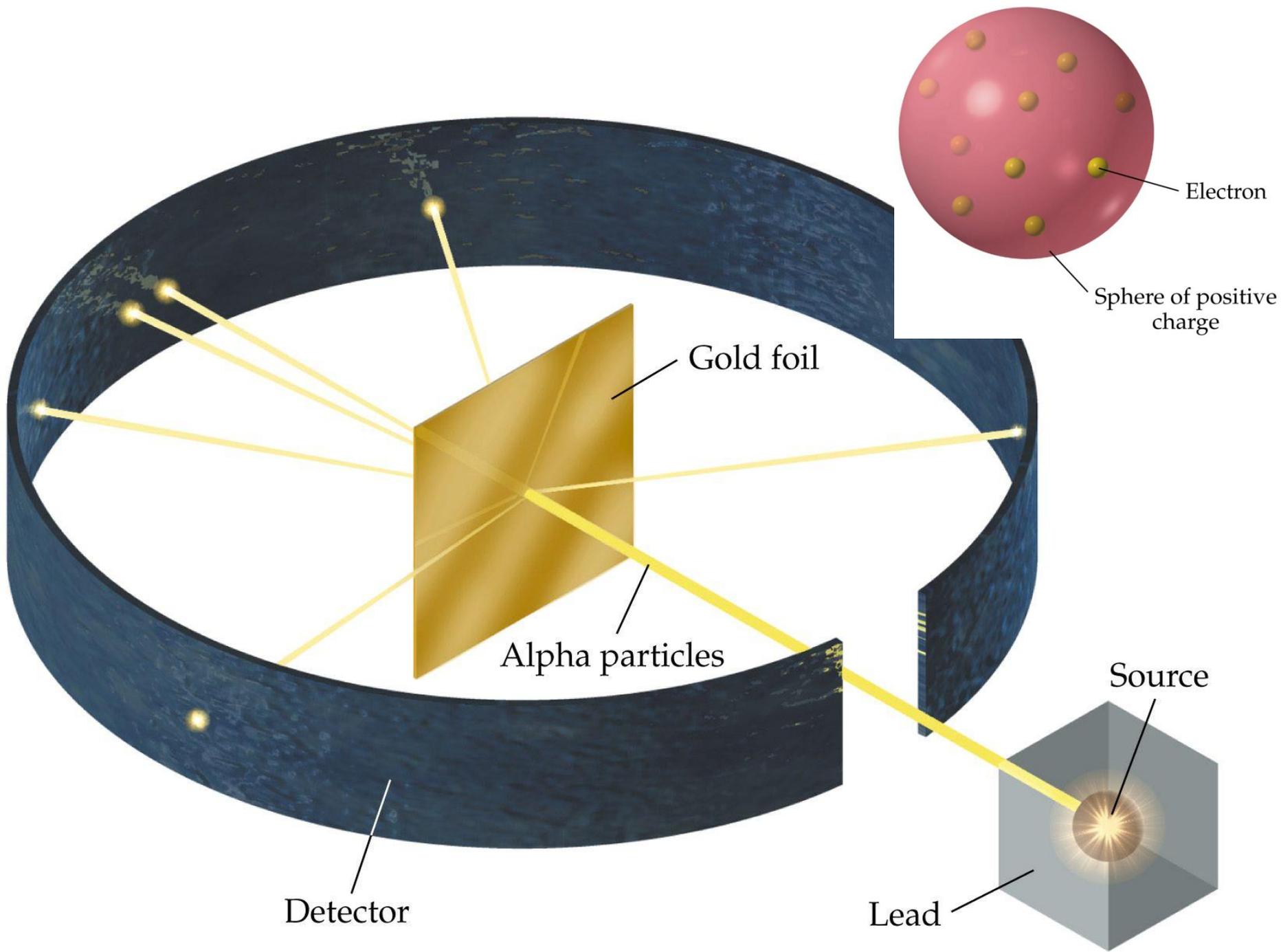
(in Nelson, New Zealand)

d. 1937

## Alpha, Beta, and Gamma

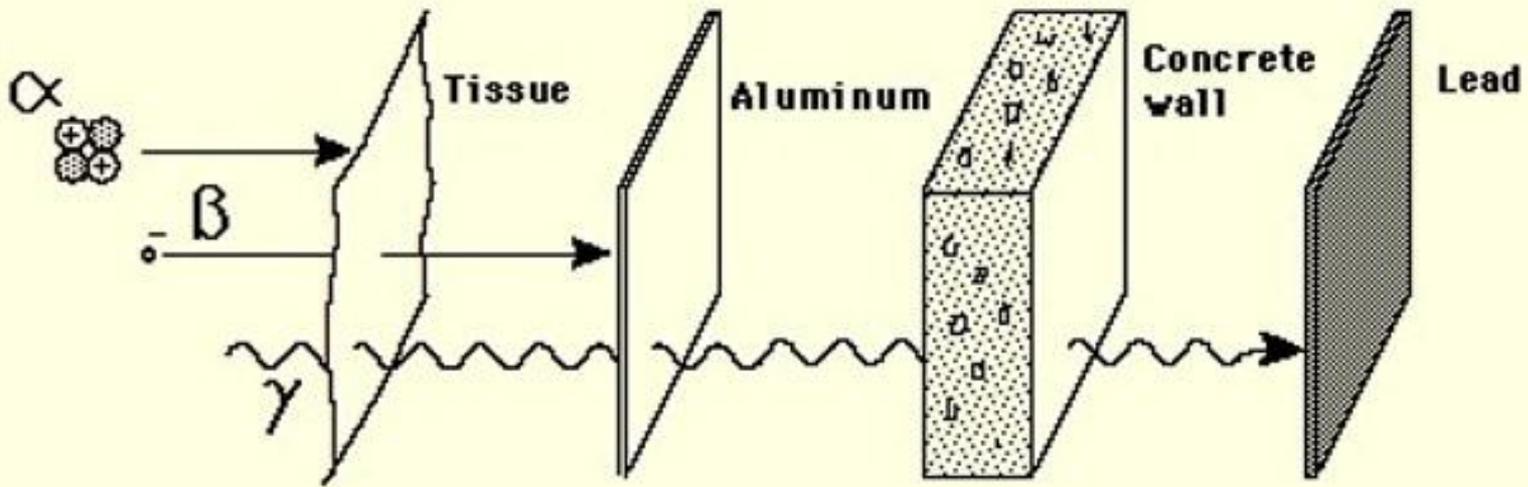
Historically, the products of radioactivity were called alpha, beta, and gamma when it was found that they could be analyzed into three distinct species by either a magnetic field or an electric field.





# Penetration of Matter

Though the most massive and most energetic of radioactive emissions, the alpha particle is the shortest in range because of its strong interaction with matter. The electromagnetic gamma ray is extremely penetrating, even penetrating considerable thicknesses of concrete. The electron of beta radioactivity strongly interacts with matter and has a short range.

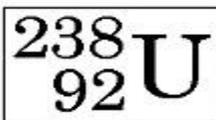


$$I = I_0 e^{-\lambda t}$$

Rutherford – quantitative measurements

Mass Number = #p + #n

Atomic Number = # protons



# Radioactive Decay

Remember that the lower number is the atomic number and the upper number is the mass number.

## Alpha Decay

In 1899, Ernest Rutherford wrote the following words:

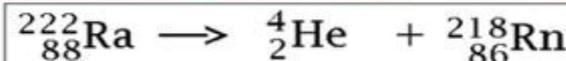
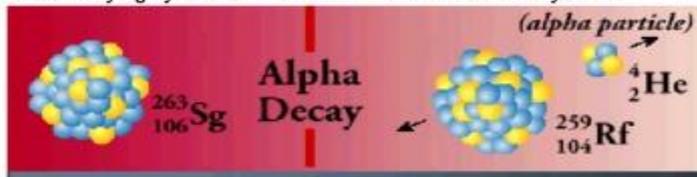
"These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation - one that is very readily absorbed, which will be termed for convenience the alpha-radiation, and the other of more penetrative character which will be termed the beta-radiation."

The image to the right is of a twenty-eight year old Ernest Rutherford while at McGill University in 1899.

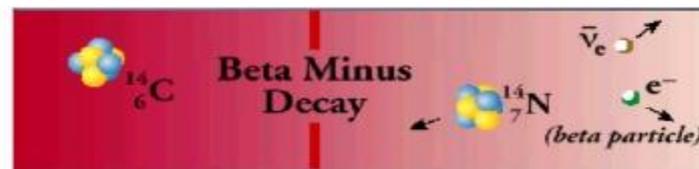


**Ernest Rutherford  
1899**

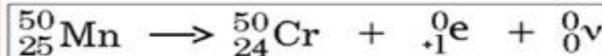
**Alpha**



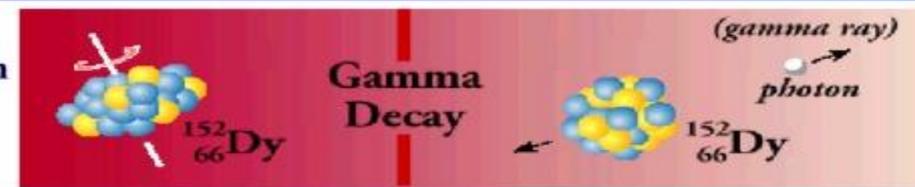
**Beta -**



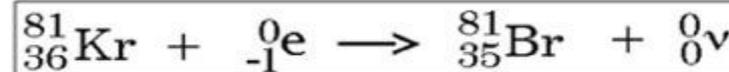
**Beta +  
(positron)**



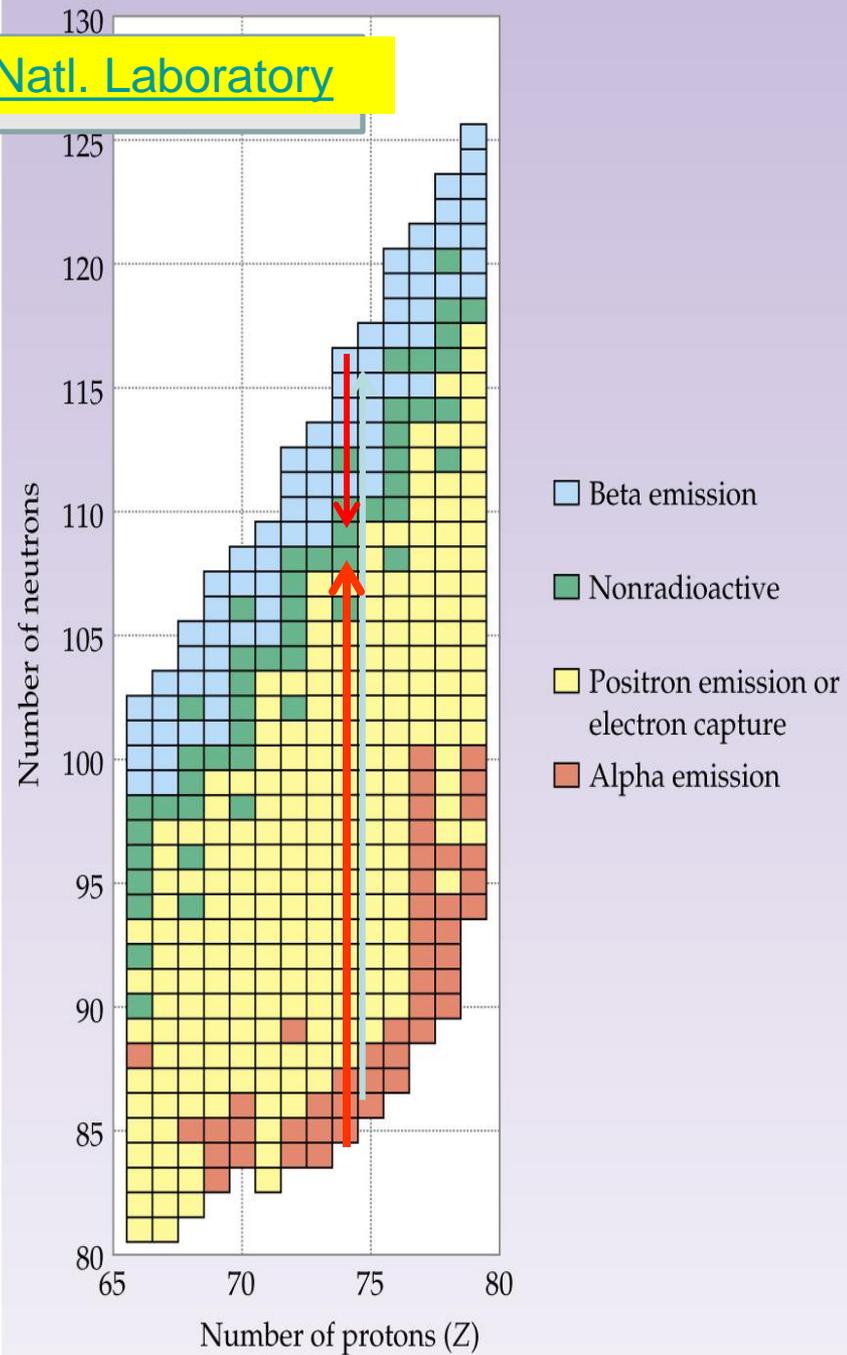
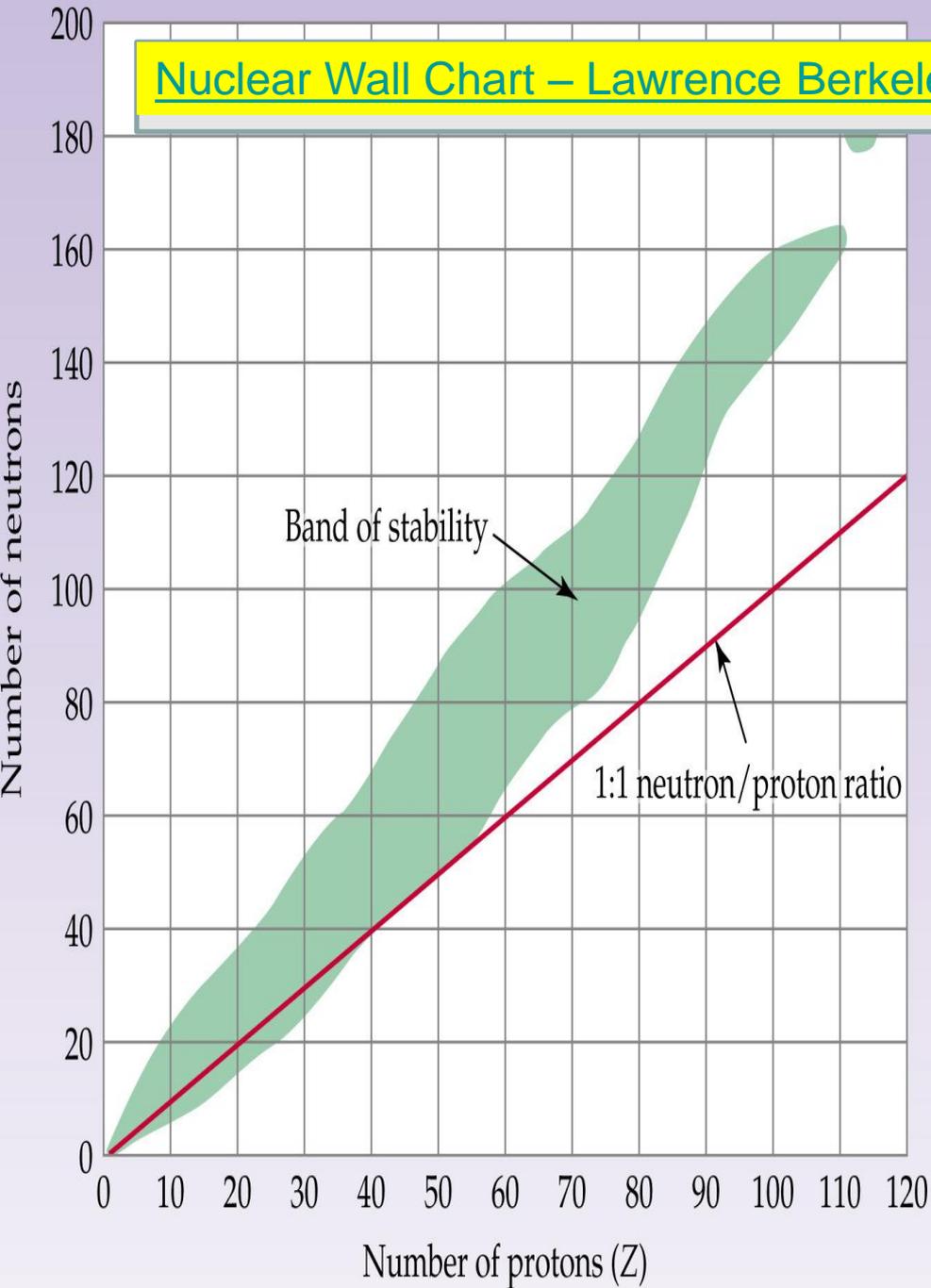
**Gamma  
Emission**



**Electron  
Capture**



# Nuclear Wall Chart – Lawrence Berkeley Natl. Laboratory



# What is a "half-life"?

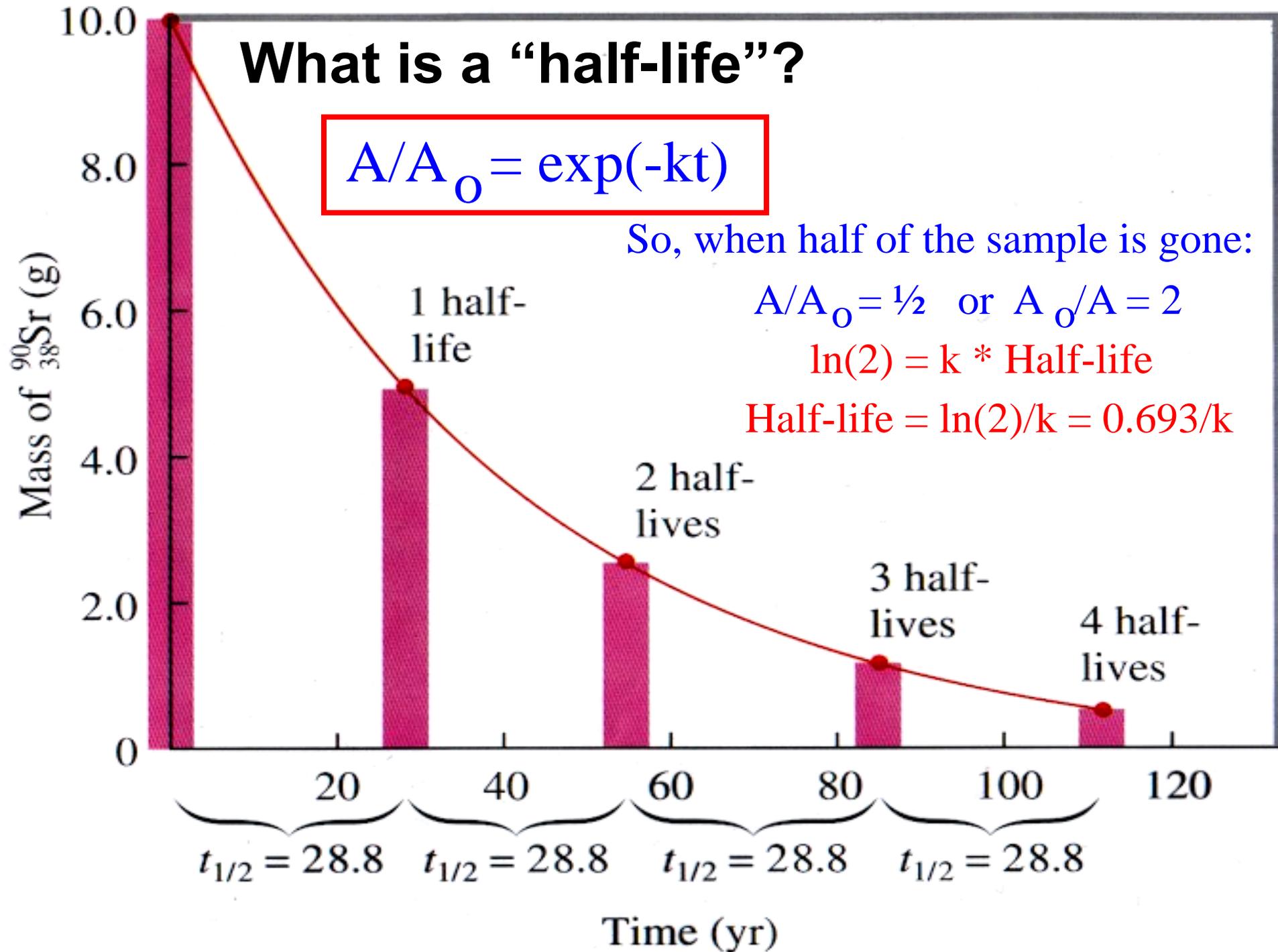
$$A/A_0 = \exp(-kt)$$

So, when half of the sample is gone:

$$A/A_0 = 1/2 \quad \text{or} \quad A_0/A = 2$$

$$\ln(2) = k * \text{Half-life}$$

$$\text{Half-life} = \ln(2)/k = 0.693/k$$



# Characteristics of Biologically Significant Isotopes

**TABLE 6-1. Half-life, decay constant, type of radiation, and maximum energy of radioisotopes important in biochemistry**

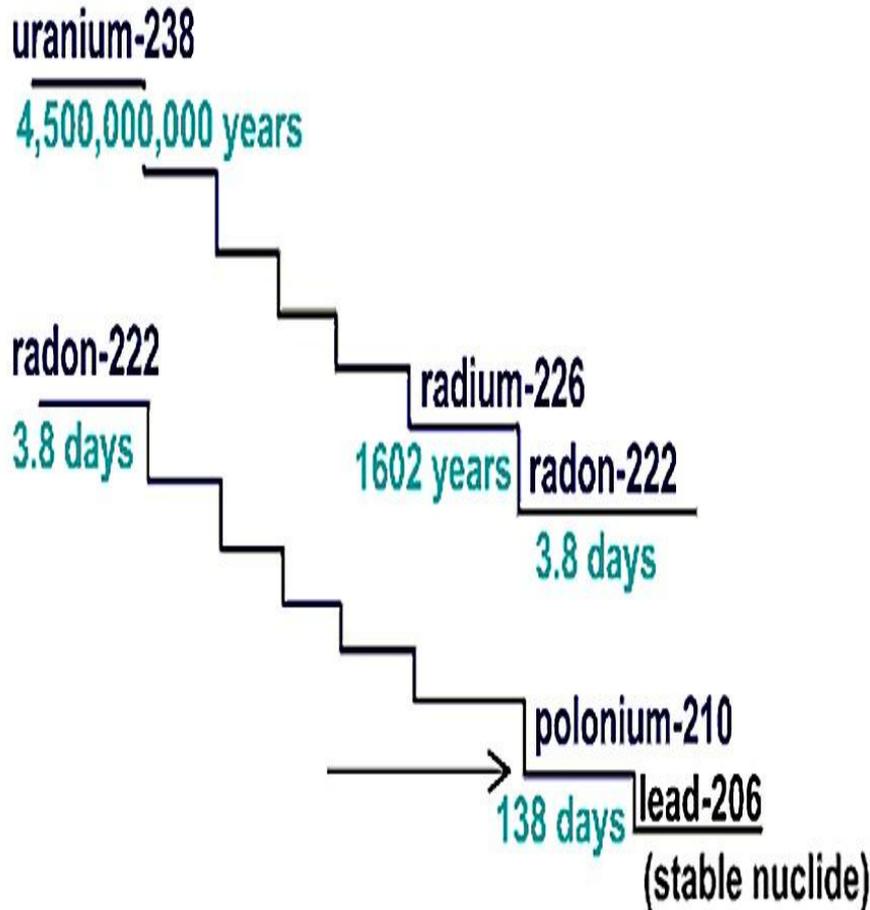
Isotope	Half-life	Decay constant ( $\lambda$ )	Type of radiation	Maximum energy (MeV)
$^3\text{H}$	12.26 yrs	$1.55 \times 10^{-4}/\text{day}$	$\beta^-$	0.018
$^{14}\text{C}$	5730 yrs	$1.21 \times 10^{-4}/\text{year}$	$\beta^-$	0.156
$^{22}\text{Na}$	2.62 yrs	$7.24 \times 10^{-4}/\text{day}$	$\beta^+ + \gamma$	0.55 (1.28) <sup>a</sup>
$^{32}\text{P}$	14.3 days	$4.85 \times 10^{-2}/\text{day}$	$\beta^-$	1.71
$^{33}\text{P}$	25 days	$2.77 \times 10^{-2}/\text{day}$	$\beta^-$	0.25
$^{35}\text{S}$	87 days	$7.97 \times 10^{-3}/\text{day}$	$\beta^-$	0.167
$^{36}\text{Cl}$	$3 \times 10^5$ yrs	$2.31 \times 10^{-6}/\text{year}$	$\beta^-$	0.71
$^{40}\text{K}$	$1.3 \times 10^9$ yrs	$5.33 \times 10^{-10}/\text{year}$	$\beta^- + \gamma$	1.4 (1.5)
$^{45}\text{Ca}$	165 days	$4.2 \times 10^{-3}/\text{day}$	$\beta^- + \gamma$	0.26 (0.013)
$^{59}\text{Fe}$	45 days	$1.54 \times 10^{-2}/\text{day}$	$\beta^- + \gamma$	0.46 (1.1)
$^{60}\text{Co}$	5.3 yrs	$3.58 \times 10^{-4}/\text{day}$	$\beta^- + \gamma$	0.318 (1.33)
$^{65}\text{Zn}$	245 days	$2.83 \times 10^{-3}/\text{day}$	$\beta^+ + \gamma$	0.33 (1.14)
$^{90}\text{Sr}$	29 yrs	$6.54 \times 10^{-5}/\text{day}$	$\beta^-$	0.54
$^{125}\text{I}$	60 days	$1.16 \times 10^{-2}/\text{day}$	$\gamma$	0.036
$^{131}\text{I}$	8.06 days	$8.60 \times 10^{-2}/\text{day}$	$\beta^- + \gamma$	0.61 (0.36)
$^{137}\text{Cs}$	30.2 yrs	$6.28 \times 10^{-5}/\text{day}$	$\beta^- + \gamma$	0.51 (0.66)
$^{226}\text{Ra}$	1620 yrs	$4.28 \times 10^{-4}/\text{year}$	$\alpha + \gamma$	4.78 (0.19)

<sup>a</sup> Where two types of radiation occur, the number in parentheses is the maximum energy for the second type of radiation.

$$t_{1/2} = \frac{0.693}{\lambda}$$

$$I = I_0 e^{-\lambda t}$$

## Uranium-238 Decay Chain

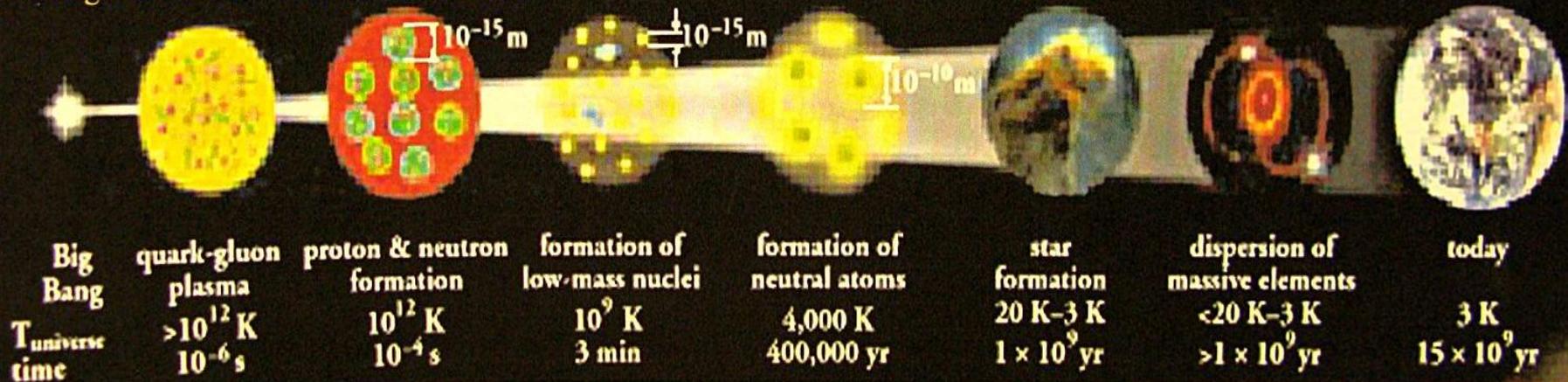


## URANIUM 238 (U238) RADIOACTIVE DECAY

type of radiation	nuclide	half-life
	uranium—238	$4.5 \times 10^9$ years
$\alpha$	↓	
	thorium—234	24.5 days
$\beta$	↓	
	protactinium—234	1.14 minutes
$\beta$	↓	
	uranium—234	$2.33 \times 10^5$ years
$\alpha$	↓	
	thorium—230	$8.3 \times 10^4$ years
$\alpha$	↓	
	radium—226	1590 years
$\alpha$	↓	
	radon—222	3.825 days
$\alpha$	↓	
	polonium—218	3.05 minutes
$\alpha$	↓	
	lead—214	26.8 minutes
$\beta$	↓	
	bismuth—214	19.7 minutes
$\beta$	↓	
	polonium—214	$1.5 \times 10^{-4}$ seconds
$\alpha$	↓	
	lead—210	22 years
$\beta$	↓	
	bismuth—210	5 days
$\beta$	↓	
	polonium—210	140 days
$\alpha$	↓	
	lead—206	stable

# Expansion of the Universe

After the BIG BANG, the universe expanded and cooled. After about  $10^{-6}$  sec and temperatures over  $10^{12}$  K, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. After about  $10^{-4}$  sec and about  $10^{12}$  K, this soup coalesced into protons, neutrons, and electrons. After about 3 min and cooling to  $10^9$  K, some of the protons and neutrons formed light nuclei like deuterium, helium and lithium. Further cooling and at about 400,000 years, electrons combined with the light nuclei to form small, neutral atoms. With further cooling and gravity clouds of atoms contracted to form stars where H and He fused to form heavier elements. Exploding stars (supernovae) form even more massive elements and disperse them across space. Earth is thought to have formed from such debris.



Nuclear Wall Chart - Lawrence Berkeley National Laboratory  
Contemporary Physics Education Project (CPEP)

## The Standard Model

In the Standard Model of particles and forces, everything in the Universe is made from **twelve basic building blocks** called **fundamental particles**, governed by **four fundamental forces**.



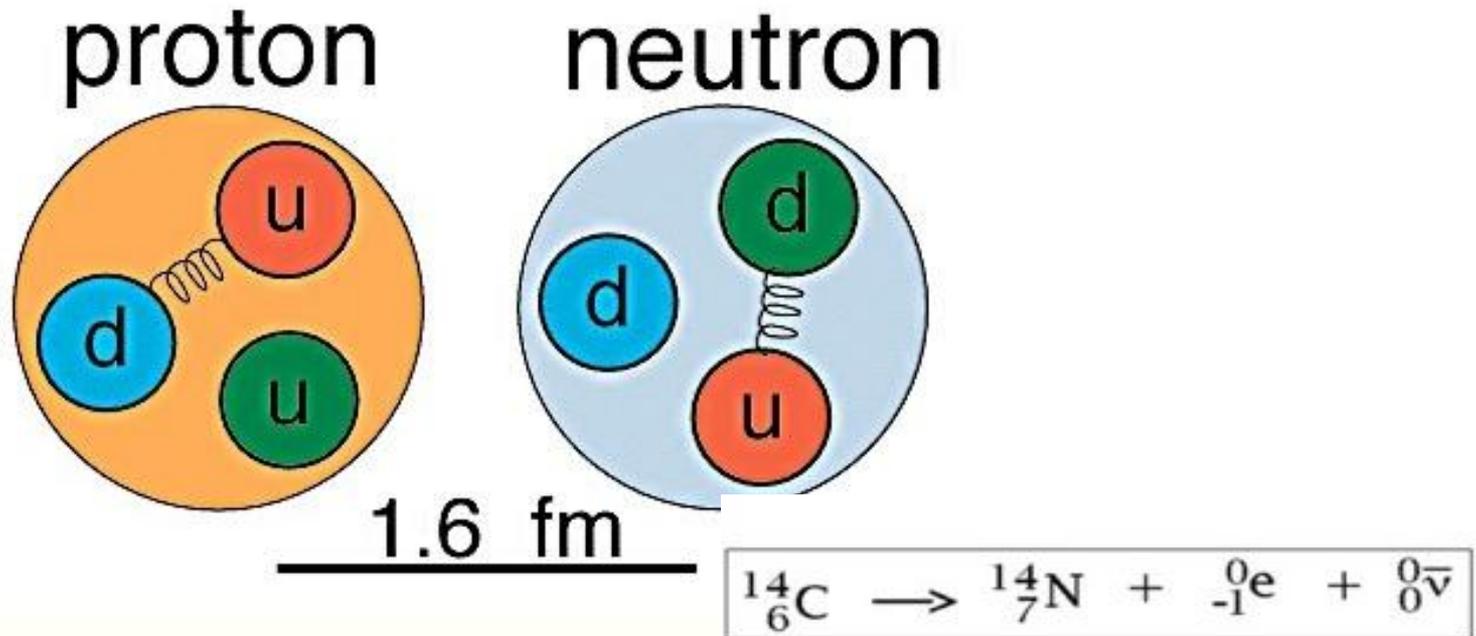
### Matter particles

Everything around us is made of matter particles in two basic types called **quarks** and **leptons**. All stable matter in the Universe is made from first generation particles; the 'up quark', 'down quark', electron, e-neutrino. Neutrinos are electrically neutral with very little mass.

### Forces and carrier particles

There are four fundamental forces at work in the Universe: the strong force, the weak force, the electromagnetic force, and the gravitational force. They work over different ranges and have different strengths. Gravity is the weakest but it has an infinite range. The weak and strong forces are effective only over a very short range and dominate only at the level of subatomic particles.

**Protons and Neutrons (Hadrons) are both made up of Quarks. In the Quark Model the only difference between a Proton and a Neutron is that an “up” Quark has been replaced by a “down” Quark.**

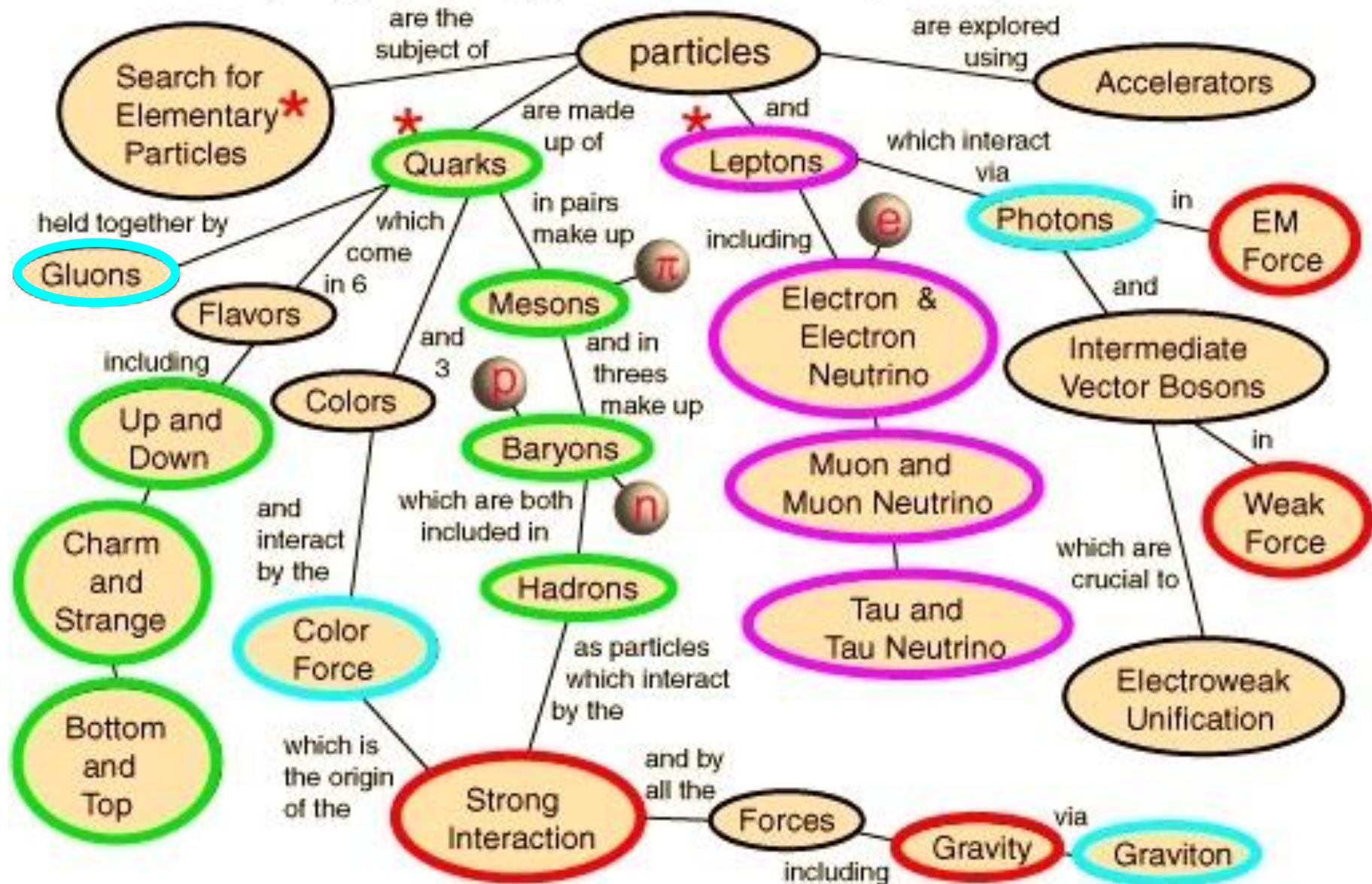


The little spring in the drawing is used to indicate that the quarks inside a nucleon are held together by a force we call gluon exchange.

### Size of Nucleons

# Particle Concepts Roadmap

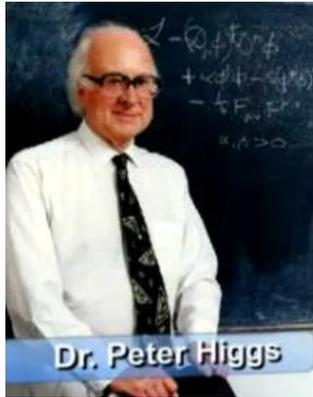
<http://hyperphysics.phy-astr.gsu.edu/Hbase/particles/parcon.html>





# Higgs Boson Particle -

July 4, 2012 – Announcement of experimental evidence for the Higgs Particle!



Dr. Peter Higgs

## What exactly is the Higgs field?

A theoretical, invisible energy field that stretches throughout the universe. It clings to fundamental particles wherever they are, dragging on them and making them heavy.



## The Large Hadron Collider

Our understanding of the Universe is about to change...

The Large Hadron Collider (LHC) is a gigantic scientific instrument near Geneva, where it spans the border between Switzerland and France about 100m underground. It is a particle accelerator used by physicists to study the smallest known particles – the fundamental building blocks of all things. It will revolutionise our understanding, from the minuscule world deep within atoms to the vastness of the Universe.

Two beams of subatomic particles called "hadrons" – either protons or lead ions – travel in opposite directions inside the circular accelerator, gaining energy with every lap. Physicists use the LHC to recreate the conditions just after the Big Bang, by colliding the two beams head-on at very high energy. Teams of physicists from around the world then analyse the particles created in the collisions using special detectors in a number of experiments dedicated to the LHC.

There are many theories as to what will result from these collisions. For decades, the Standard Model of particle physics has served physicists well as a means of understanding the fundamental laws of Nature, but it does not tell the whole story. Only experimental data using the high energies reached by the LHC can push knowledge forward, challenging those who seek confirmation of established knowledge, and those who dare to dream beyond the paradigm.

<http://bcove.me/v34o1pf6>

<http://www.squidoo.com/higgs-boson-for-dummies>

<http://vimeo.com/41038445>

# Counting Radioactivity

- 1) Film
  - 2) Geiger Counter
  - 3) Liquid Scintillation Counters
  - 4) PhosphorImager
- 

**Efficiency of counting:** It is relatively easy to detect gamma rays emitted from isotopes such as  $^{125}\text{I}$  with LSC, so efficiencies are usually over 90%. With  $^3\text{H}$ , the efficiency of counting is much lower, often about 40%.

**Errors in counting:** Poisson distribution

## Counting errors and the Poisson distribution

The decay of a population of radioactive atoms is random, and therefore subject to a sampling error. For example, the radioactive atoms in a tube containing 1000 cpm of radioactivity won't give off exactly 1000 counts in every minute. There will be more counts in some minutes and fewer in others, with the distribution of counts following a Poisson distribution. This variability is intrinsic to radioactive decay and cannot be reduced by more careful experimental controls. So long as the number of counts,  $C$ , is greater than about 50 you can calculate the confidence interval using this approximate equation:

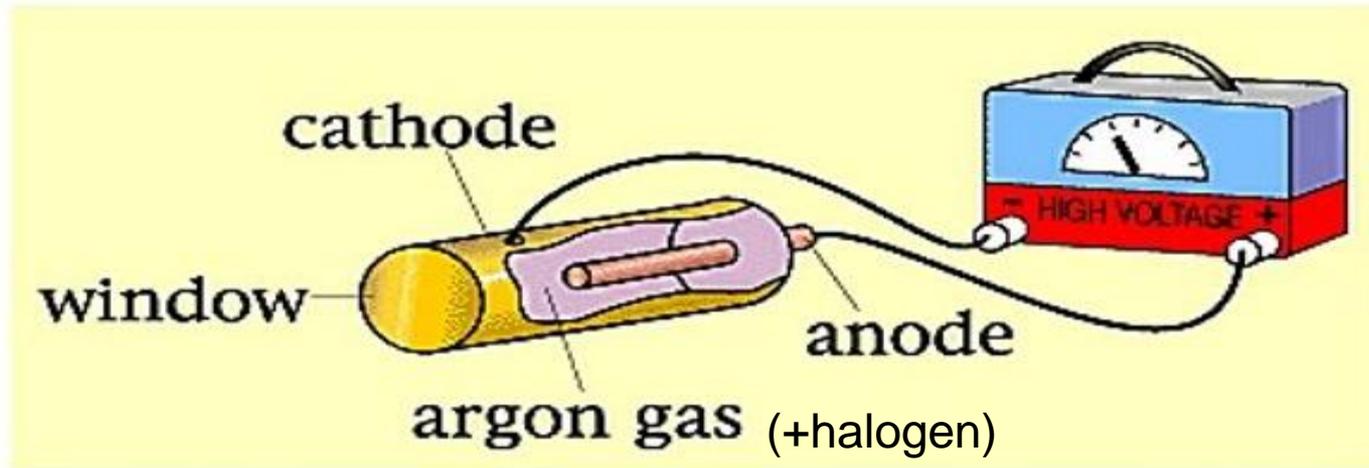
$$95\% \text{ Confidence Interval: } (C - 1.96\sqrt{C}) \text{ to } (C + 1.96\sqrt{C})$$

The Poisson distribution explains the advantages of counting your samples for a longer time. For example, the table below shows the confidence interval for 100 cpm counted for various times. When you count for longer times, the confidence interval will be narrower.

	1 minute	10 minutes	100 minutes
Counts per minute (cpm)	100	100	100
Total counts	100	1000	10000
95% CI of counts	81.4 to 121.6	938 to 1062	9804 to 10196
95% CI of cpm	81.4 to 121.6	93.8 to 106.2	98.0 to 102.0

# Geiger Counters

This form of detection device is small, portable, and relatively inexpensive. It consists of a metal tube filled with argon or neon and kept at low pressure. Into the center of this tube a wire has been anchored with high voltage set up between the wire and the tube. When ionizing particles enter this tube, it ionizes the entrapped gas and causes an electrical pulse. By adding up the number of pulses, the intensity of radiation can be detected. This type of detector is good for high energy beta particle producers, but not gamma rays or alpha particles.



Hans Geiger worked as a lab tech for Rutherford for 5 years counting subatomic particles in a dark room using a screen and a microscope!

Geiger moved from England to teach in Germany in 1907 and quickly he perfected an automatic way to count these particles (tic tic tic tic ....).



CCDM ITEM NO. CVV-700  
MODEL NO. 6A SER. NO.  
THE VICTORCEN INSTRUMENT CO.  
CLEVELAND, OHIO

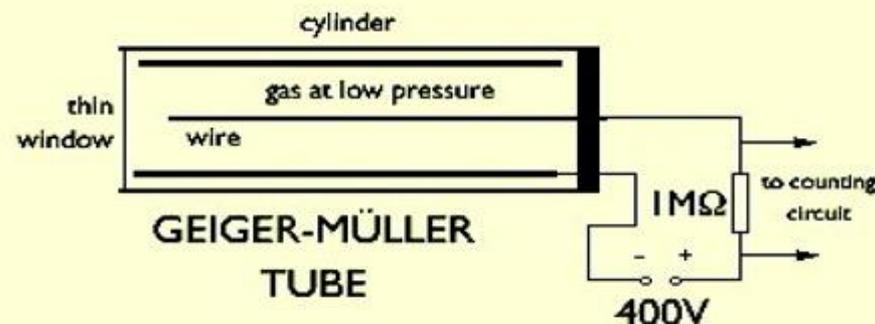
CLEAR CHANNEL  
SEARCH

A Geiger counter depends on the fact that radiation knocks electrons out of the atoms in a gas and leaves them with an electric charge. These charged atoms (or ions) can then carry an electric current through the gas.

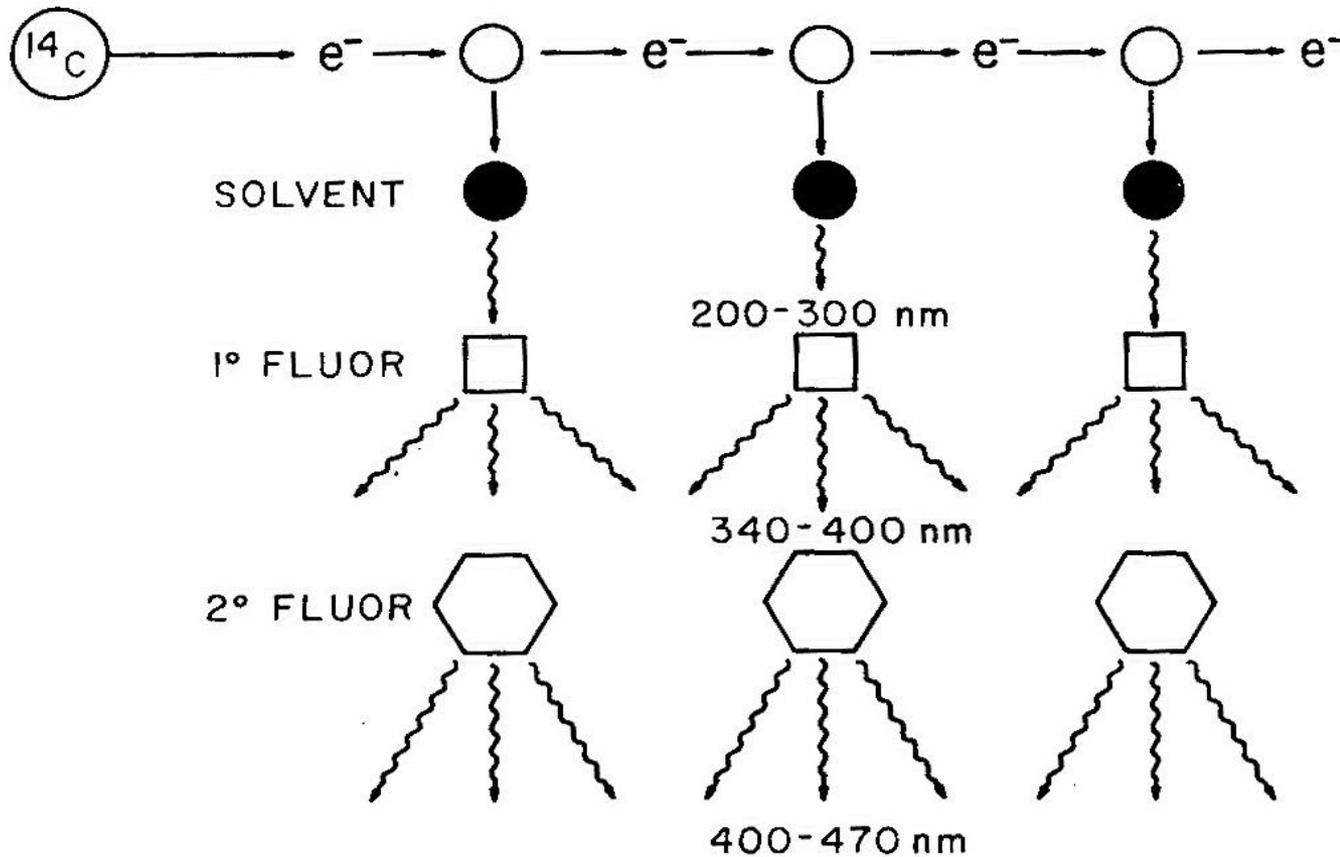
A Geiger-Müller (G-M) tube consists of a metal cylinder with a wire along its axis, sealed inside a glass envelope. At one end there is a very thin mica window, which allows radiation to enter the tube. The tube contains gas at low pressure. There is a high voltage between the wire and the cylinder. This produces a very strong electric field close to the wire. Normally no current can cross the gap. This means that there is no voltage across the 1 megohm resistor.

When an alpha- or beta-particle enters the tube, it produces some ions in the gas. These ions are then accelerated by the strong field close to the wire. They soon gain enough energy to ionise more atoms by bumping into them. There is an avalanche of ions which allows a current to flow through the gas. This current also flows through the resistor and produces a pulse of voltage across it. These pulses are counted by a special electronic circuit. Sometimes they give a click in a loudspeaker.

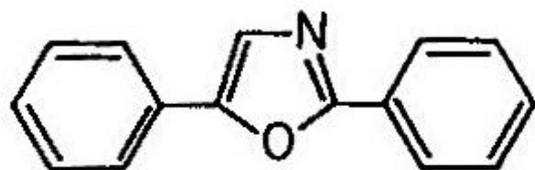
Geiger counters are best at counting beta-particles and those alpha-particles that have sufficient energy to pass through the window. Gamma-rays and X-rays will also be counted if they produce ions in the tube, but they often just go straight through.



# Liquid Scintillation Counting



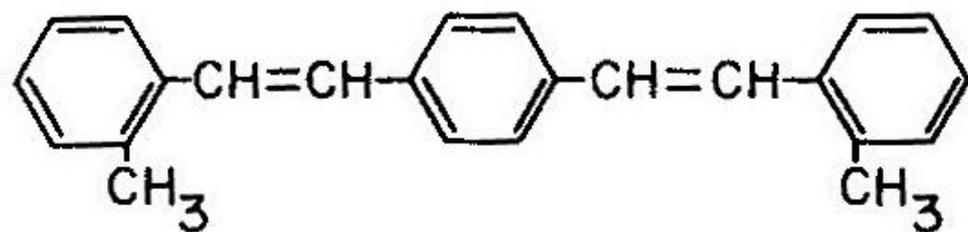
**Figure 3-2.** Interaction of  $\beta$  particles with aromatic solvents and subsequent fluor excitation.  $e^-$  represents the emitted  $\beta$  particles,  $\circ$  indicates a solvent molecule in its ground state, and  $\bullet$  denotes solvent molecules in the triplet state. (From E. Rapkin, *Preparation of Samples for Liquid Scintillation Counting*, Picker Nuclear Corp., White Plains, New York.)



PPO

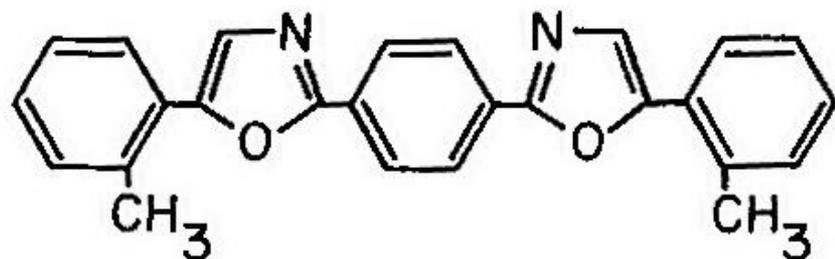
$\lambda_f \sim 365 / 380$

2,5-diphenyloxazole  
(phenyl-oxazole-phenyl)



bis-MSB

$\lambda_f \sim 420 / 441$



dimethyl-POPOP

# Photomultiplier Tubes

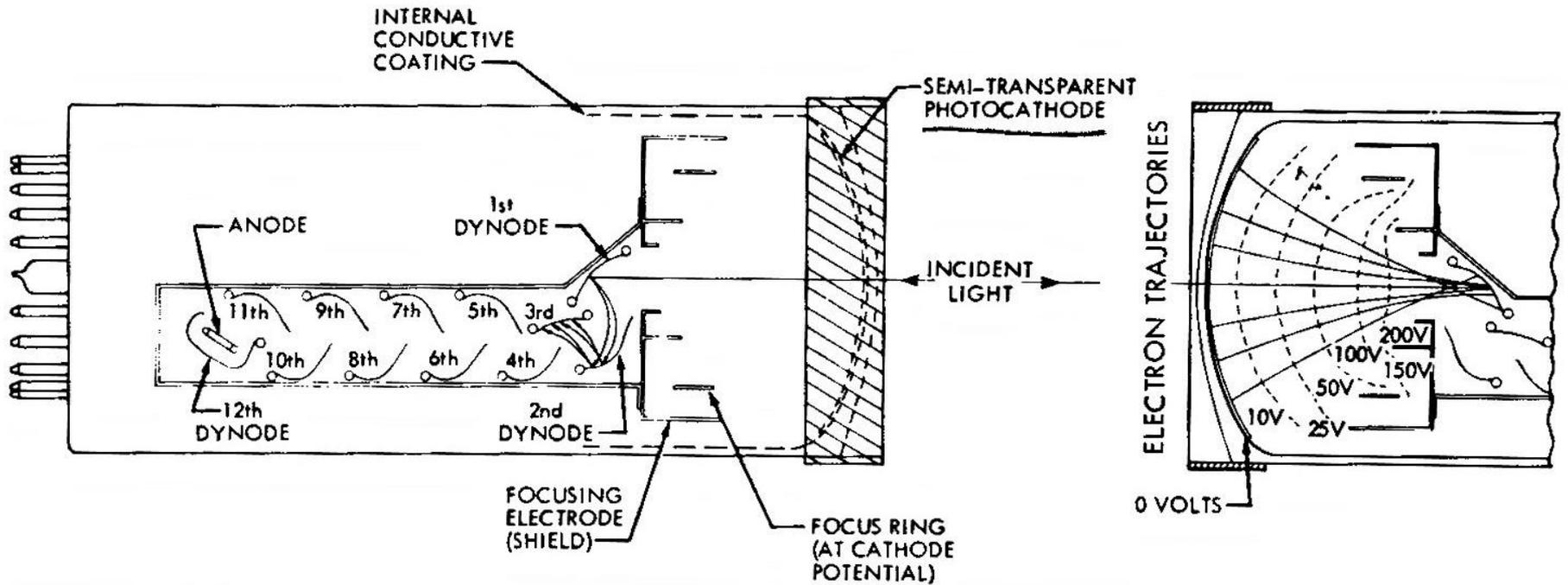


Figure 3-8. Beckman-RCA Bialkali 12-stage Photomultiplier Tube. (Courtesy of Beckman Instruments, Inc., Instruction Manual 1553-D.)

$\sim 10^{-9}$  seconds

$3.5 e^- / e^- / \text{dynode}$   
 $\Rightarrow 1 e^- \rightarrow 10^6 e^-$

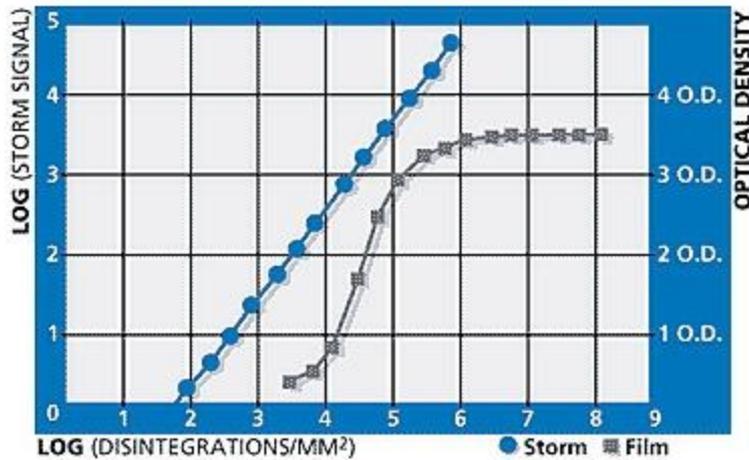
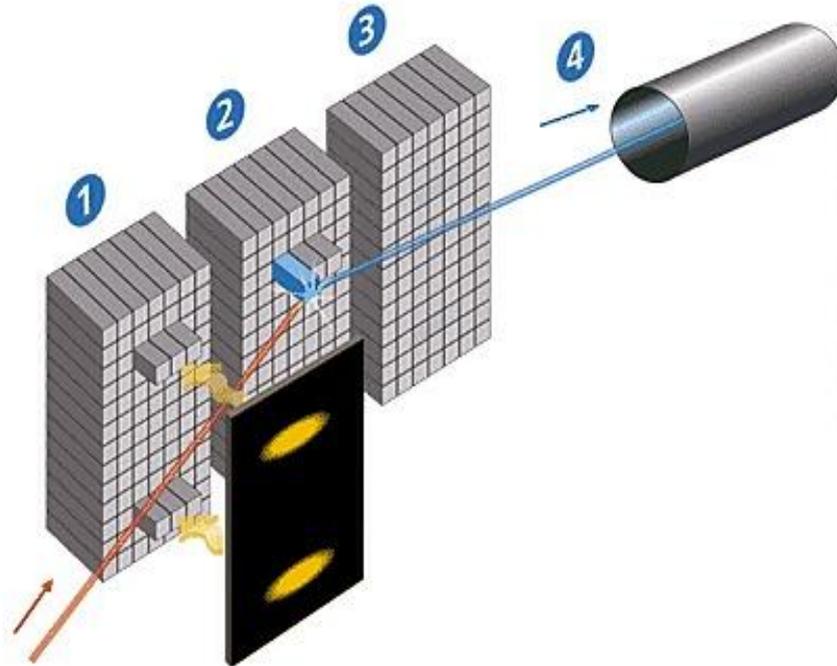


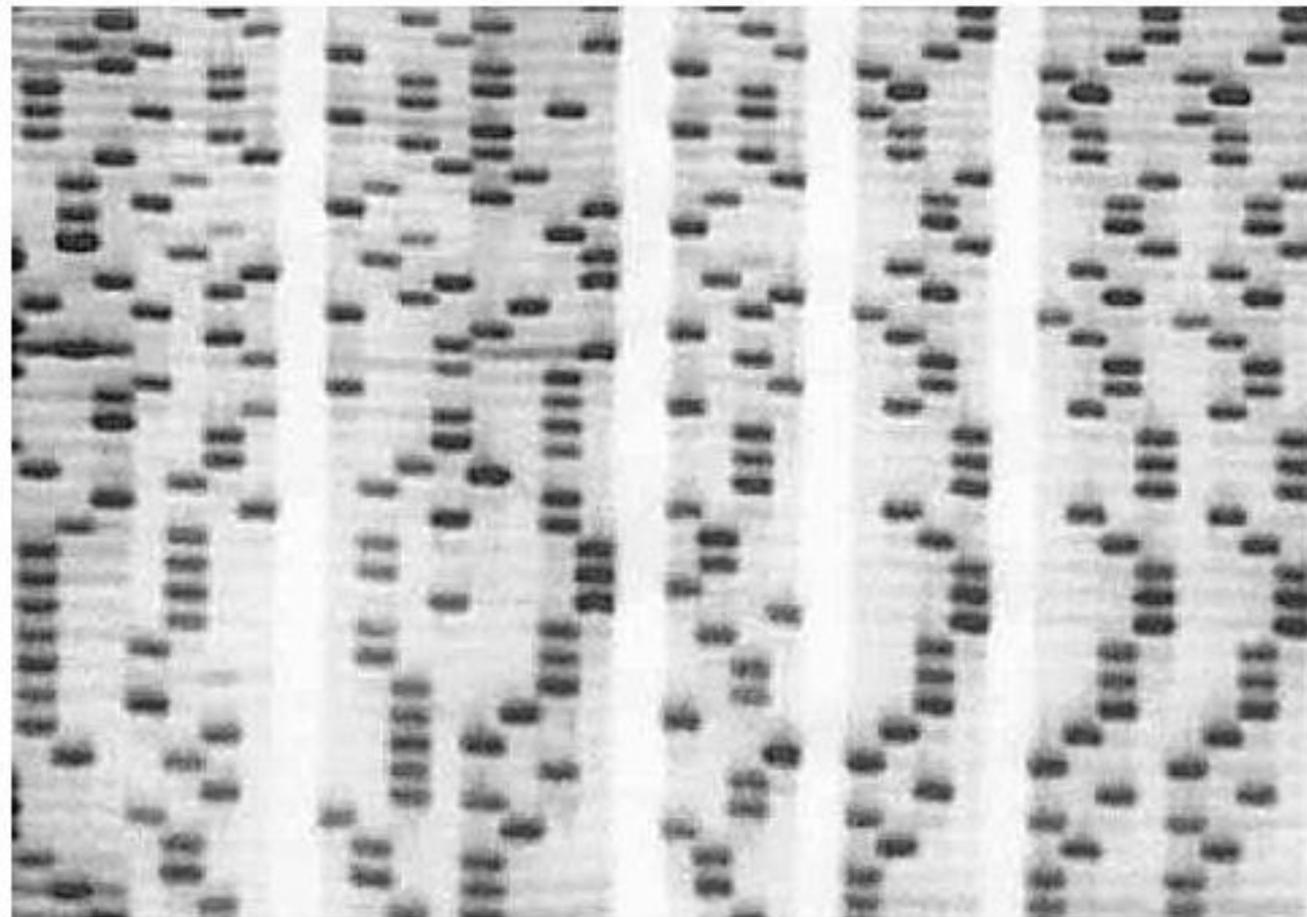
Fig 1. With five orders of linear dynamic range, Storm captures the image from both strong and weak signals in a single exposure. The Storm system's linear dynamic range is 1000 times greater than film.

### How storage phosphor works

## PhosphorImager



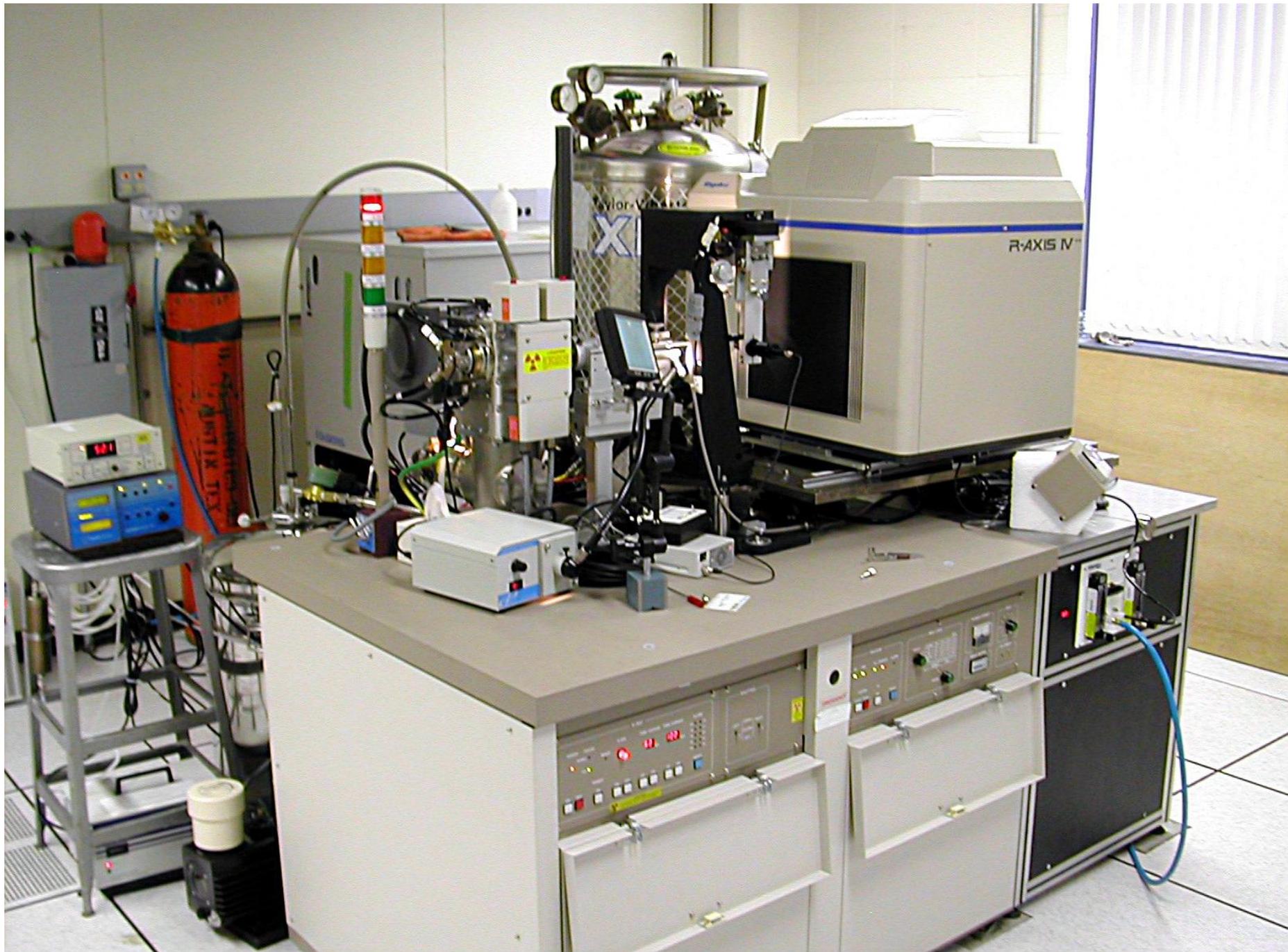
1. Exposure of the storage phosphor screen to ionizing radiation induces latent image formation
2. During laser scanning, the BaFBR:EU+2 crystals in the screen release energy as blue light
3. and return to ground state
4. Blue light is collected and measured to form a quantitative representation of the sample.



## DNA Sequencing Gels

DNA Sequencing gels and other large samples fit on the Storm system's 35 x 43 cm scan area. Storm offers the high resolution you need for DNA base identification.

Storm has a 35 x 43 cm (14" x 17") sample area that accepts large samples so you can scan sequencing-sized gels. Or, you can use the large sample area to expose many small gels and blots simultaneously for maximum throughput. Sample exposures take place in cassettes -- not in the instrument -- so the Storm system is always available for scanning. With the Windows NT operating system, scanning can continue even while you're using the same computer to analyze your data and prepare your results for presentation.



**TABLE 22.2**

## Half-Lives of Some Useful Radioisotopes

Radioisotope	Symbol	Radiation	Half-Life	Use
Tritium	${}^3_1\text{H}$	$\beta^-$	12.33 years	Biochemical tracer
Carbon-14	${}^{14}_6\text{C}$	$\beta^-$	5730 years	Archaeological dating
Phosphorus-32	${}^{32}_{15}\text{P}$	$\beta^-$	14.26 days	Leukemia therapy
Potassium-40	${}^{40}_{19}\text{K}$	$\beta^-$	$1.28 \times 10^9$ years	Geological dating
Cobalt-60	${}^{60}_{27}\text{Co}$	$\beta^-, \gamma$	5.27 years	Cancer therapy
Technetium-99 $m^*$	${}^{99m}_{43}\text{Tc}$	$\gamma$	6.01 hours	Brain scans
Iodine-123	${}^{123}_{53}\text{I}$	$\gamma$	13.27 hours	Thyroid therapy
Uranium-235	${}^{235}_{92}\text{U}$	$\alpha, \gamma$	$7.04 \times 10^8$ years	Nuclear reactors

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



## The Nobel Prize in Chemistry 1960

"for his method to use carbon-14 for age determination in archaeology, geology, geophysics, and other branches of science"



**Willard Frank Libby**

USA

## Common Isotopes of Carbon

Relative abundance of these isotopes in atmospheric CO<sub>2</sub>

**C<sup>12</sup> - 98.89 %**

**C<sup>13</sup> - 1.11 %**

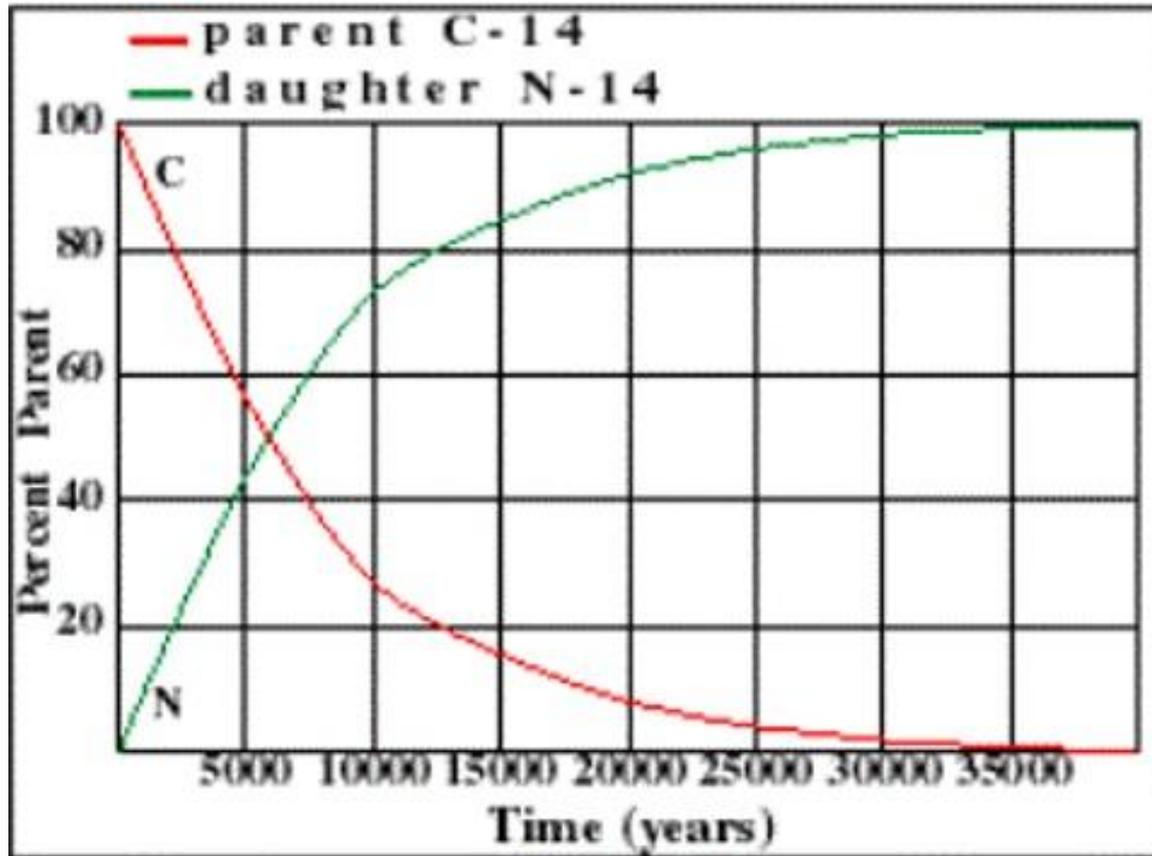
**C<sup>14</sup> - 0.0000000001 %**

# C-14 Dating

1. What is a “half-life”
2. Where does carbon-14 come from?
3. How is radiocarbon dating done?  
What assumptions must we make?



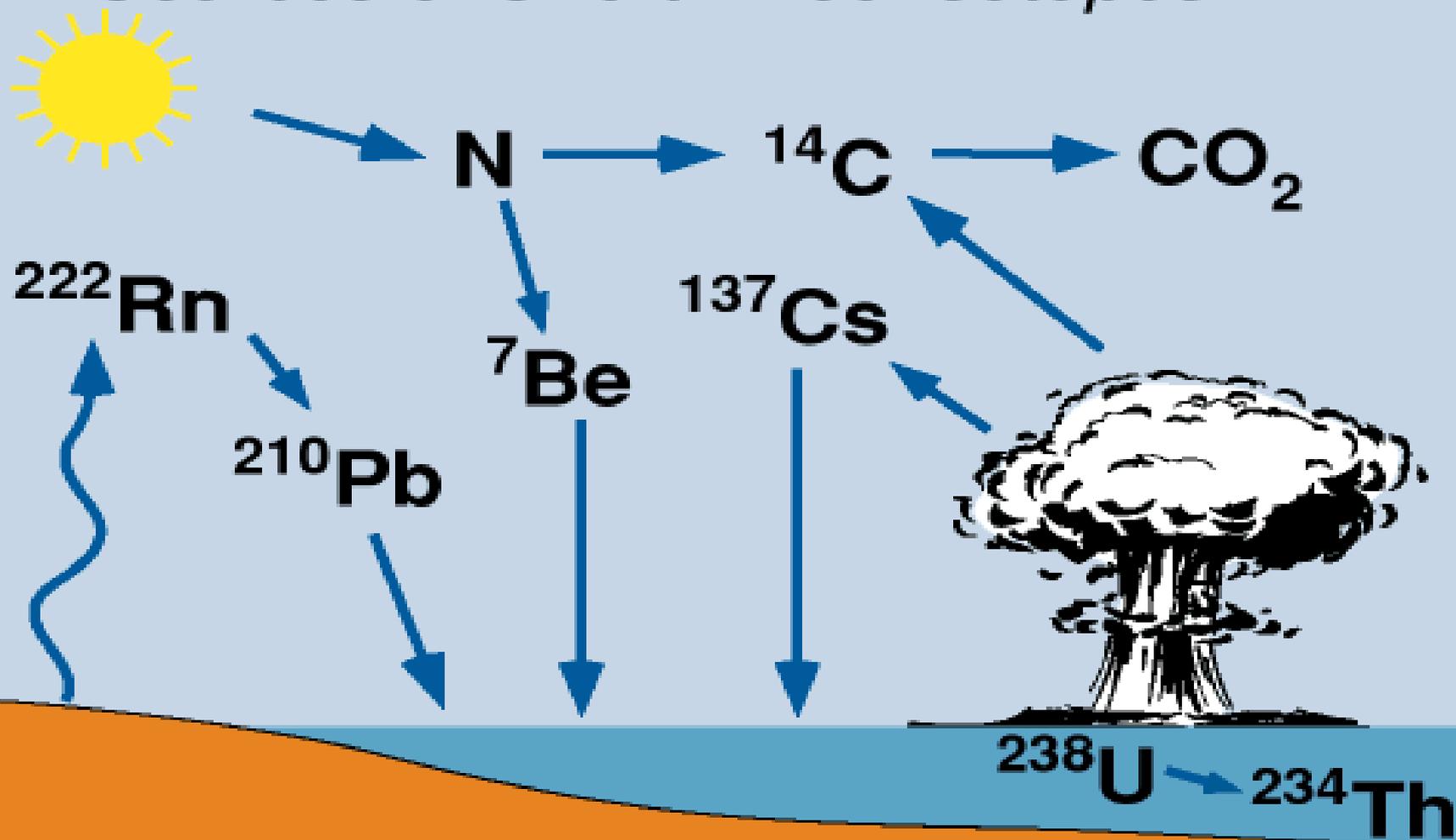
# Carbon-14 Decay



**Half-life of C-14 is ~5730 years**

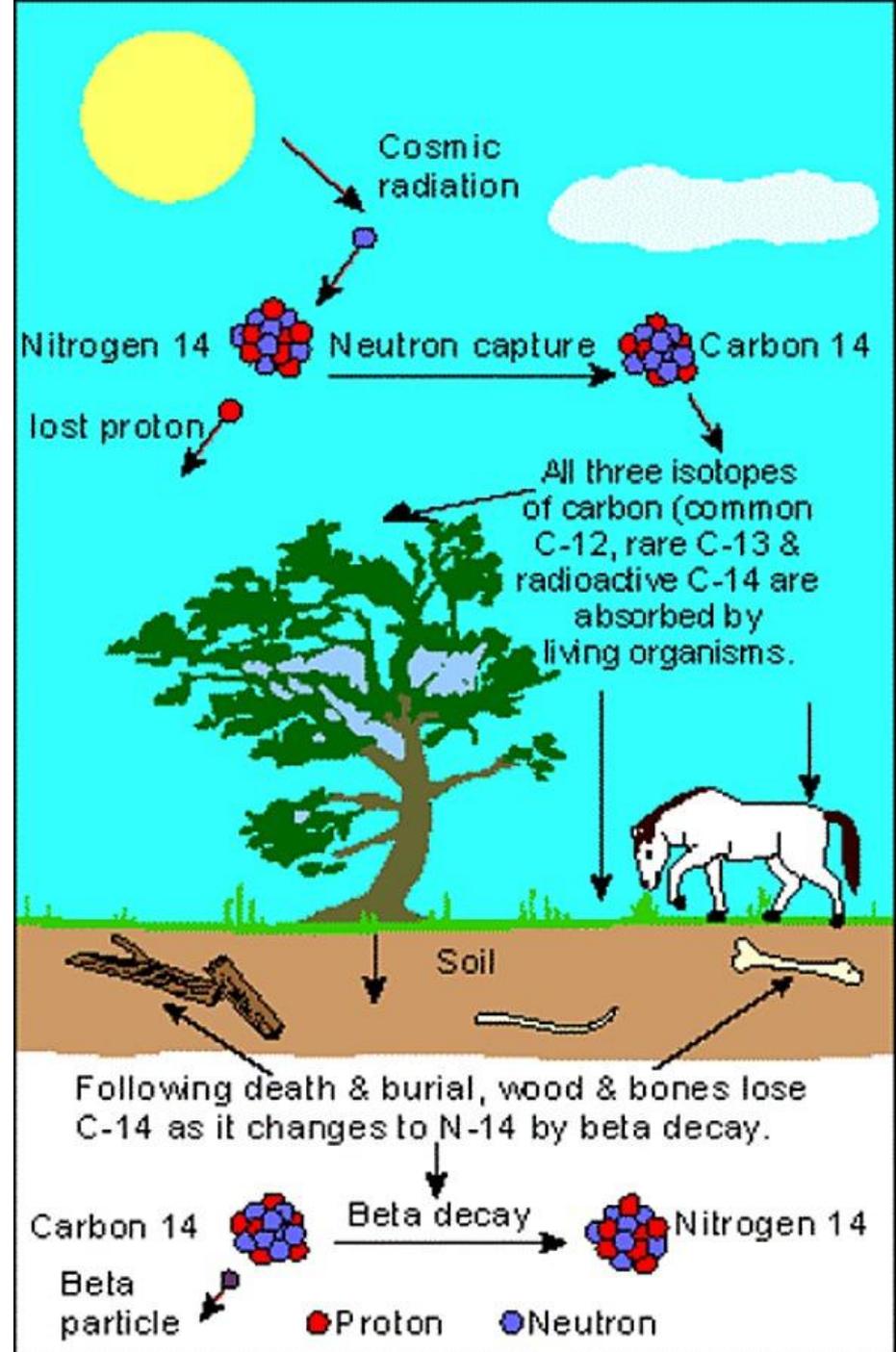
# Where does carbon-14 come from?

## *Sources of Short Lived Isotopes*



As long as an animal / human is alive, the percentage of  $C^{14}$  present in his body is the same as that in the atmosphere. This is because the food that we eat ultimately comes from plants. And carbon present in plants is produced from atmospheric  $CO_2$  during photosynthesis.

However when a plant / animal / human dies, intake of carbon ceases.  $C^{12}$  and  $C^{13}$  being stable remains, but  $C^{14}$  decays. Thus by measuring the amount of  $C^{14}$  left, the age of a fossil is computed. This computation is based on the assumption that the amount of  $C^{14}$  present in the atmosphere has remained constant.



# Complications

The simplified approach described above does not tell the whole story, There are two principal sources of error:

1. The original half-life of carbon-14 measured by Libby has not withstood the test of time. The currently accepted half-life of this nucleus is 5730 years, Libby's measurement of 5668 years is still used (for consistency) in calculations.

**(can correct for this with math)**

2. Over time, the abundance of carbon-14 in the atmosphere has undergone variations. These result directly from fluctuations in the flux of cosmic rays, burning of fossil fuels and atmospheric testing of nuclear bombs in the period following WWII.

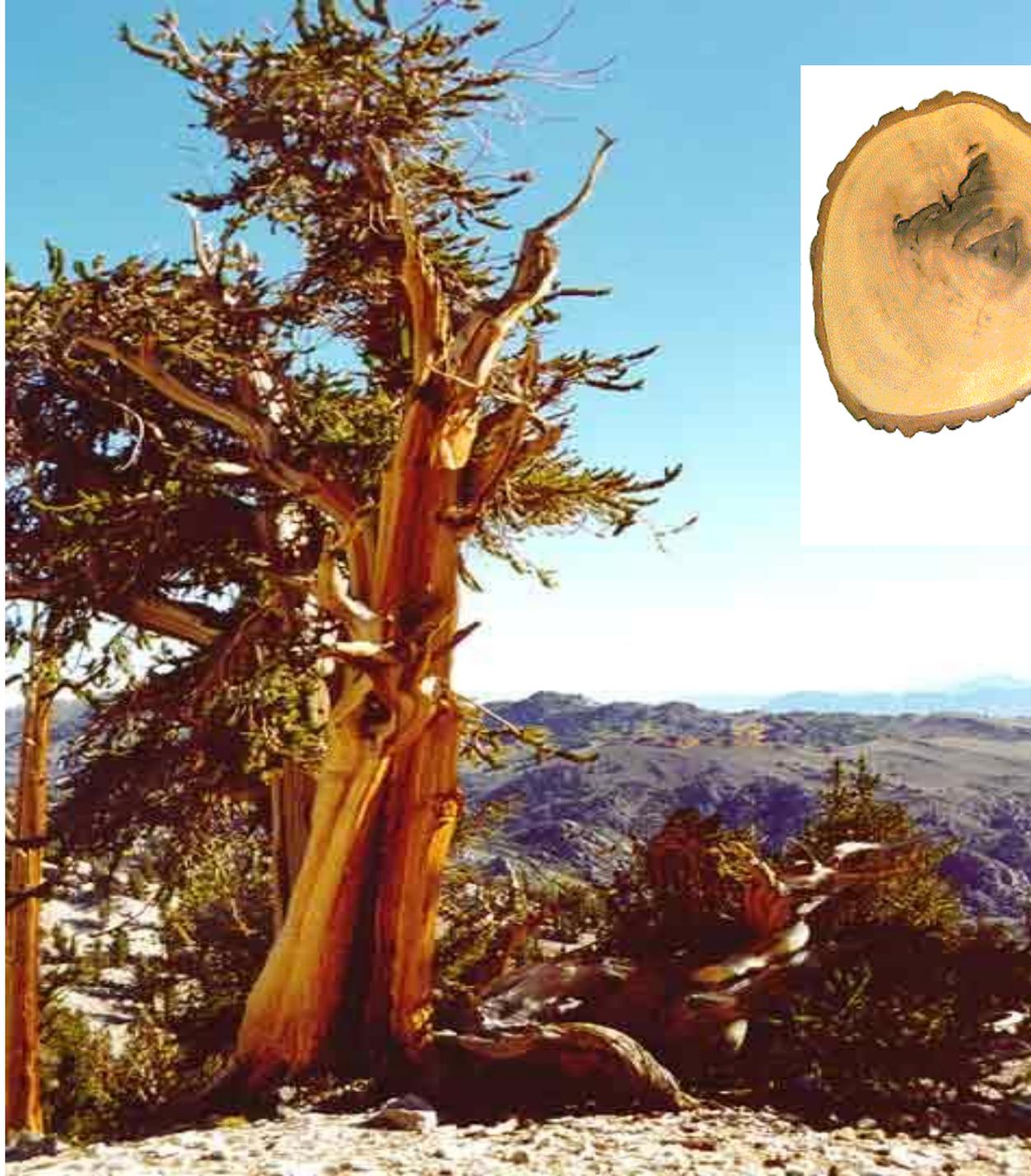
**????????**

**Solution:**

Measure C14/C12 ratio in samples of  
KNOWN ages.

Plot ratios v. age, use these for calibration.

Allow for uncertainties in all measured  
C14/C12 ratios.





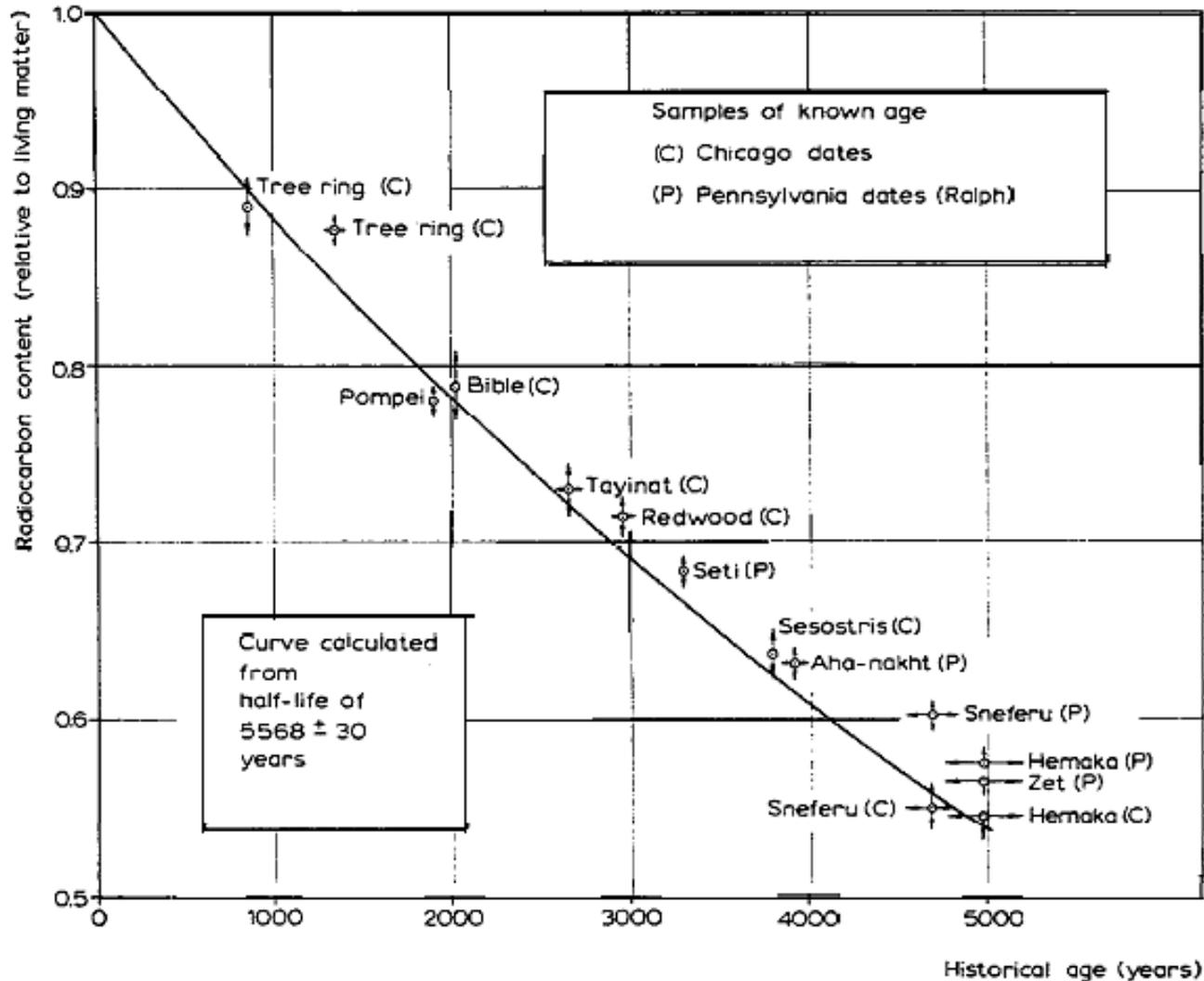


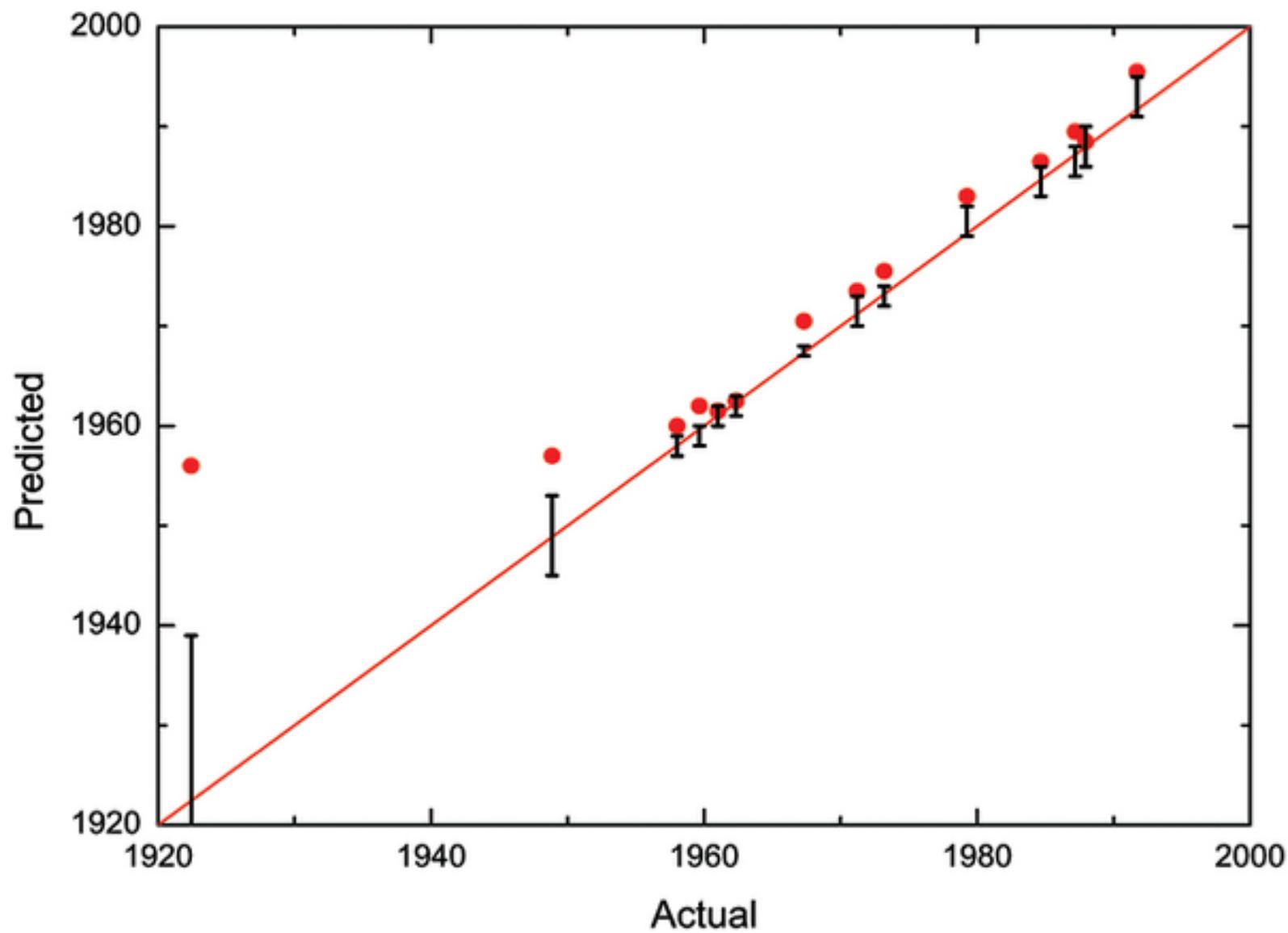
Fig. 3. Curve of Knowns.

# Forensic Uses

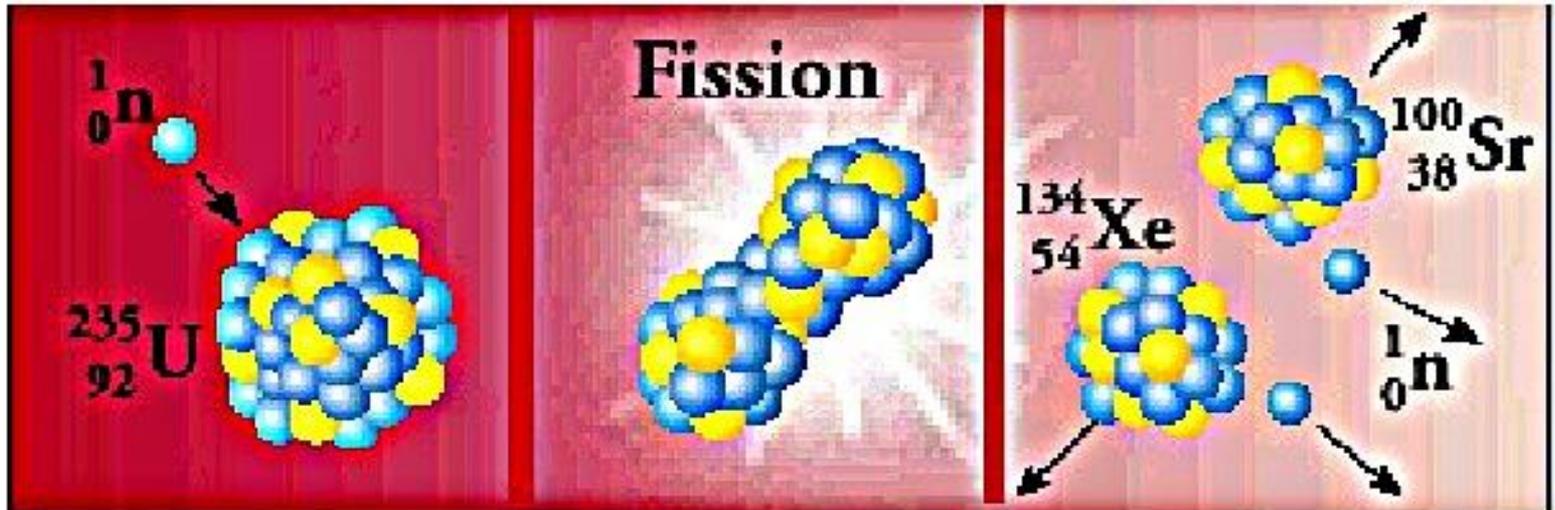
## Radiocarbon Dating of the Human Eye Lens Crystallines Reveal Proteins without Carbon Turnover throughout Life

Niels Lynnerup<sup>1\*</sup>, Henrik Kjeldsen<sup>2</sup>, Steffen Heegaard<sup>3</sup>,  
Christina Jacobsen<sup>1</sup>, Jan Heinemeier<sup>2</sup> 2008

**Lens crystallines are special proteins in the eye lens. Because the epithelial basement membrane (lens capsule) completely encloses the lens, desquamation of aging cells is impossible, and due to the complete absence of blood vessels or transport of metabolites in this area, there is no subsequent remodelling of these fibers, nor removal of degraded lens fibers. Human tissue ultimately derives its  $^{14}\text{C}$  content from the atmospheric carbon dioxide. The  $^{14}\text{C}$  content of the lens proteins thus reflects the atmospheric content of  $^{14}\text{C}$  when the lens crystallines were formed. Precise radiocarbon dating is made possible by comparing the  $^{14}\text{C}$  content of the lens crystallines to the so-called bomb pulse, i.e. a plot of the atmospheric  $^{14}\text{C}$  content since the Second World War, when there was a significant increase due to nuclear-bomb testing. Since the change in concentration is significant even on a yearly basis this allows very accurate dating.**

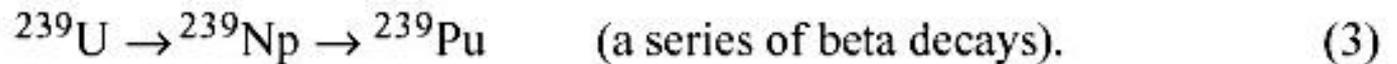
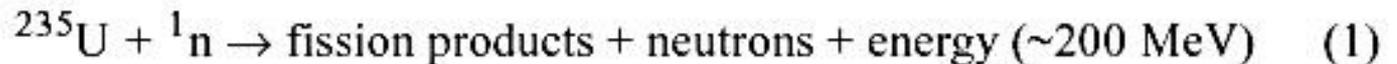


**Figure 2.** Predicting the year of birth by the  $^{14}\text{C}$  of eye lens crystallines.



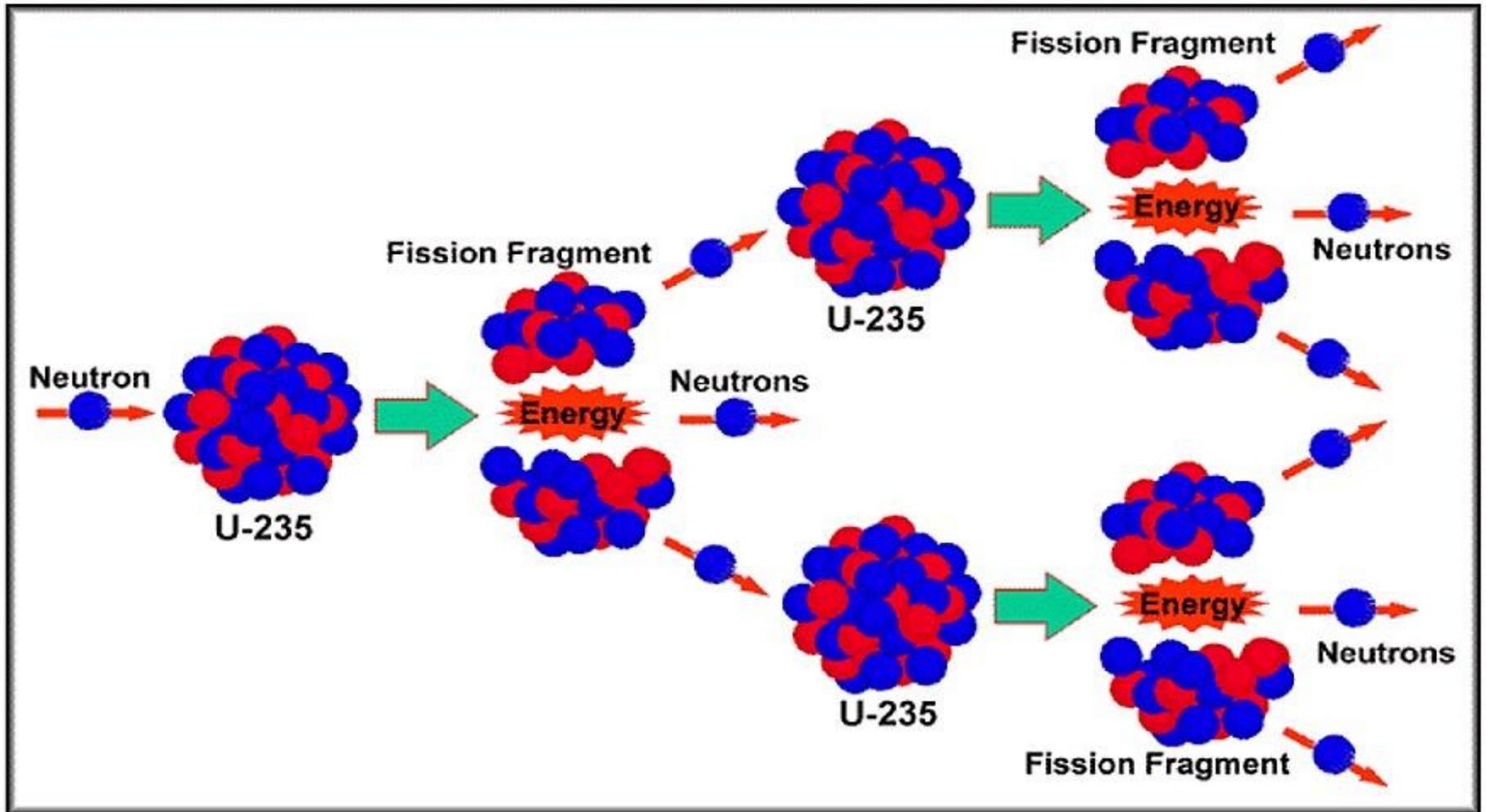
Fission of  $^{235}\text{U}$  after absorption of a thermal neutron.

The relevant nuclear reactions can be written as follows:



**Mass defect = sum of mass of nucleons - mass of nucleus**

$$\text{Binding energy} = \Delta m \times c^2$$

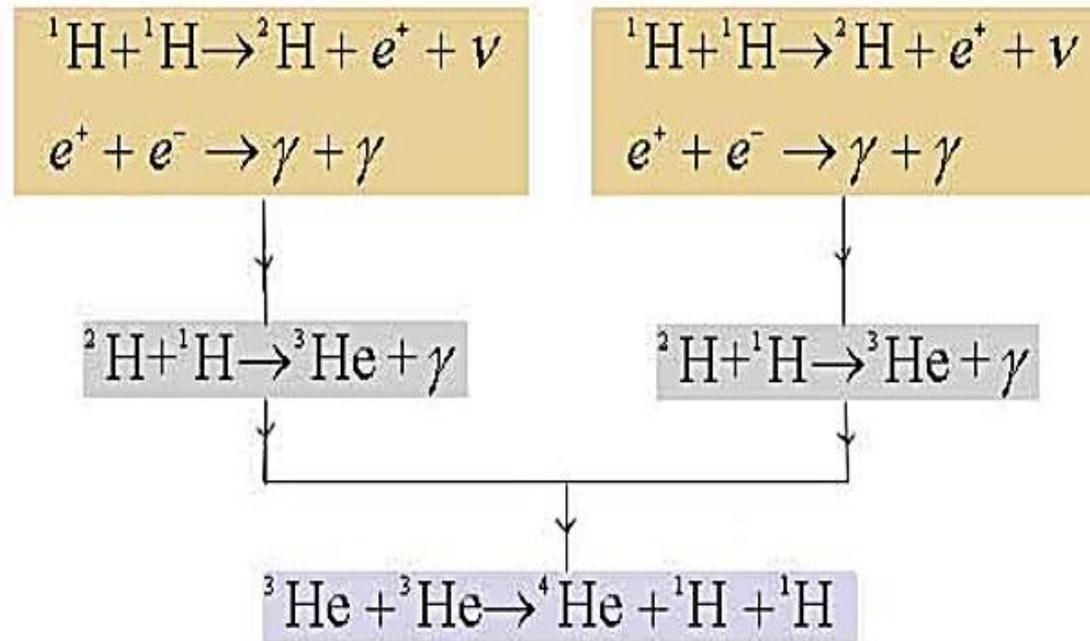


**Fission of uranium 235 nucleus.** Adapted from *Nuclear Energy. Nuclear Waste* <sup>13</sup>.

U-235 (~0.7% abundance) is the only fissile isotope that is found in significant quantity in nature.. The fission of one atom of U-235 generates  $\sim 200 \text{ MeV} = 3.2 \times 10^{-11} \text{ J}$  or **over  $80 \times 10^{(+12)} \text{ J/kg}$**  (1 eV is 96.5 kJ/mole)

# Thermonuclear Fusion in the Sun and other Stars

The sun radiates energy at the rate of  $3.9 \times 10^{26}$  W (watts) and has been doing so for several billion years. The sun burns hydrogen in a "nuclear furnace." The fusion reaction in the sun is a multistep process in which hydrogen is burned into helium, hydrogen being the "fuel" and helium the "ashes." The figure below shows the cycle.



**Fusion cycle of the Sun**

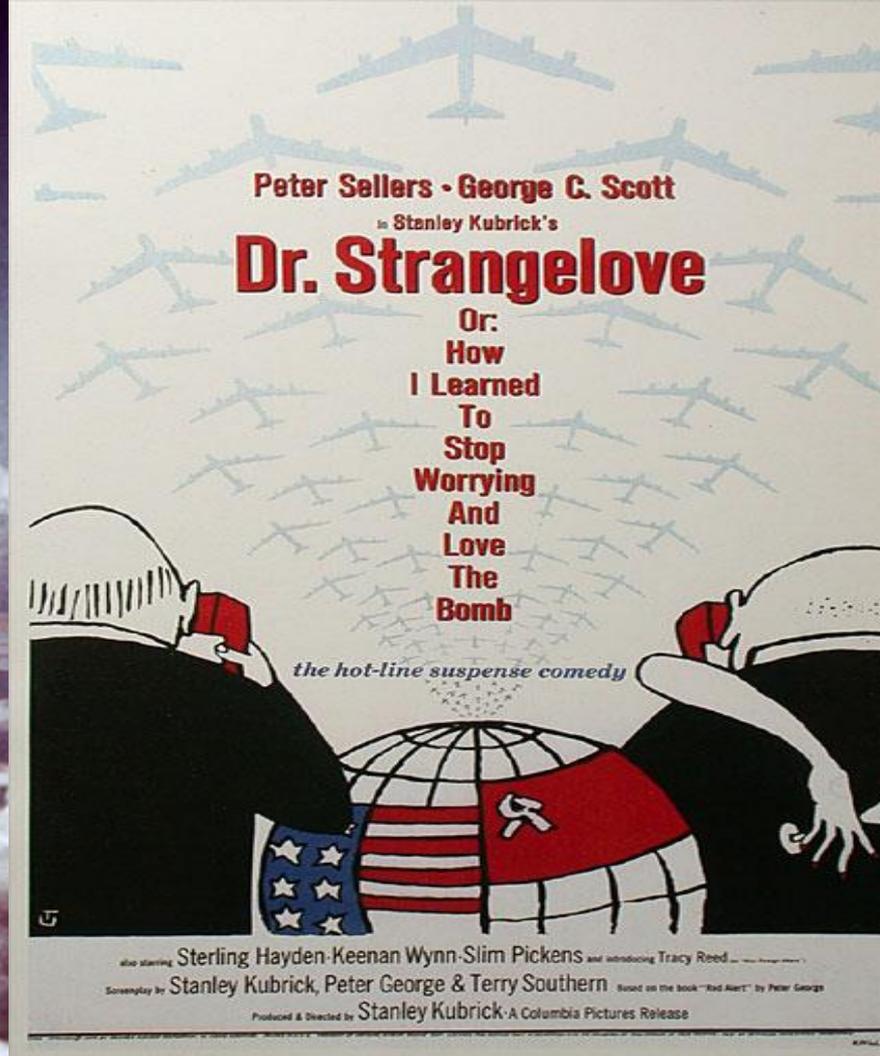
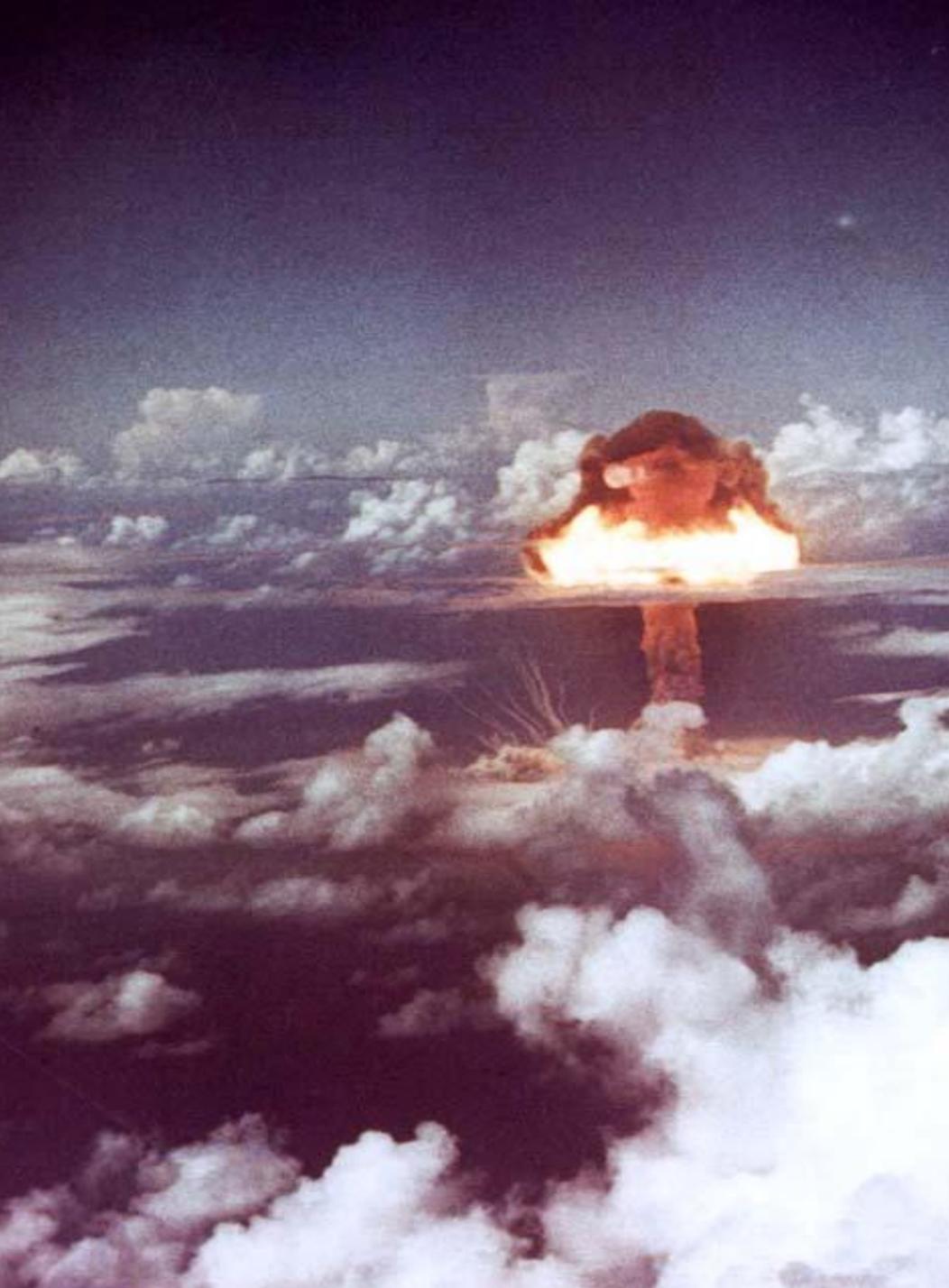
## Nuclear Fusion - Hydrogen Bomb

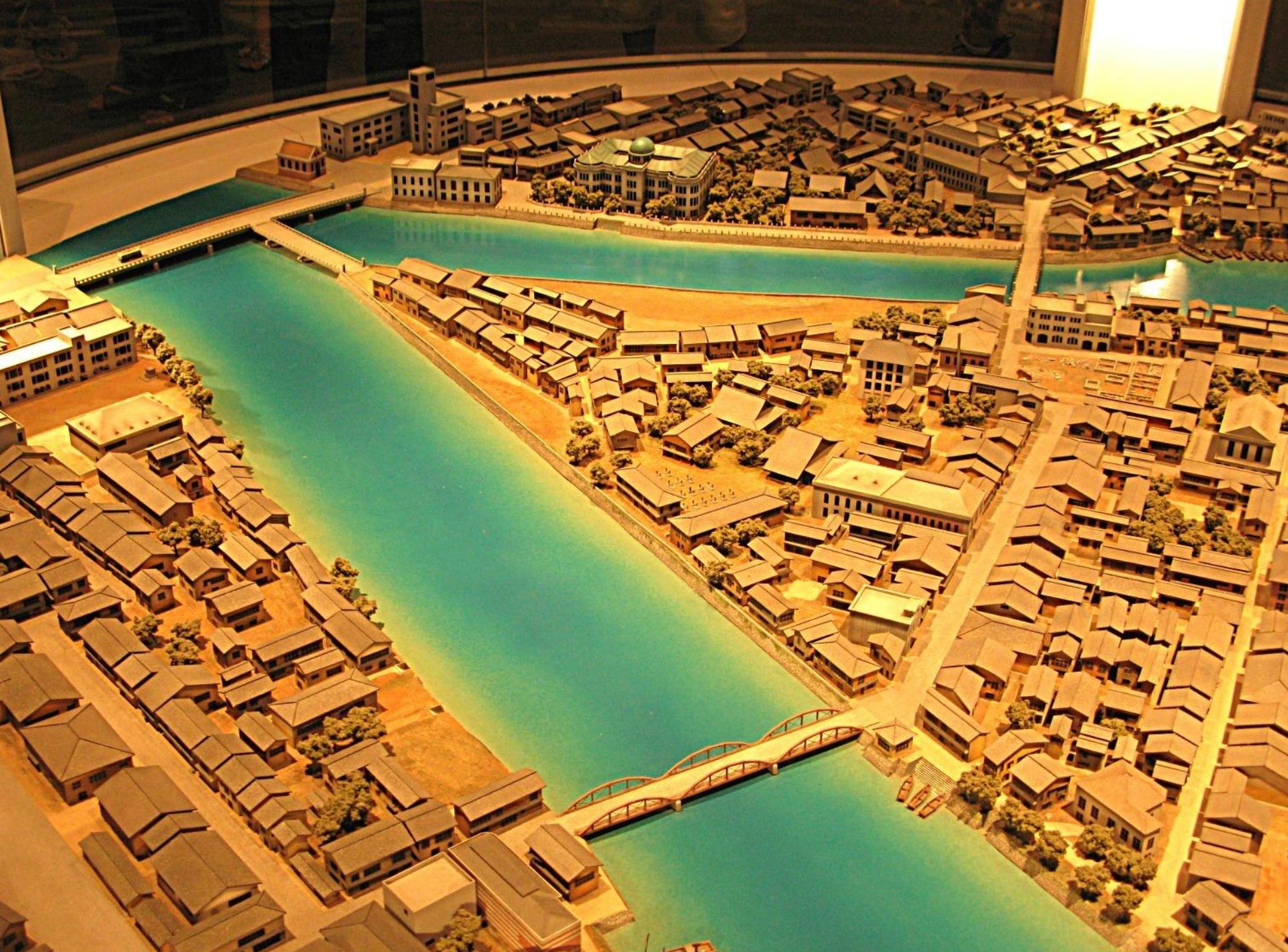
Fusion releases energy due to the overall loss in mass. If you add up the masses of the particles which go into a fusion reaction, and you add up the masses of the particles which come out, there is frequently a difference. According to Einstein's famous law relating energy and mass,

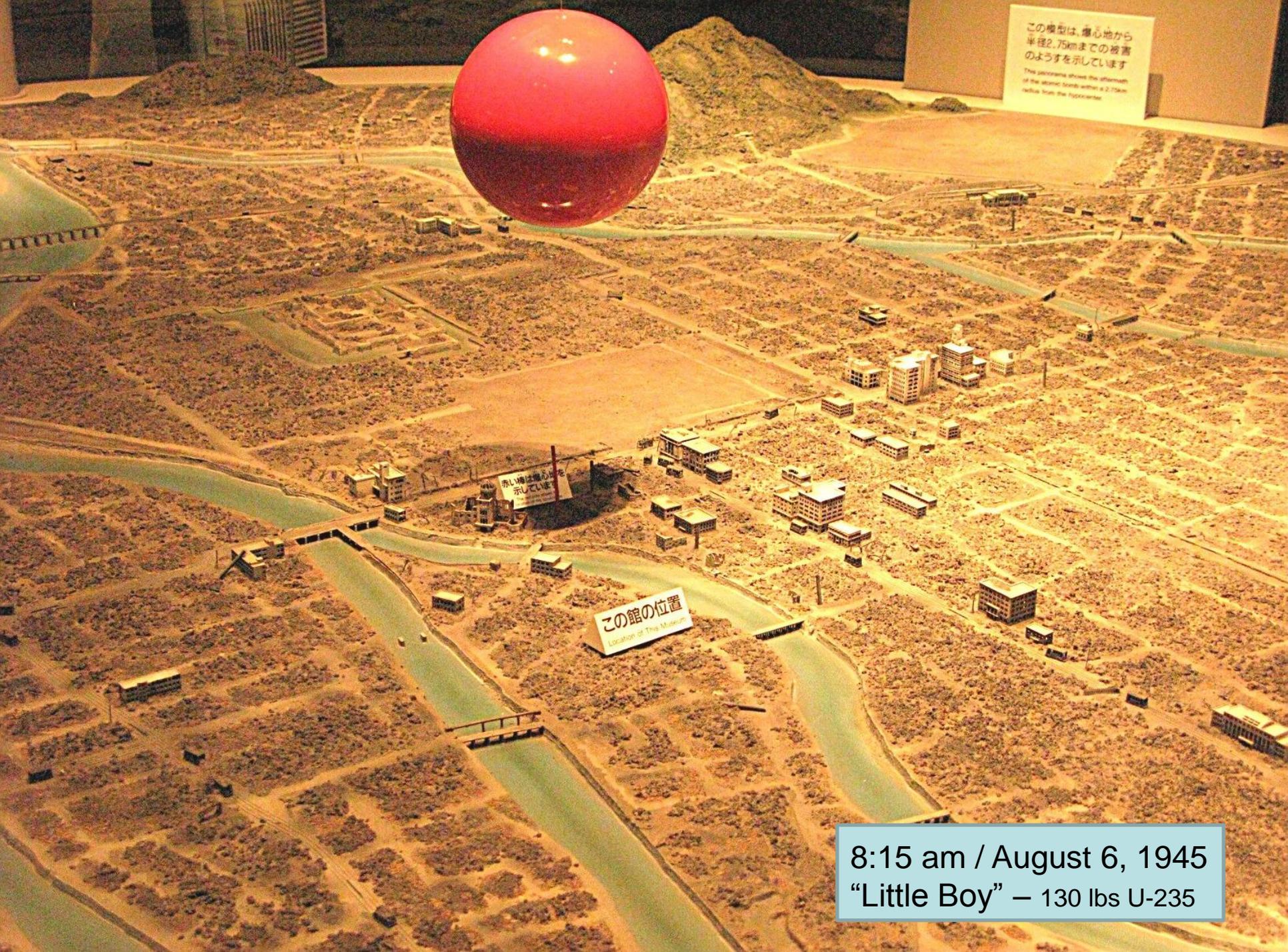
$$E = mc^2, \quad \Delta \text{Energy} = \Delta m \times c^2$$

the "mass difference" can take the form of energy. Fusion reactions involving nuclei lighter than iron typically release energy, but fusion reactions involving nuclei heavier than iron typically absorb energy. The amount of energy released depends on the specifics of the reaction. The reaction used in the hydrogen bomb, though, produces one of the greatest changes in mass.

The hydrogen bomb is thousands of times more powerful than an atomic bomb. There have not been any hydrogen bombs used in warfare, however there have been hydrogen bomb tests. Most of these tests are done underwater due to risk of destruction. To give you an idea of how strong the H-bomb is, think about this. This atomic bomb dropped on Hiroshima, Japan which killed over 140,000 people had the power of 13 kilotons. A common hydrogen bomb has the power of up to 10 megatons. All the explosions in World War II totalled "only" 2 megatons -- 20% of the power of ONE common hydrogen bomb.





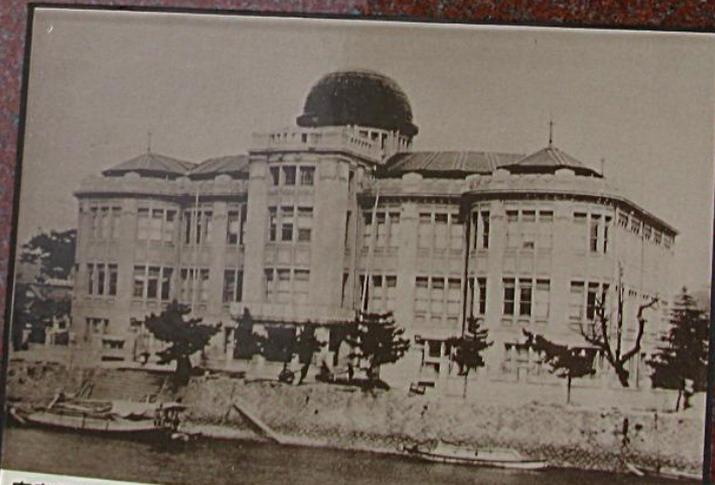


この模型は、爆心地から  
半径2.75kmまでの被害  
のようすを示しています  
This scenario shows the aftermath  
of the atomic bomb within a 2.75km  
radius from the hypocenter.

赤い球は爆心を示しています

この館の位置  
Location of This Museum

8:15 am / August 6, 1945  
“Little Boy” – 130 lbs U-235

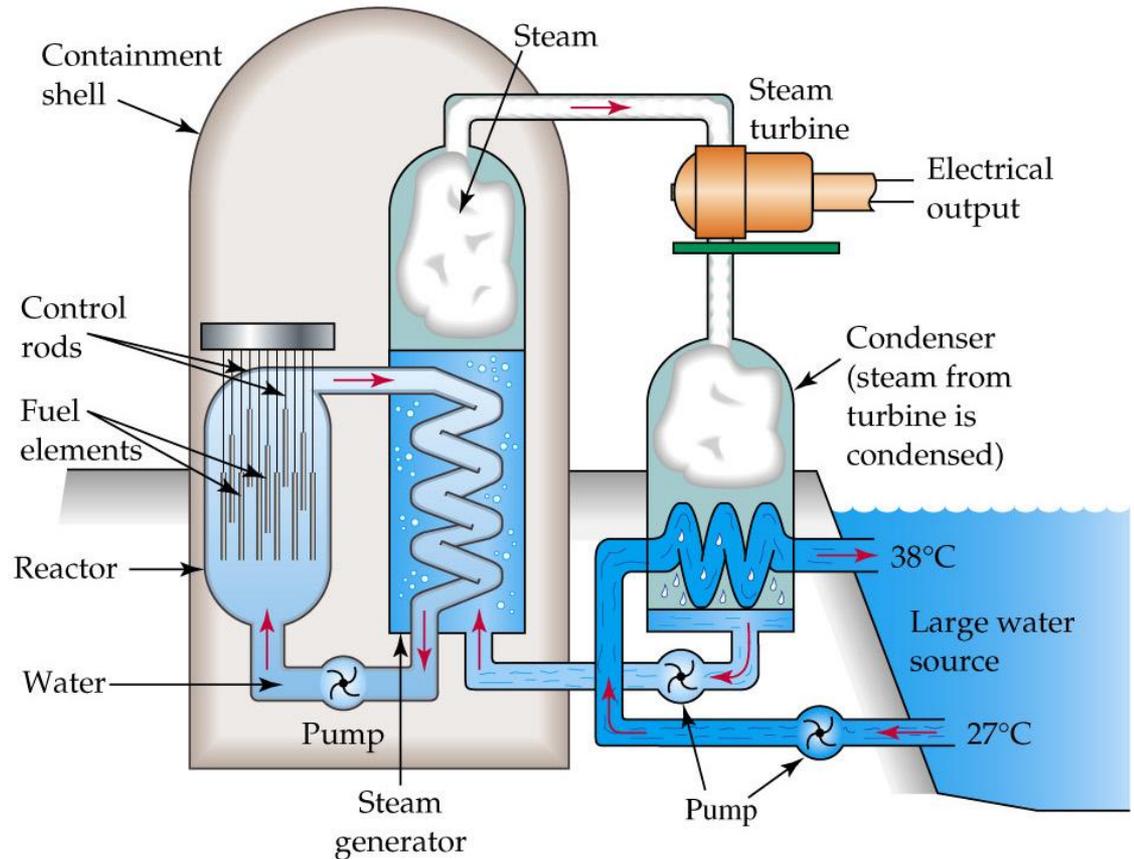


広島県産業奨励館（「原爆ドーム」；爆心地から約160メートル）

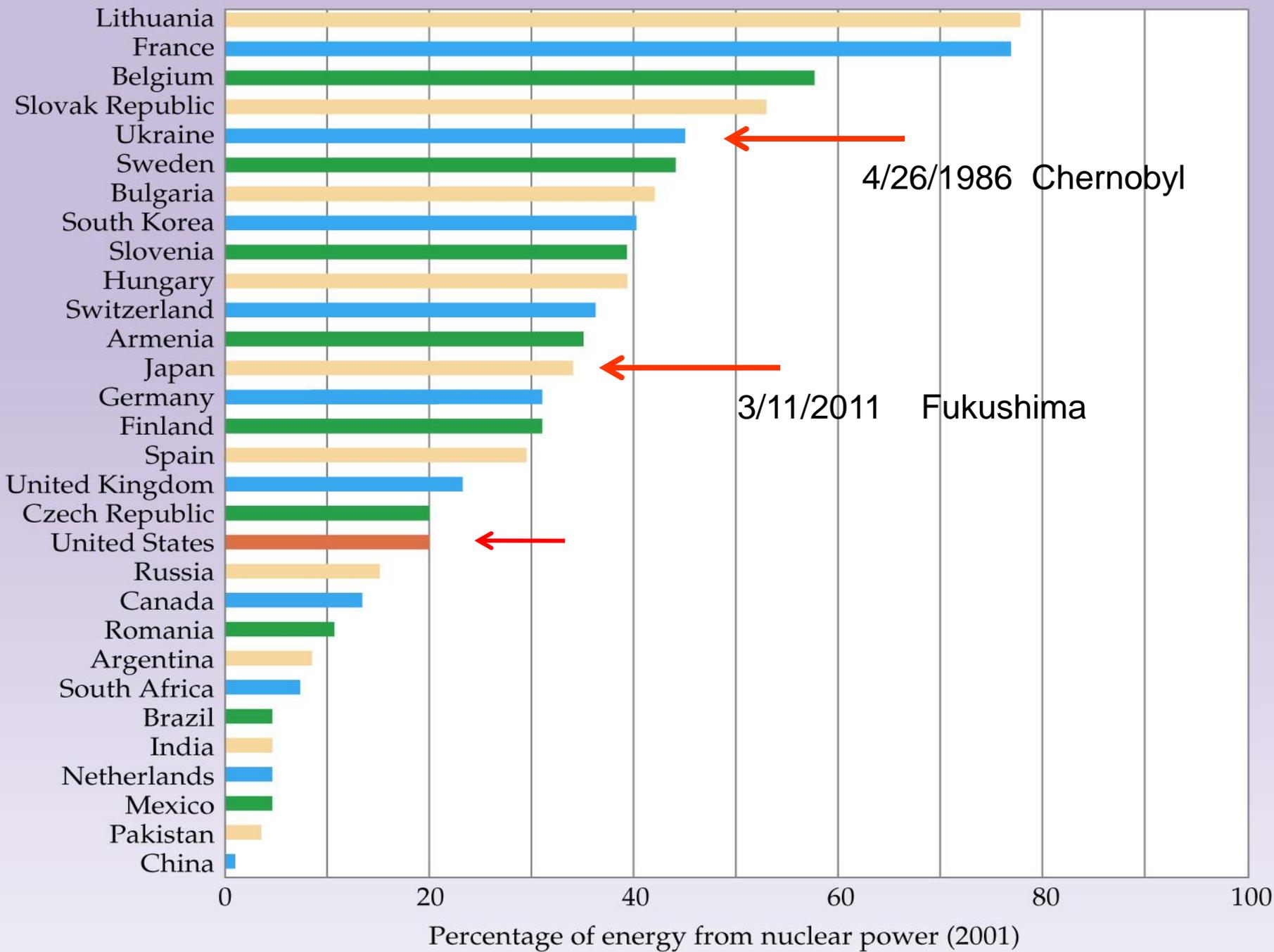
この建物は、チェコの建築家ヤン・レツルの設計監督により1915（大正4）年4月に完成し、特徴ある緑色のドームによって市民に親しまれていました。原爆はこの建物の南東約160メートルの上空約580メートルでさく裂したため、建物は大破・全焼して館内にいた全員が即死しました。その後、原爆の惨禍を表に記録されるとともに、世界平和へのシンボルとして1996（平成8）年12月、ユネスコの世界遺産一翼

（破壊前の広島県産業奨励館）  
The Hiroshima Prefectural Industrial Promotion Hall  
(Approx. 160 meters from the hypocenter)





$$\Delta \text{Energy} = \Delta m \times c^2$$



***Since nuclear radiation affects people, we must be able to measure radioactivity. We also need to relate the amount of radiation received by the body to its physiological effects. Two terms used to relate the amount of radiation received by the body are exposure and dose.***

## **Radioactivity**

**Original unit** - amt of **radioactivity** was the **curie (Ci)** - activity of one gram of radium-226.

Today **1 curie** =  **$3.7 \times 10^{10}$**  *radioactive decays per second* [exactly].

International System of Units (SI) the **becquerel (Bq)** has replaced the curie, where

**1 becquerel** = **1 radioactive decay per second** =  **$2.703 \times 10^{-11}$**  Ci.

The magnitude of radiation **exposures** is specified in terms of the **radiation dose**.

## Exposure:

**Roentgen** - It is the **amount of radiation** required to liberate positive and negative charges of one esu of charge in 1 cm<sup>3</sup> at STP. This corresponds to the generation of approximately **2.08×10<sup>9</sup> ion pairs**.

**Dose:** There are two important categories of **dose**:

1. **Rad:** **radiation absorbed dose**, also known as the **physical dose**, defined by the amount of energy deposited in a unit mass in human tissue. The original unit is the **rad** [100 erg/g]; it is now being widely replaced by the **SI unit, the gray (Gy)** [1 J/kg], where **1 gray = 100 rad**.

2. **Rem:** The **Roentgen equivalent in man** or **biological dose** or **dose equivalent**, expressed in units of **rem** or, in the **SI system, sievert (Sv)**. This dose reflects the fact that the biological damage caused by a particle depends not only on the total energy deposited but also on the rate of energy loss per unit distance traversed by the particle (or "**linear energy transfer**"). (**Q ~ 1 for gamma or beta; ~ 5 protons; ~ 20 for alpha particles.**)

**1 Sv = 100 rem. 1 rem is the average dose received in 3 years of exposure to natural radiation.**

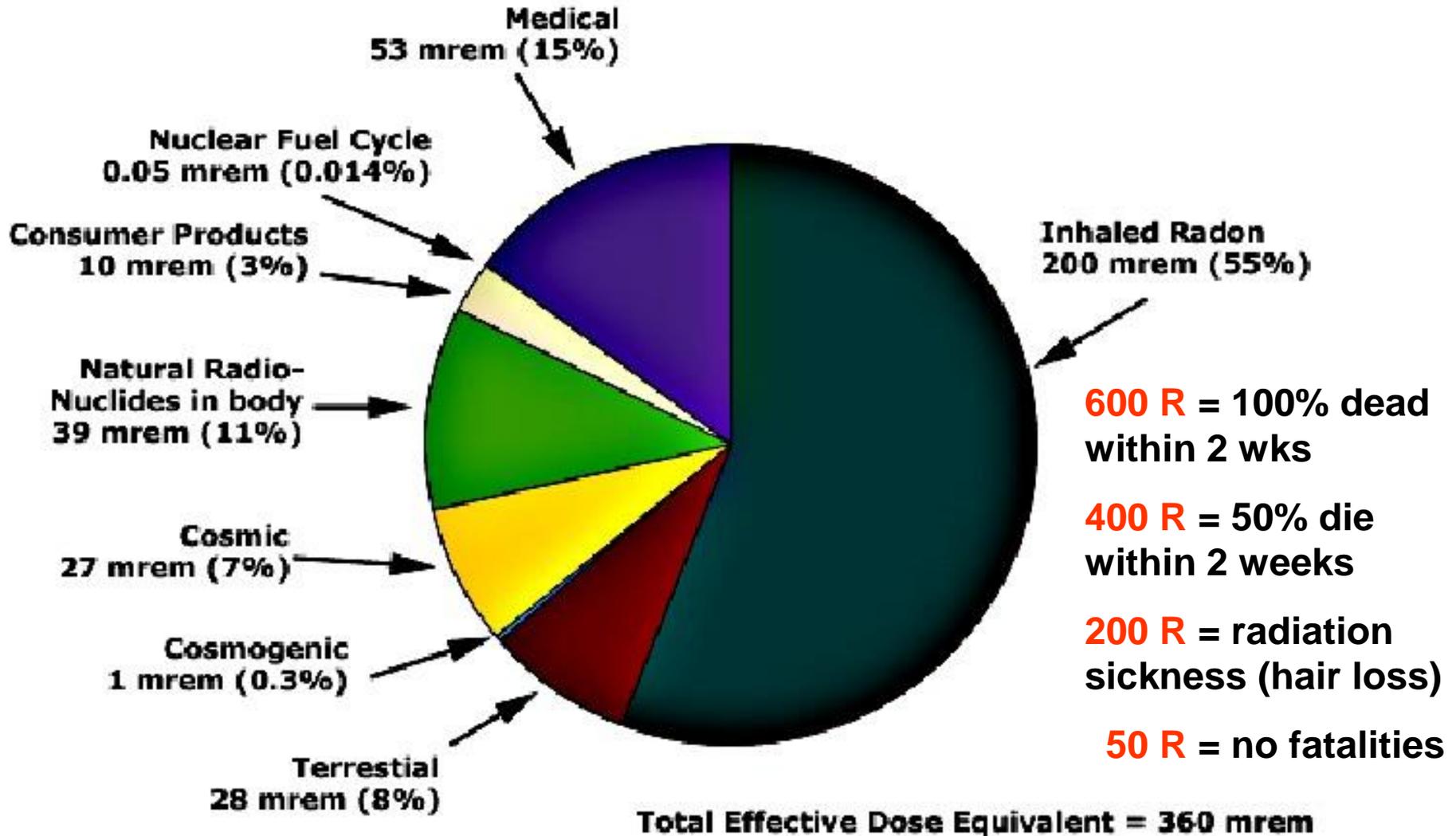
Although a dose of just 25 rems causes some detectable changes in blood, doses to near 100 rems usually have no immediate harmful effects. Doses above 100 rems cause the first signs of radiation sickness including:

- nausea
- vomiting
- headache
- some loss of white blood cells

Doses of 300 rems or more cause temporary hair loss, but also severe loss of white blood cells, which are the body's main defense against infection, makes radiation victims highly vulnerable to disease. Radiation also reduces production of blood platelets, which aid blood clotting, so victims of radiation sickness are also vulnerable to hemorrhaging.

Half of all people exposed to 450 rems die, and doses of 800 rems or more are always fatal. Besides the symptoms mentioned above, these people also suffer from fever and diarrhea. As of yet, there is no effective treatment--so death occurs within two to fourteen days.

## Sources of Exposure



Natural Background Radiation = 295 mrem (82%)  
Manmade Radiation = medical + consumer products = 63 mrem (18%)