Introduction to Radiochemistry

Lecture 1

Luca Doria
SFU & TRIUMF

Fall 2014

Course Outline

- 3 lectures and 1 tutorial per week:
  - Tue: 10:30 – 12:30 , room AQ 5007, Lecture
  - Thu: 10:30 – 11:30 , room AQ 5007, Lecture
  - Thu: 11:30 - 12:30 , room AQ 5007: Tutorial

- Material: Notes and Slides provided online:

  trshare.triumf.ca/~luca/nusc341

- Suggested book:

  RADIOCHEMISTRY and NUCLEAR CHEMISTRY, 3rd Edition, 2002
  By: Gregory Choppin, Jan-Olov Liljenzin, Jan Rydberg
  http://jol.liljenzin.se/BOOK.HTM

- 2 Midterms + Final

- Final Grade:
  40% Final, 20% each midterm,
  20% Presentation/Project/Assignments

Instructor's Contacts

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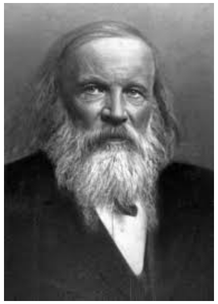
Office hours:

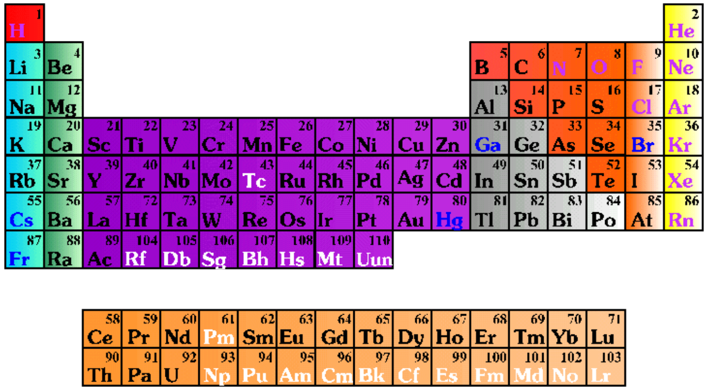
Tue,Thu ~13:30-16:00. By email/phone Mon-Wed-Fri.

A Short History of Nuclear Science

What's Matter made of?

4 fundamental elements, >2500yrs ago
Ancient Philosophers

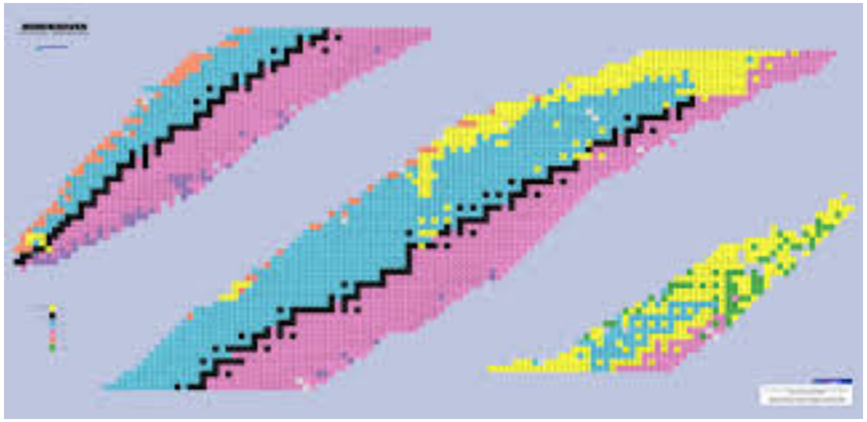




Chemical Elements and
the Periodic Table, 1896
Mendeleev and Lothar Mayer

Time

Nuclei, '900s
Many contributors:
- Rutherford
- Curie
- ...



Radioactivity

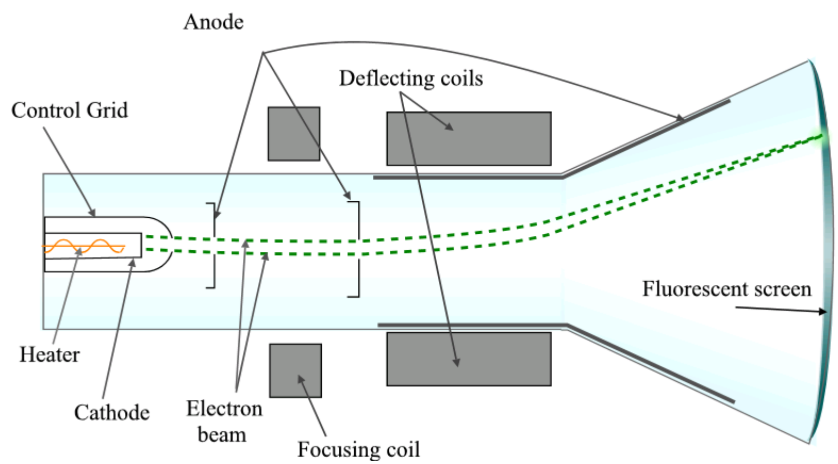
Henry Becquerel in 1896 discovered the phenomenon of **radioactivity.**

This is the birthday of Radiochemistry and over the years there were:

- 12 Nobel Prizes in Chemistry
- 13 Nobel Prizes in Physics

connected with this discovery.

Wilhelm C. Röntgen (1845 -1923) in ~1895



Cathode ray tube

Henri Becquerel (1852 - 1908)

Fluorescence of potassium uranyl sulfate:

$$[K_2UO_2(SO_4)_2 \cdot 2H_2O]$$

Exposed the crystal on photographic plates, covered them with an opaque material and exposed them to sunlight.

In the absence on sunlight, he still noticed the silhouettes of the crystals

Uranium activity: 1896

Marie and Pierre Curie

Pursued the study of "Becquerel rays" with other minerals.

U and Th compounds produced ionizing radiation independent of the chemical composition of the salts. Some U minerals (pitchblends) had greater activity than in potassium uranyl sulfate crystals.

Assumed is due to an active substance other than U or Th.

Chemical extractions of U from pitchblende isolated a new active substance in the bismuth fraction of the separation: **Polonium**

Another substance in the barium-containing fraction: **Radium**

"**Radioactive**" term to describe the activity

The Work of Marie and Pierre Curie

- Isolate a pure sample of radium from the pitchblende
- 2 tons of pitchblende ore (75% U_3O_8)

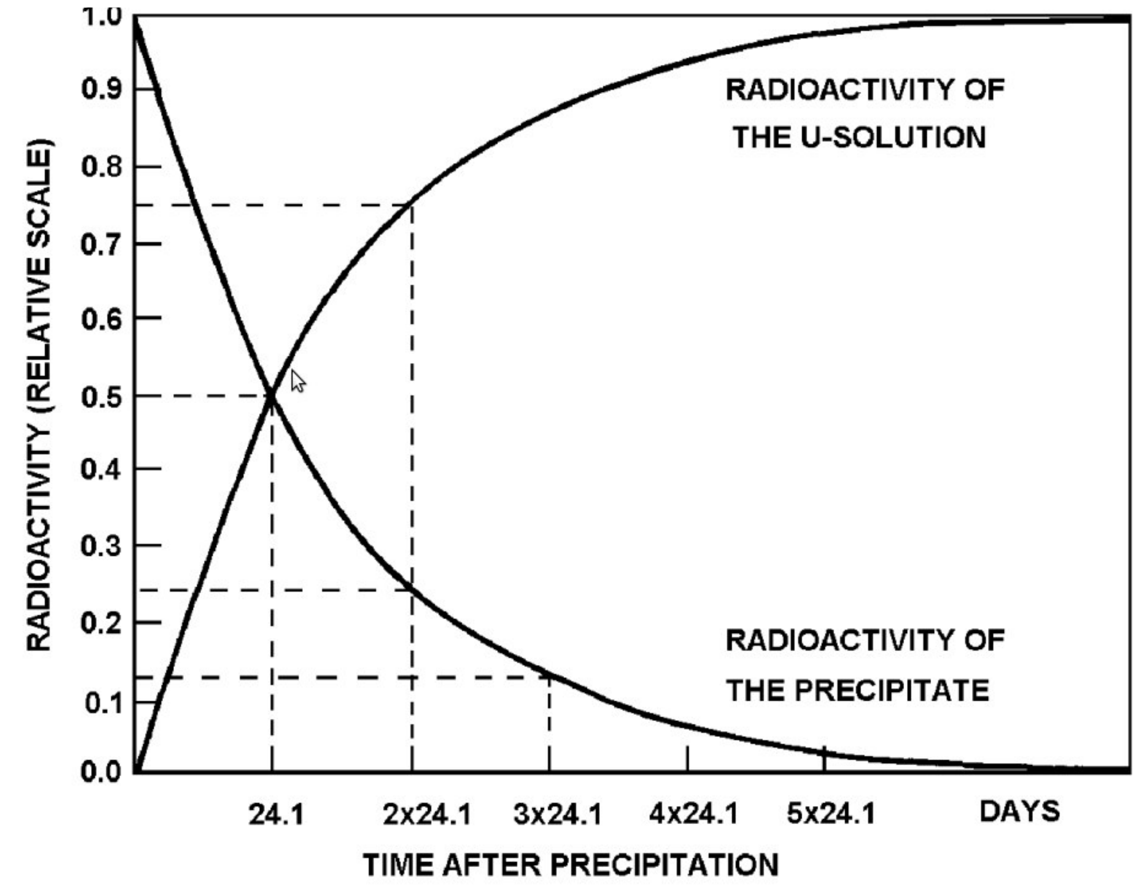
  —> 100 mg $RaCl_2$
- 25% of the total amount of Ra that has actually been present in the ore

Radioactive Decay

W. Crookes and H. Becquerel:

- Precipitate a carbonate salt from a solution containing uranyl ions
- Uranium remained in the supernatant liquid in the form of the soluble uranyl carbonate complex
- Radioactivity now present in the precipitate which contained no U
- Radioactivity of the precipitate slowly decreased with time; while the supernatant liquid showed a growth of radioactivity during the same period
- Beta and gamma-ray and no alpha-radiation was detected (emitted by U)

Separation of daughter element UX (Th) from parent radioelement uranium



$t_{1/2}$ = 24.1 days

Ernest Rutherford (1871-1937)

Together with Frederick Soddy in 1903 they postulated that "radioactivity was not just a consequence of an atomic change that has been previously taking place, but rather that the radioactive emission were directly associated with that change."

When radioactive decay occurred, the atoms of original elements (U, Th) were transformed into atoms of new elements.

Radioelements

U –> UX –> UY

Th –> ThX –> ThY

UX and ThX had chemical properties that were different from original elements and could be separated from them through chemical processes.

3 types of radiations:

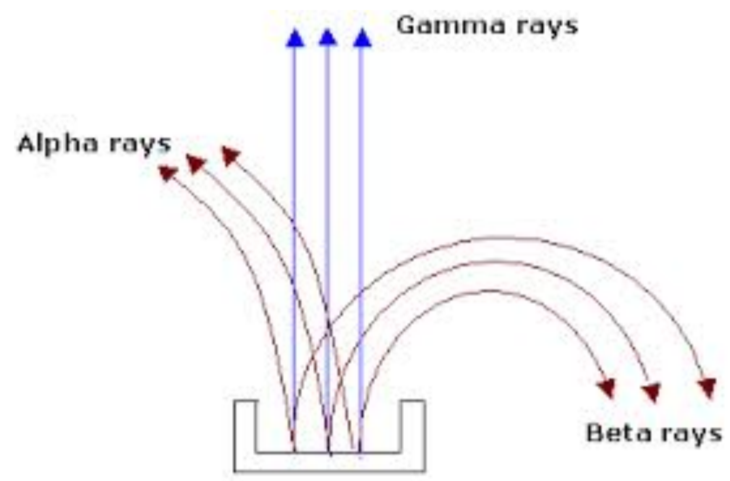
alpha (α), beta (β), and gamma (γ) rays

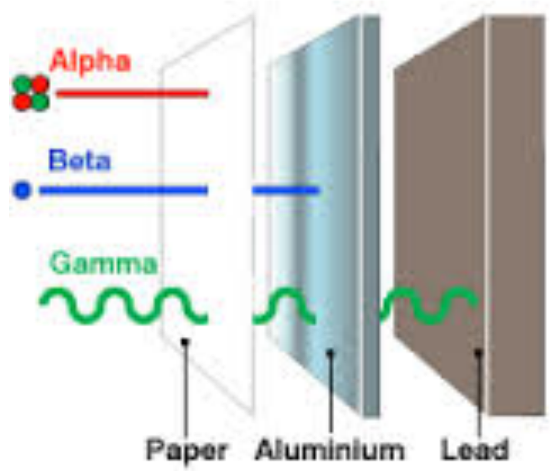
α, β, and γ rays

α **rays:** deflected by electric and magnetic fields in a direction opposite to that of cathode rays: positively charged

β **rays:** behaved in the same manner as the cathode rays, so they thought they were negatively charged

γ **rays:** extremely penetrating and unaffected by electrical or magnetic fields





Induced Nuclear Transformation by Rutherford

Source of α particles in a box, surrounded by ZnS detection screen

α particles produced scintillations at the interaction with the screen

Moved ZnS screen far out of the range of α particles and still observed scintillations

Nitrogen (N) atoms in the air were being disintegrated by collision with α particles and that H atoms were being emitted

$$^{4}He + ^{14}N \longrightarrow ^{17}O + ^{1}H + Q$$

$$^{14}N(\alpha,p)^{17}O$$

"If α particles – or similar projectiles – of still greater energy were available for experiment, we might expect to break down the nuclear structure of many of the lighter atoms"

1929 E.O. Lawrence developed the first cyclotron

Decay Rate

- Experimental fact: Rate of decay per mass unit was constant regardless of the chemical or physical state of radioelement; different for each element.

- **Half-life $t_{1/2}$**: the time it takes for the radioactivity of an element to decay to one-half of its original value

ThA 0.1 s; UX 24.1 days; U millions of years

The atom: status in ~1910

- By 1910 40 different chemical species have been identified by their chemical nature, radiation, $t_{1/2}$
- Space for only 11 elements between lead and uranium
- 40 elements were known in the decay series from U to Pb

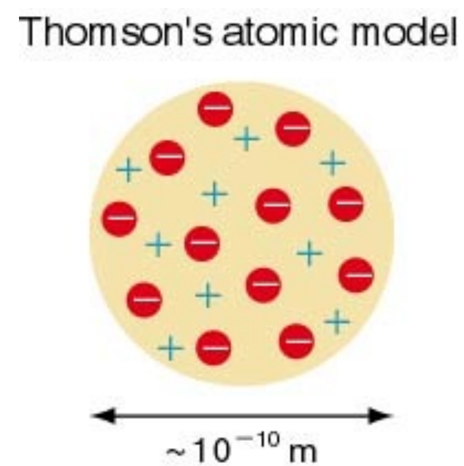
The atom and atomic models

Question at the beginning of the 20th century:

What was the internal structure of atoms?

- 1897 J.J. Thomson discovers the **electron**

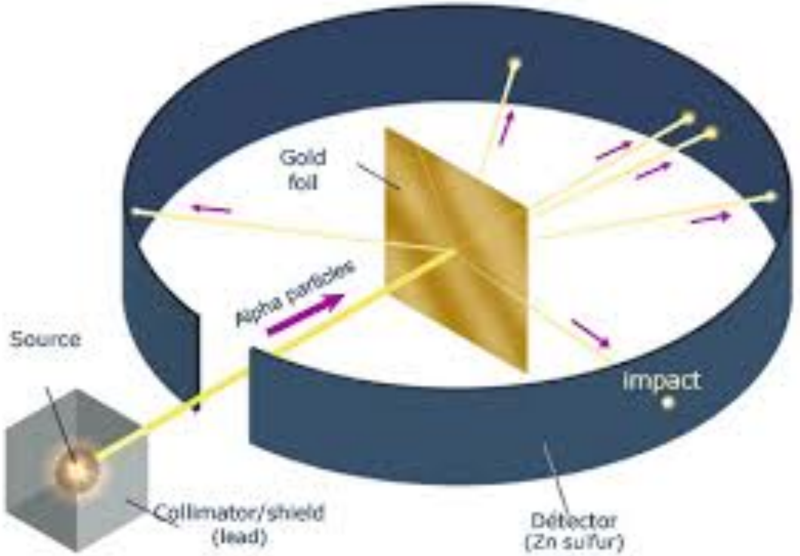
- The discovery of the **proton** was a gradual process and is attributed to Rutherford (cc 1911)



Atom:
Positive (protons) and negative (electrons) particles evenly distributed throughout the atom.

Rutherford's Experiment, or the Discovery of the Nucleus
(with H. Geiger and E. Marsden)

1911:
Alpha and Beta particles bombarded a gold foil of 0.00004cm (0.4um) thickness
The angle of scattering was measured.
1/8000 alphas were strongly deflected (angles > 90deg).



Conclusion: Particles were not evenly distributed in the atom but there is a central charge concentrated in a small space.
The nucleus: 10^{-14}m, positively charged

Watch the experiment on youtube:
http://www.youtube.com/watch?v=5pZj0u_XMbc

Conclusions of Rutherford`s experiment

1) The entire positive charge of the atom is concentrated in a small volume (10^{-14} m), called the **nucleus**

2) Atomic electrons have a much smaller mass and surround the nucleus

Atom (10^{-10} m)

1913 N. Bohr using quantum mechanical concepts described such a model.

Isotopes

1913 F. Soddy observed that radioactive "elements" with different mass have the same chemical properties.

He called the similar elements, isotopes.

New elements are produced by α-decay, two places to the left of the mother element in the periodic system

Beta-decay produces a new element one place to the right of the mother element

The elements that fall in the same place in the periodic system are chemically identical.

ISOTOPE (Soddy): different radioactive species with the same chemical identity. Same Z.

Isotopes

J.J. Thompson: Also non-radioactive elements have isotopes.

Charged gaseous ions allowed to pass through electric or magnetic fields followed hyperbolic paths which are dependent on masses and charges of the ions; darkening spots on photographic places proportional to the number of ions that strike the plates

Ne consists of two types of atoms with different atomic masses 20 and 22.

The degree of darkening on the photographic plates consisted to about 90% of atoms with mass 20 and 10% of atoms with number 22.

A chemical element may consists of several kinds of atoms with different masses but with the same chemical properties.

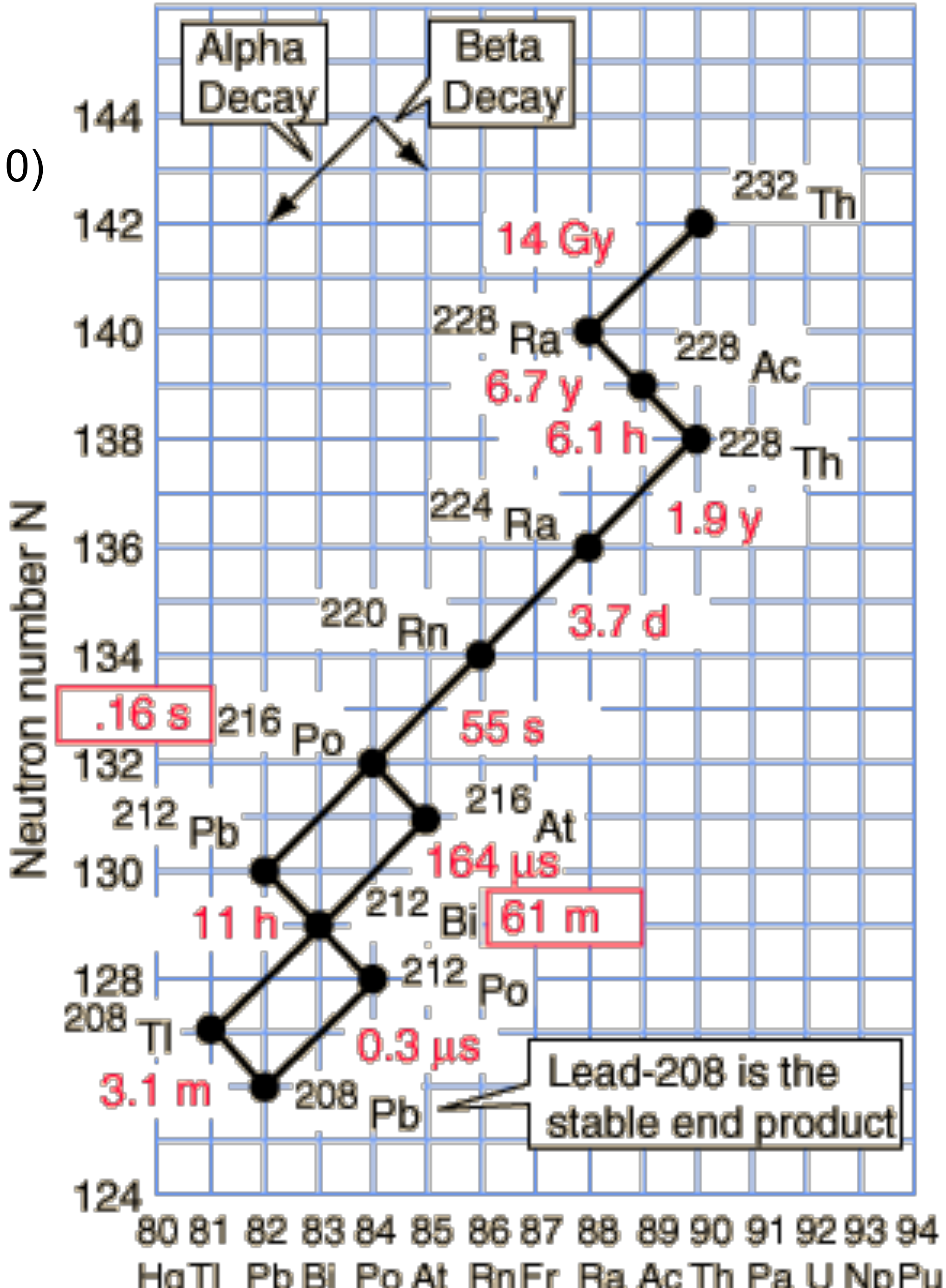
The Thorium-232 Decay Series (4n + 0)

- [ ] ^{235}U Series
- [x] ^{232}Th Series
- [ ] ^{238}U Series
- [ ] ^{237}Np Series

The four natural radioactive series

6 α particles
4 β^- particles

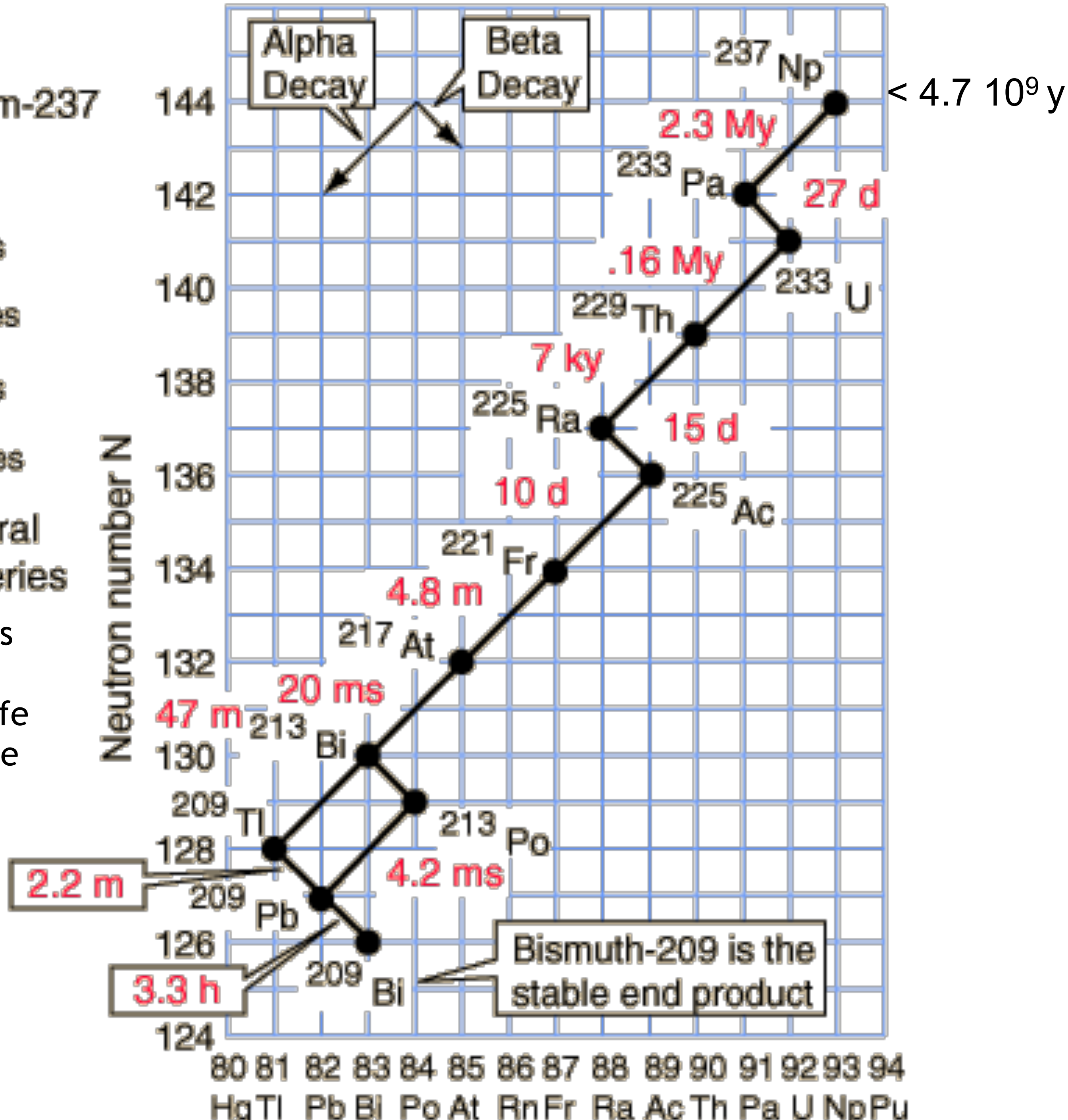
Boxed values for half-life are for multiple decay paths



The Neptunium-237 Decay Series

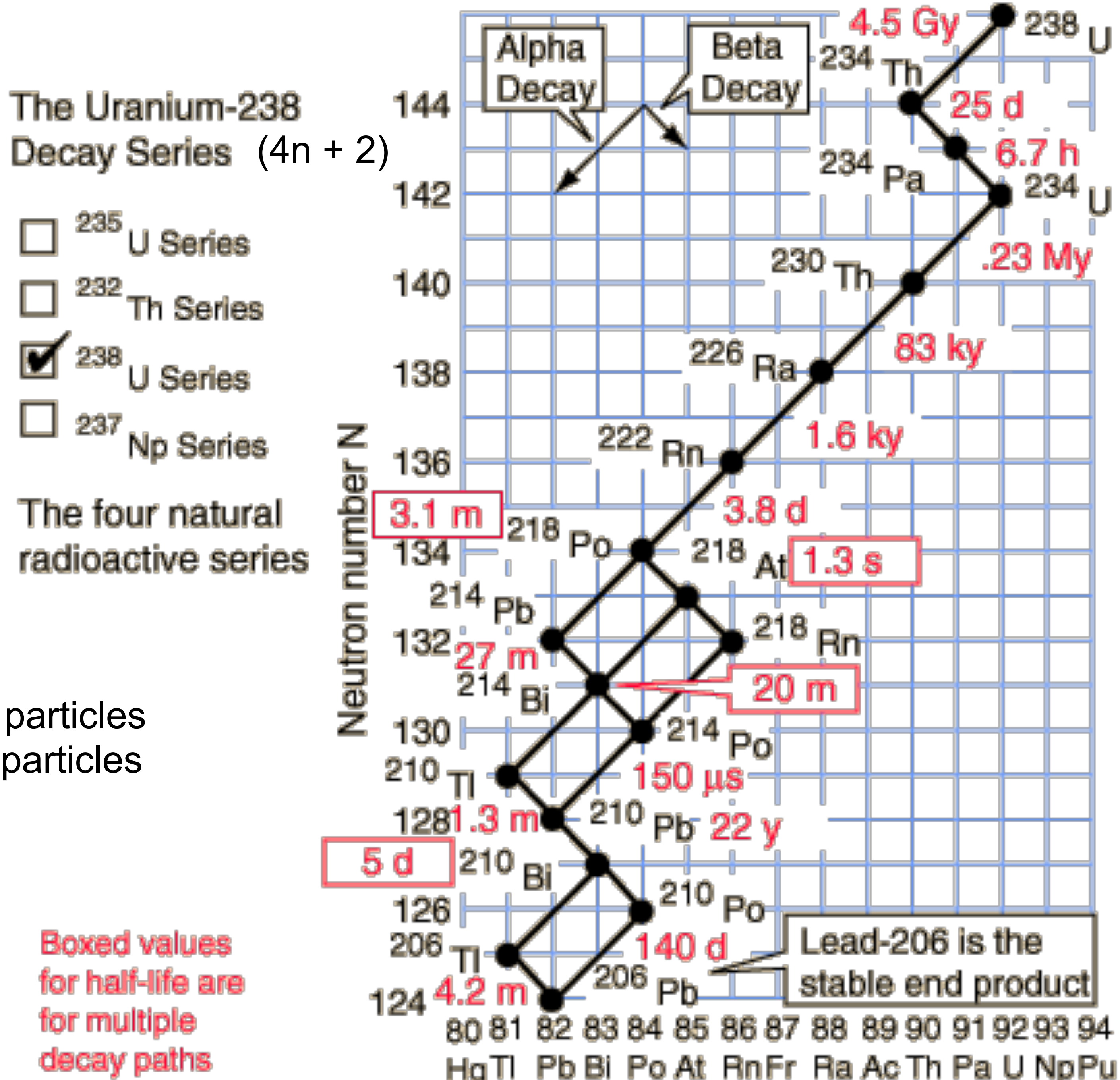
- [ ] ^{235}U Series
- [ ] ^{232}Th Series
- [ ] ^{238}U Series
- [x] ^{237}Np Series

The four natural radioactive series



The members of this series are not presently found in nature because the half-life of the longest lived isotope in the series is short compared to the age of the earth.

7 α particles
4 β^- particles



8 α particles
6 β particles

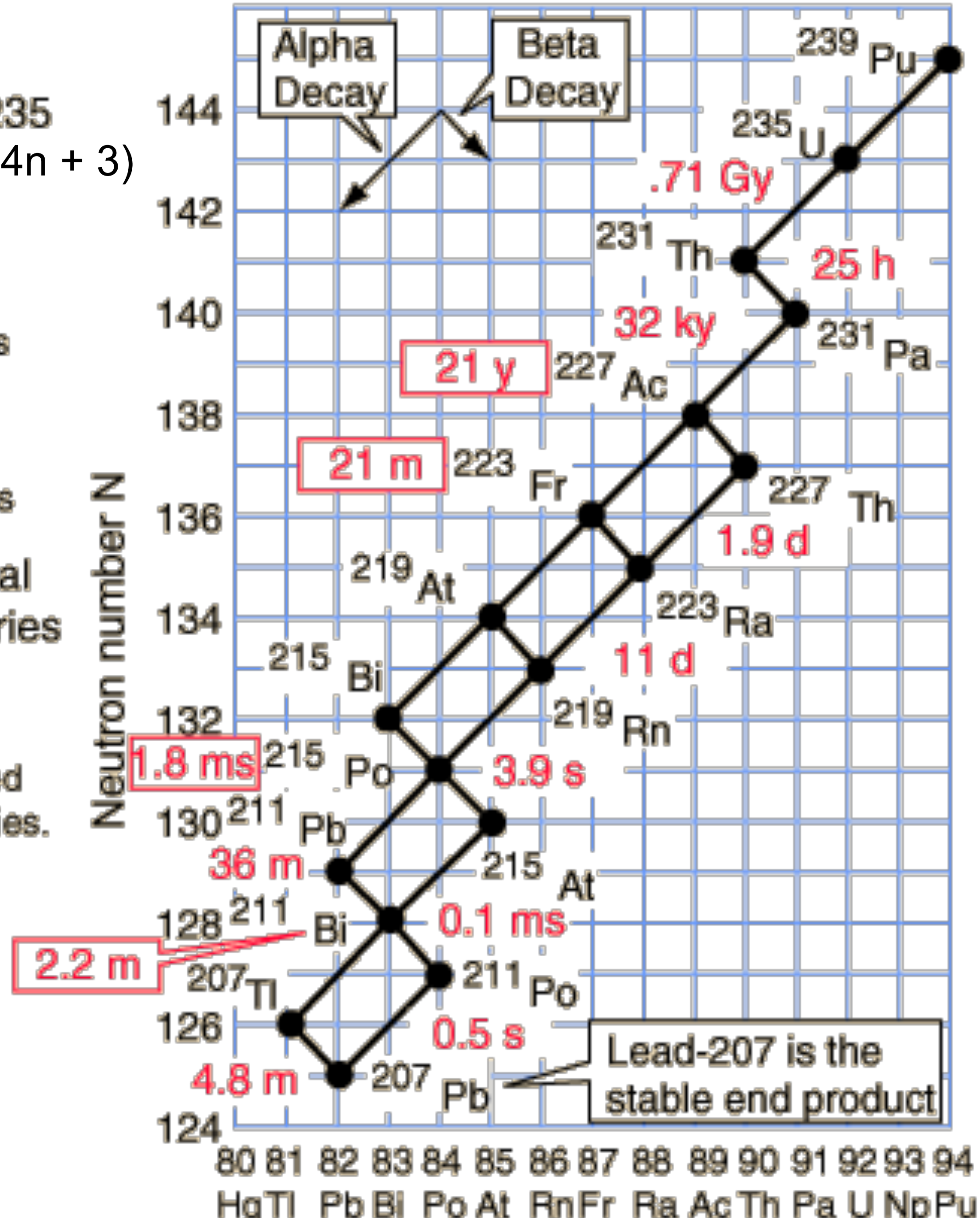
http://hyperphysics.phy-astr.gsu.edu/

The Uranium-235 Decay Series (4n + 3)

- [x] 235 U Series
- [ ] 232 Th Series
- [ ] 238 U Series
- [ ] 237 Np Series

The four natural radioactive series

This series is traditionally called the Actinium series.



7 α particles
4 β particles

Boxed values for half-life are for multiple decay paths

Introduction to Radiochemistry

Lecture 2

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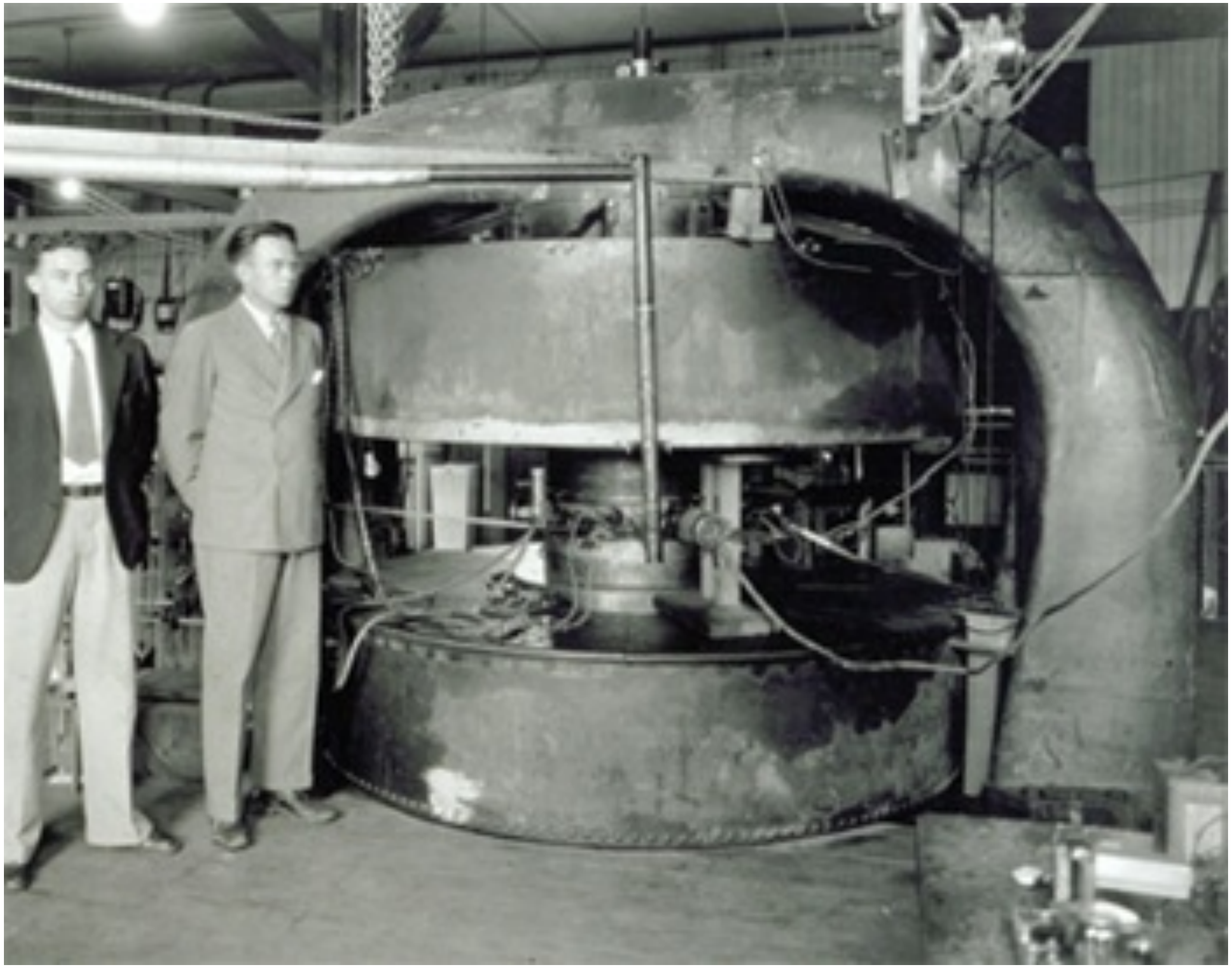
Until now, radioactivity was coming only from natural sources

For further advancements, more intense (and more energetic) sources were needed:

- **COSMIC RAYS**

- **ACCELERATORS**

22 inch cyclotron (80-keV protons)



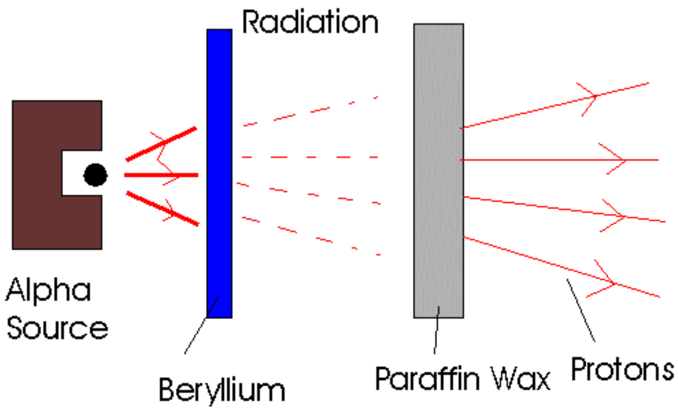
The Neutron

- **1920** Rutherford proposed the existence of a third atomic particle in addition to the proton and electron with mass = 1 amu and electrical charge 0
- **1932** James Chadwick discovered the neutron:
  Po radiation source mounted behind a disk of pure Be
  α particles from Po struck the Be and very penetrating radiation was emitted

This radiation was capable of causing the ejection of high-energy protons from paraffin wax or other hydrogen-rich materials:

$$^{9}Be(\alpha,n)^{12}C$$

Because is electrically neutral, the neutron penetrates the nucleus without suffering Coulomb repulsion.



The Positron

1932: e^+ discovered by Carl Anderson (theoretically predicted by Dirac in 1930)

Carl D. Anderson, Physical Review vol. **43**, p. 491 (1933)

$\vec{B}$

Cloud chamber photograph of cosmic-ray tracks in a magnetic field. The positron is coming from below and hits a Pb plane loosing momentum. If it would have been an electron, the curvature would have been to the other side.

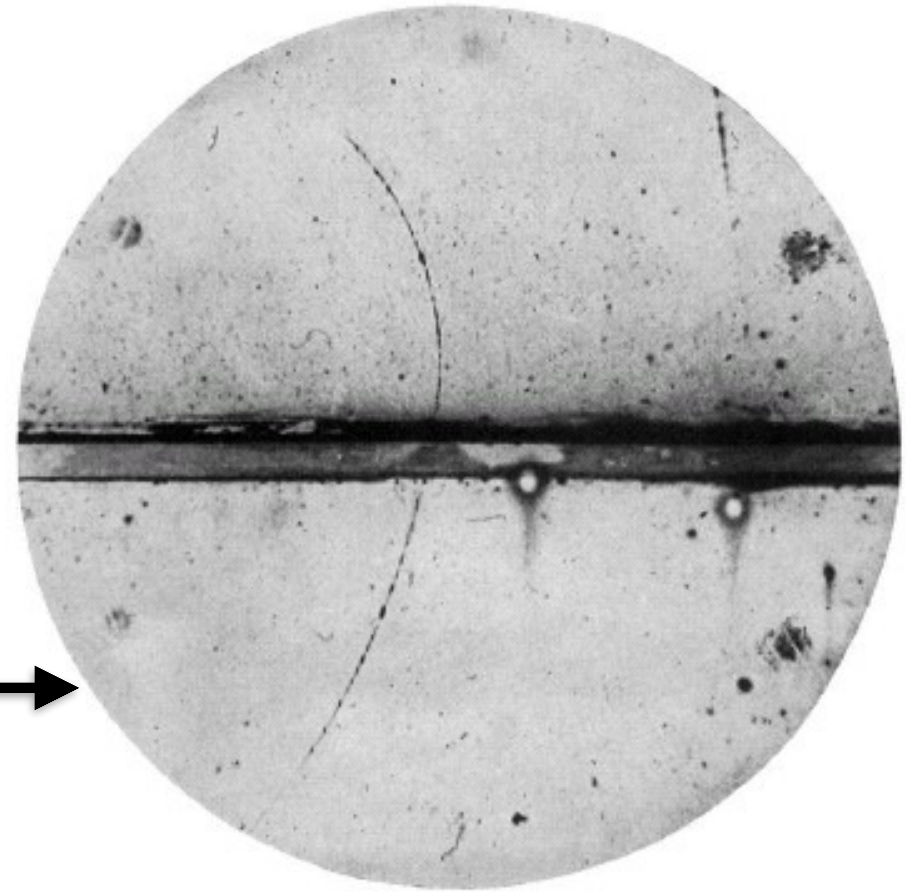


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Irene and Frederic Joliot-Curie

1934: they reported on the first artificial production of a radioelement:

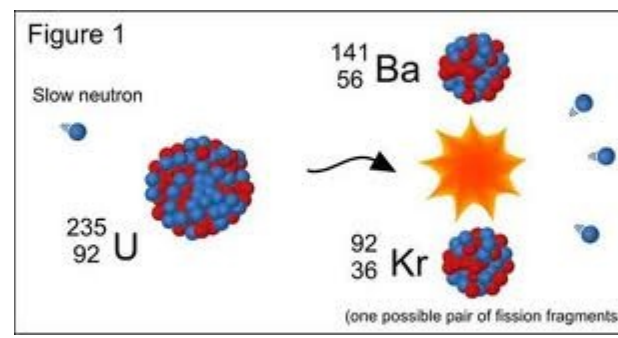
$$^{10}B(\alpha,n)^{13}N$$

Z = 7	^{13}N 9.97 m	^{14}N 99.63	^{15}N 0.368

Fission

1939 Otto Hahn and F. Strassman split an atom for the first time by bombarding U with neutrons; demonstrated that the products were much lower in mass than U

$$n + {}^{235}U \rightarrow {}^{141}Ba + {}^{90}Kr + 2\text{-}3\ n$$



Transuranic Elements
(with atomic numbers $Z_U > 92$)

1940 E.M. McMillan and P.H. Abelson
First element ^{239}U produced by

$$^{238}U(n,\gamma)^{239}U$$
$$^{239}U \rightarrow {}^{239}Np + \beta^-$$
$$^{239}Np \rightarrow {}^{239}Pu + \beta^-$$

(not observed at that time due to its long half-life of 24 100 years)

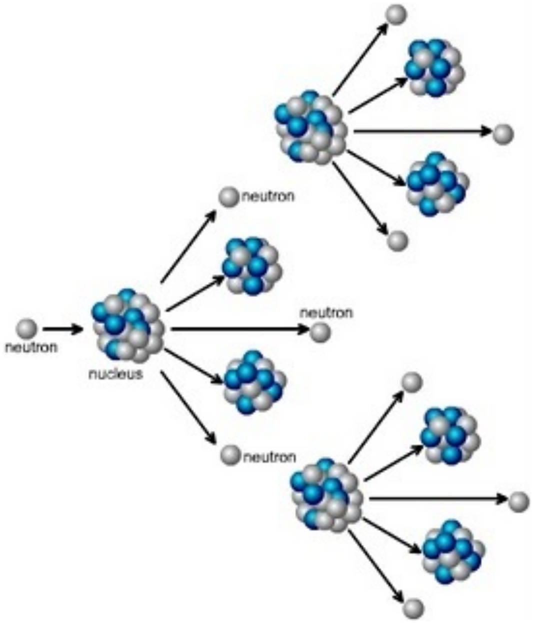
1940 Pu by Kennedy and Seaborg

$$^{238}U(d,2n)^{238}Np$$
$$^{238}Np \rightarrow {}^{238}Pu + \beta^- + \nu$$
$$^{238}Pu \rightarrow {}^{234}U + \alpha$$ (half-life 87.7 y)

Nuclear Energy

In fission, more neutrons are released than is required to for the next fission event → **chain reaction**

1940 -1942 E. Fermi build the first **nuclear reactor** ("CP-1") for controlled release of nuclear energy.



Compton: "The Italian navigator has just landed in the new world".

Conant: "Were the natives friendly?"

Compton: "Everyone landed safe and happy".

Leo Szilard: `` this day will go down as a black day in the history of man kind``

1945 – first atomic bombs on Japan

Pacific applications

- 1949 Willard Libby reported on the radiocarbon dating method
- 1986 Irradiation of fruits and vegetable to kill insects and bacteria and to slow ripening
- Energy Production
- Nuclear medicine
- Geology
- Agriculture
- Industry
- ...

Search for new elements

Z > 100

1955: Z = 101 Md (Mendelevium)

1958: Z = 102 No (Nobelium)

1961: Z = 103 Lw (Lawrencium)

1982: Z = 107 (Bh; Bohrium) and 109 (Mt; Meitnerium)

1984: Z = 108 (Hs; Hassium)

....

Superheavy elements and the island of stability

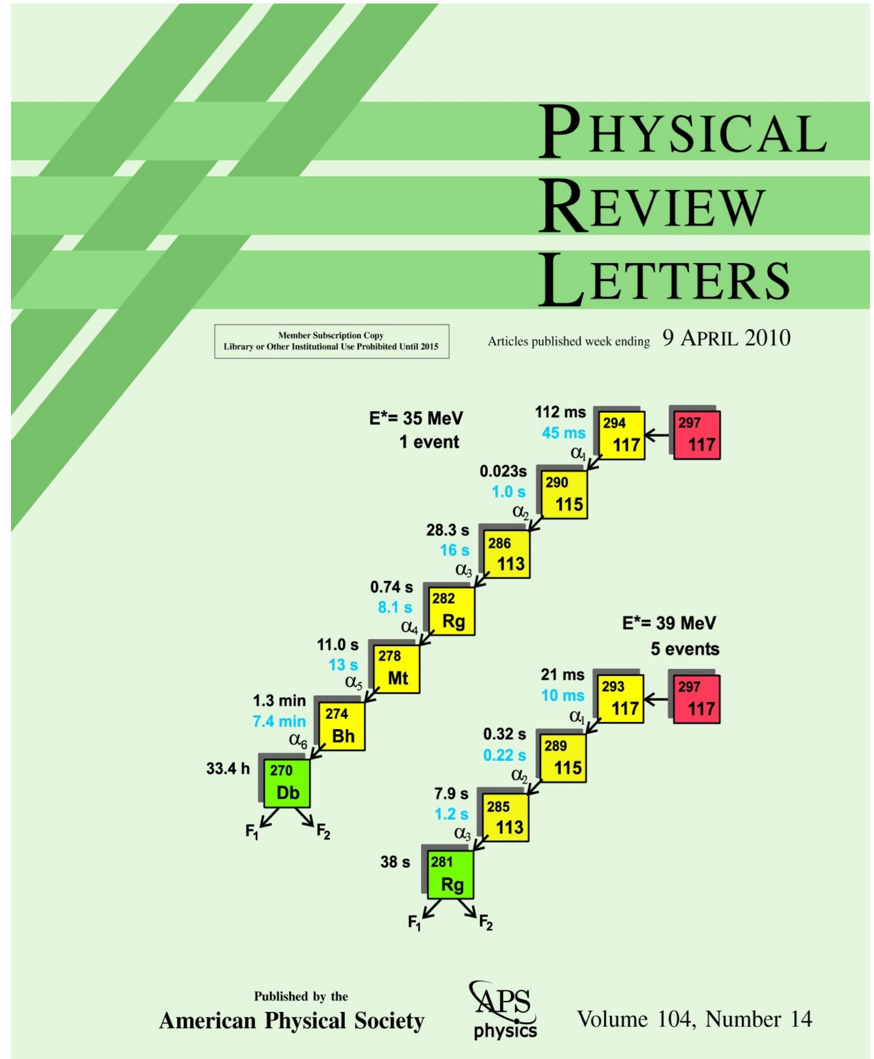
2010 `Synthesis of a new element with atomic number Z = 117` Phys. Rev. Lett. 104 (2010) 142502

Z = 117

$^{297}117$

Yuri Oganessian

Dubna, Russia



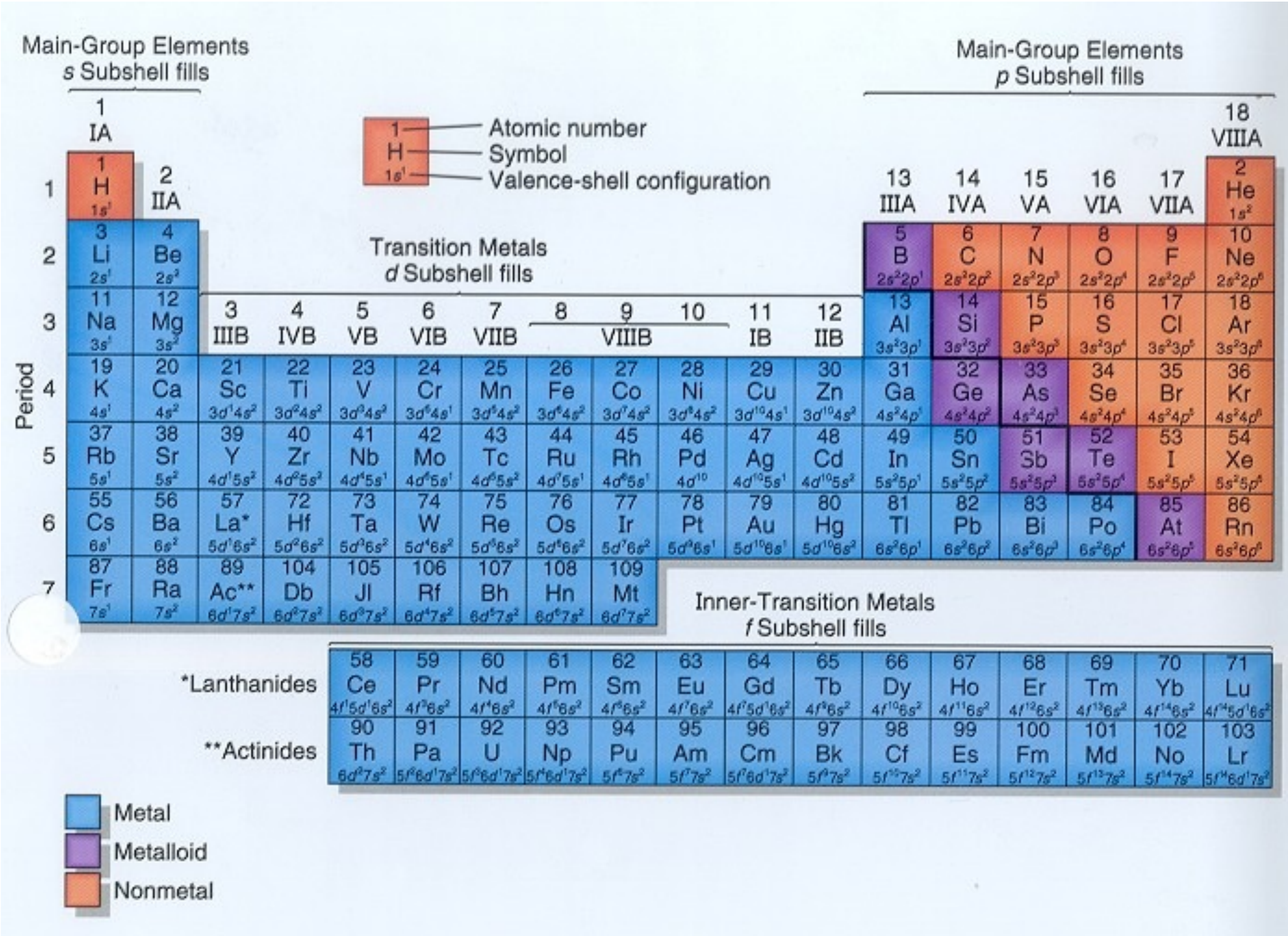
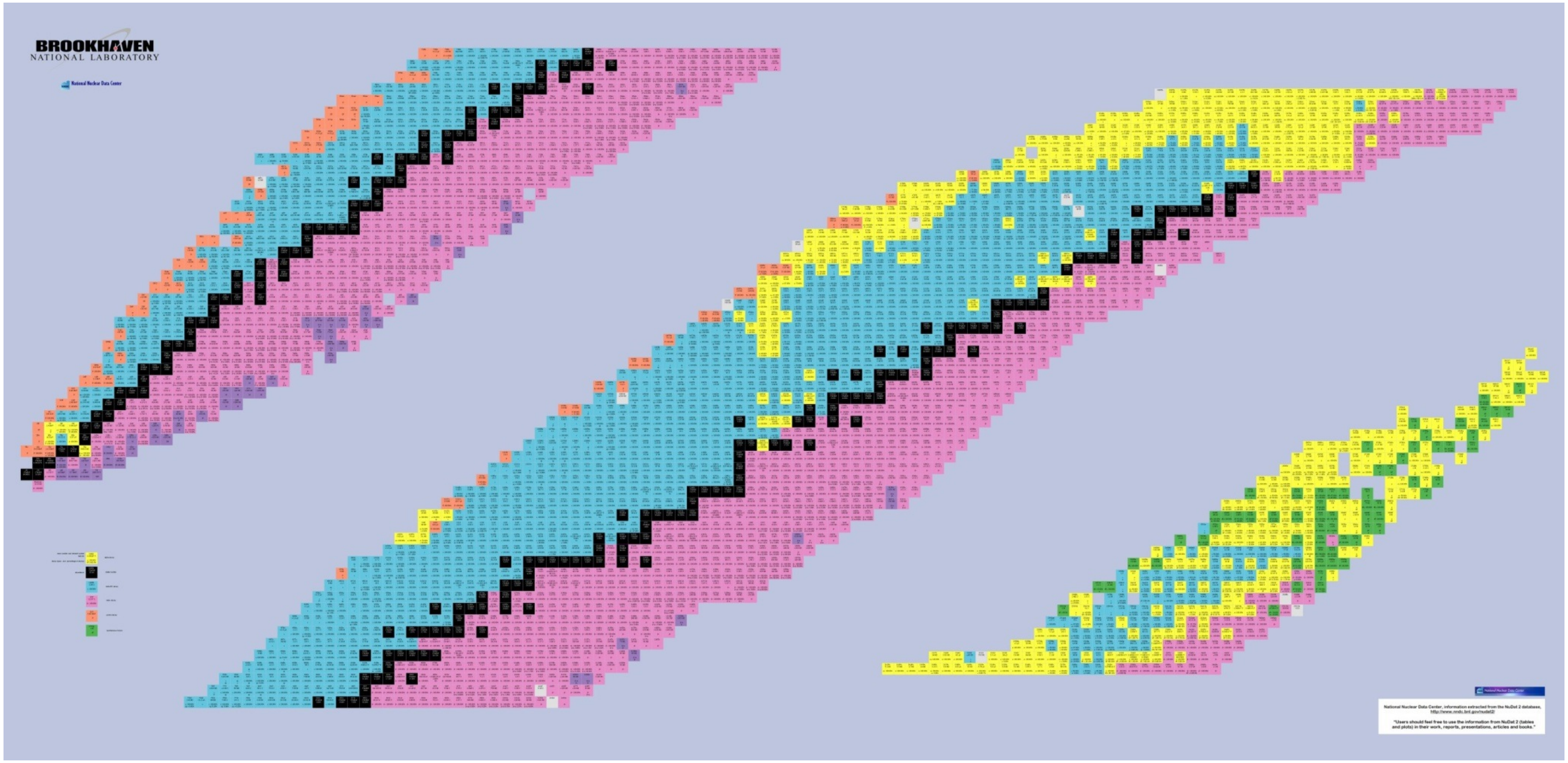

Main-Group Elements
s Subshell fills
Main-Group Elements
p Subshell fills
Atomic number
Symbol
Valence-shell configuration
Transition Metals
d Subshell fills
Inner-Transition Metals
f Subshell fills
Period
*Lanthanides
**Actinides
Metal
Metalloid
Nonmetal

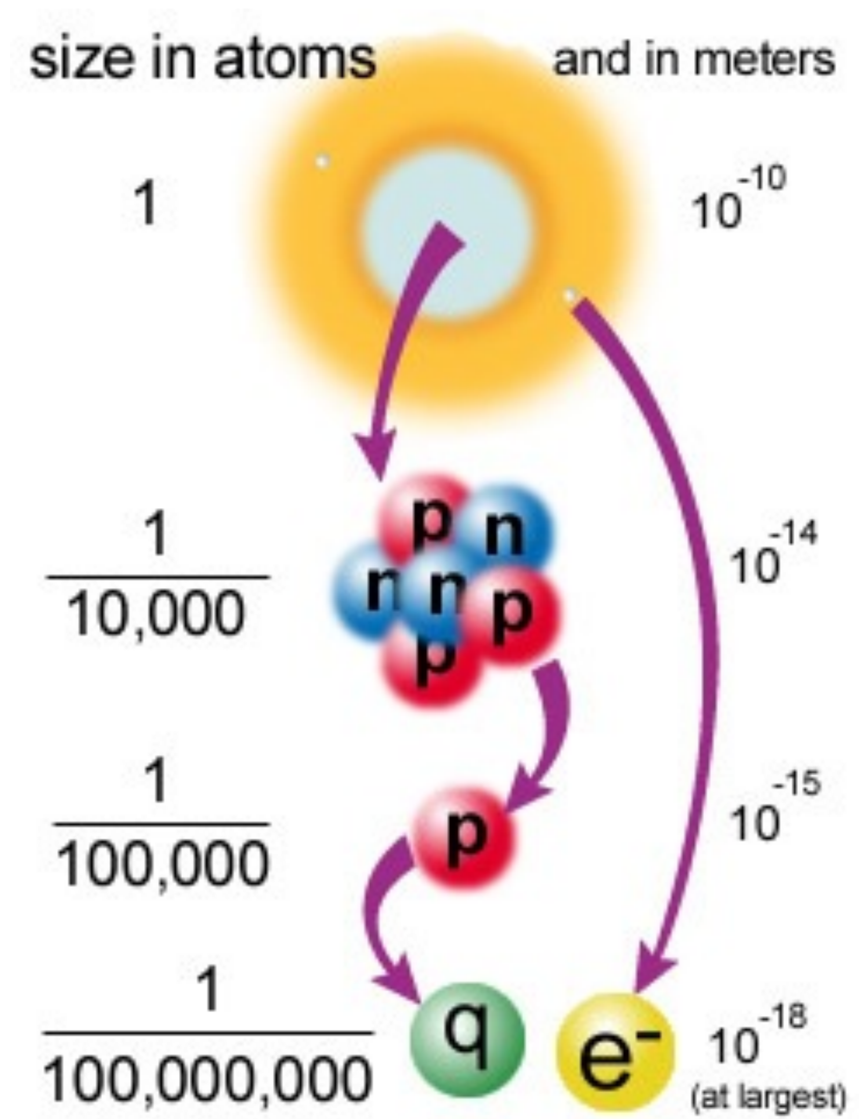
Chart of Nuclides



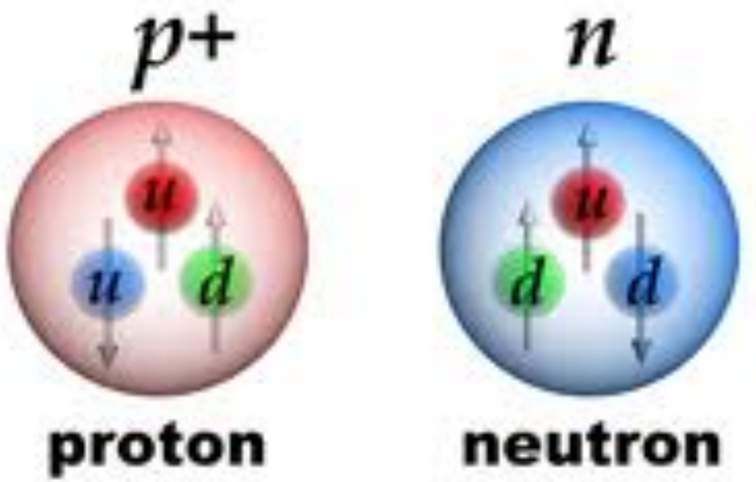
Building Blocks of Matter

The Building Blocks of Matter

- Molecules consists of electrically neutral group of at least two atoms held together by chemical bonds.
- An atom consists of a nucleus, which carries almost all the mass of the atom and a positive charge Ze, surrounded by a cloud of Z electrons.
- Nuclei consist of two types of fermions (1/2-spin particles): protons and neutrons, collectively called nucleons.
- Nucleons consists (mostly) of three quarks.


size in atoms
and in meters
1
10^-10
1/10,000
p n n n p p
10^-14
1/100,000
p
10^-15
1/100,000,000
q
e-
10^-18
(at largest)

Nucleons (Baryons)



m_p = 1.6726 x 10^{-27} kg
= 938.26 MeV
= 1.007 276 u

Charge: e

m_n = 1.6749 x 10^{-27} kg
= 939.55 MeV
= 1.008 665 u

Charge: 0

m_e = 9.10938188 × 10^{-31} kg = 5.4857990946(22)×10^{-4} u = 511 keV

Hydrogen atom 1.007 825 u

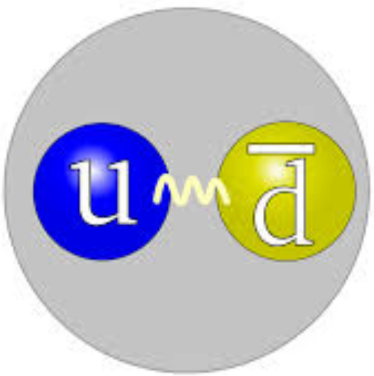
Mesons

Mesons are made by a quark and an antiquark —> color-neutral

Example: the lightest meson, the pion has quark content (ud)

Mesons have spin zero ——> bosons.

Relevant in the description of the nuclear force.



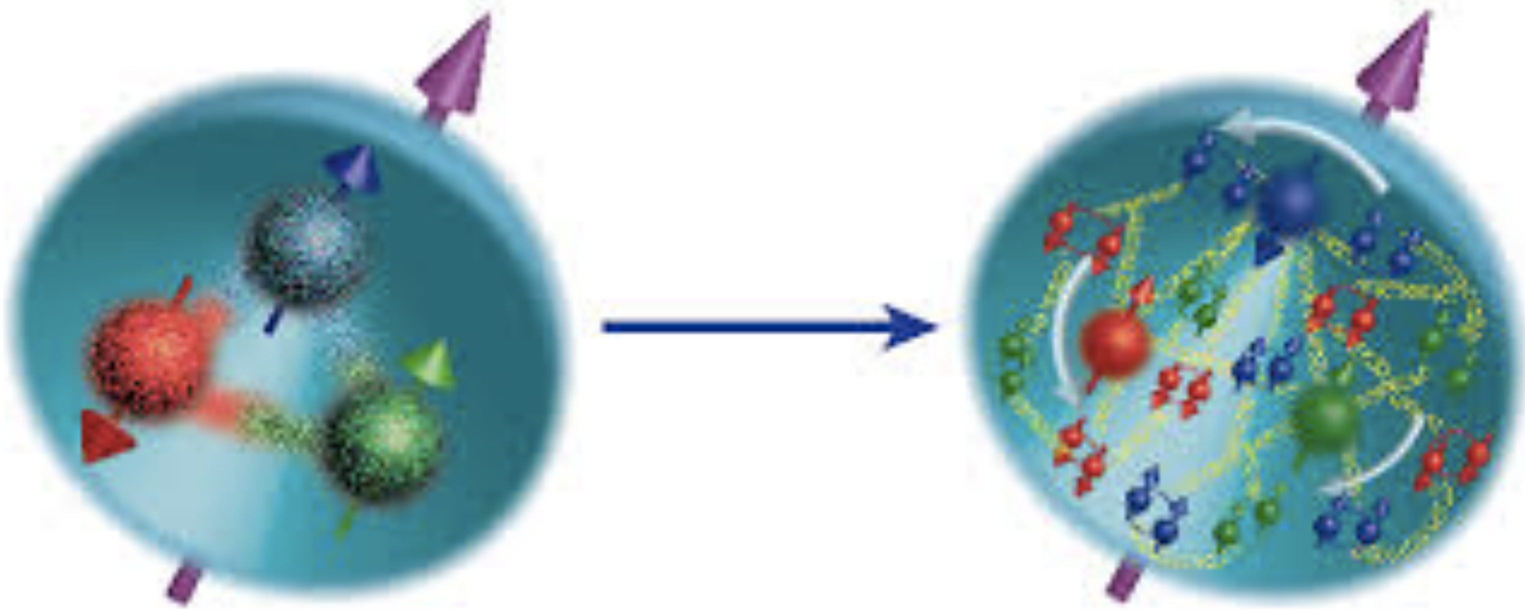
Quarks have fractional charges

Quark	Symbol	Spin	Charge	Mass*
Up	u	1/2	+2/3	1.7-3.3 MeV
Down	d	1/2	-1/3	4.1-5.8 MeV
Charm	c	1/2	+2/3	1270 MeV
Strange	s	1/2	-1/3	101 MeV
Top	t	1/2	+2/3	172 GeV same as
Bottom	b	1/2	-1/3	4.19 GeV(MS) 4.67 GeV(1S)

The proton has unit charge: 2/3 + 2/3 - 1/3 = +1
The neutron is neutral: -1/3 -1/3 + 2/3 = 0

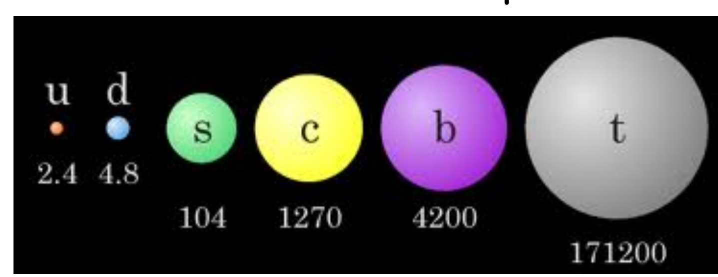
The last quark discovered, the top (in 1995) is has heavy as a nucleus!

Things are more complicated…

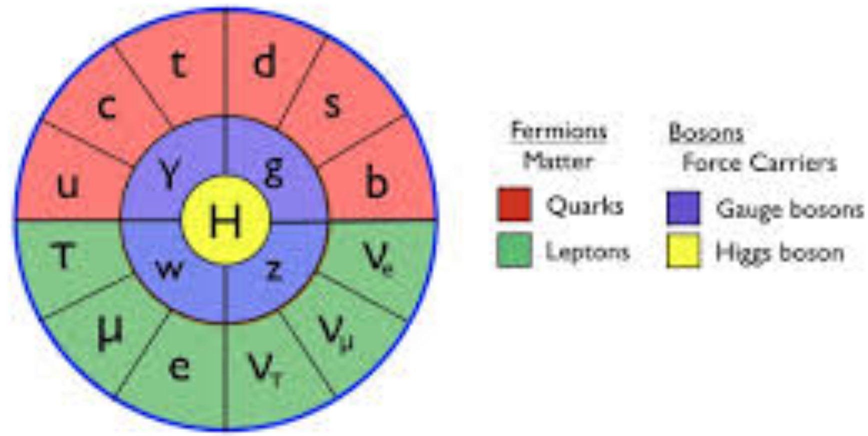


The strong force is significantly more complex wrt to electromagnetism. We will see some aspects of it later, since it is relevant to the description of nuclear forces.

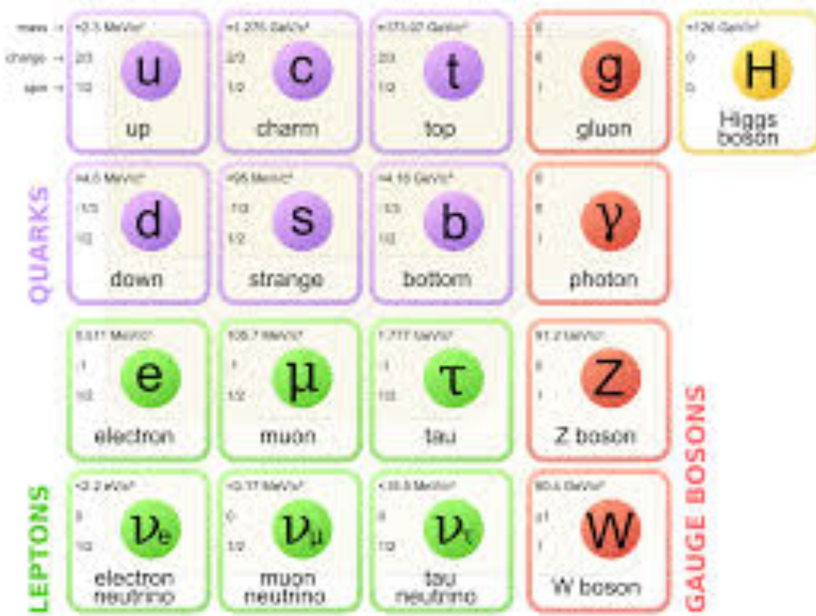
The Standard Model



Particles of the Standard Model
Classification in Types

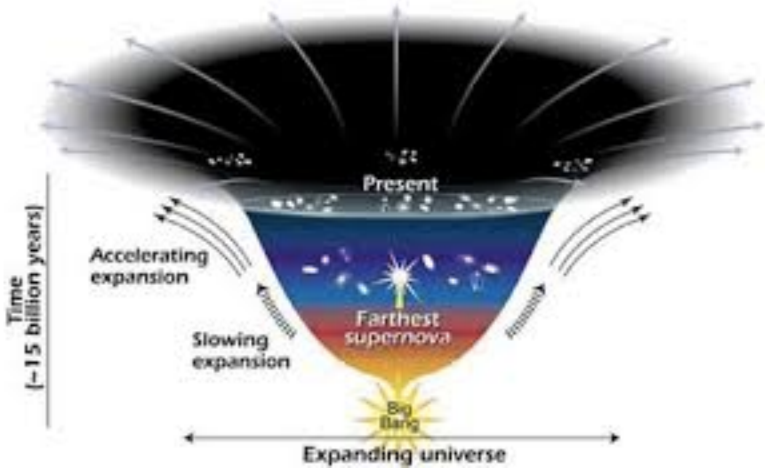


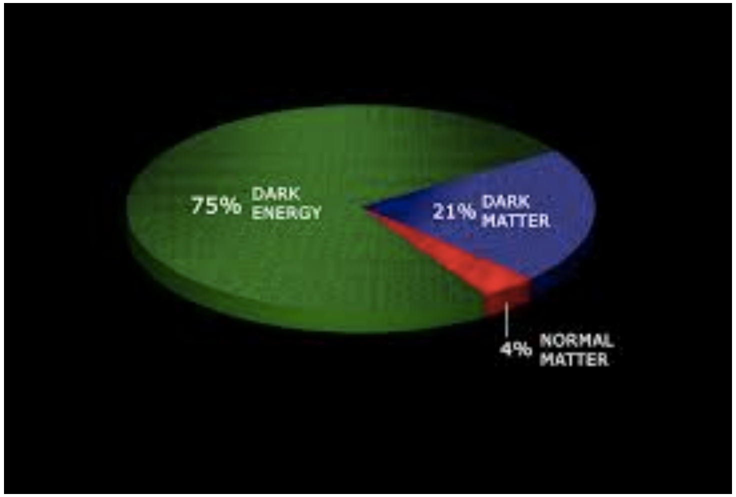
Particles Classification in Families



Quark Masses Comparison

Open Issues in Subatomic Physics





- Intersection Particles/Cosmology
- Why 3 families?
- Unification of Forces?
- Is Supersymmetry a solution?
- Nature of Neutrinos?
- Is the proton really stable?
- Is the EWSB mechanism understood?
- ....many more....

From Nuclei to Particles

1919: Proton
1932: Neutron
1932: Positron (Antimatter)
1937: Muon
1947: Pion, Kaon, Lambda0
1955: Antiproton
1956: Electron Antineutrino
1962: Muon Neutrino
196X: Many Baryons and concept of "Parton"
1974: J/Psi meson
1975: Tau
1977: Upsilon meson
1979: Gluon
1983: W/Z vector bosons
1995: Top Quark
2000: Tau neutrino
2012: Higgs Boson: the Standard Model is complete after 1 century of research!

From this..

..to this!

First assignment

Spend some time in the library and/or on the internet and:

- Write an ~1 page (more if you like) history-oriented essay about a specific part of the history of nuclear science we have discussed. The historic part should contain a discovery or key advancement.

- Use a language suitable for the general public.

- Include (at least) one figure with caption.

- Include a bibliography of your sources of information.

- Marking depends on: originality, logical consistency, (graphical) style, clarity.

<u>Bring it printed for the next Thursday's Lecture (Sept 11th).</u>

POSSIBLE TOPICS/SUGGESTIONS: Rutherford's Experiment, the Fermi's first nuclear pile, nuclear energy, first accelerators, super-heavy elements, radioactive decays, radio-dating, chart of nuclides,mass separation, transuranic elements, …