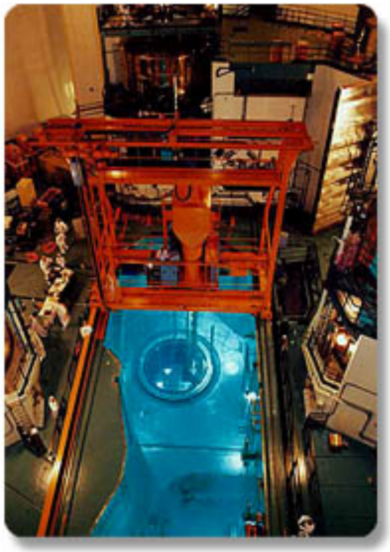
PHYS 575A/C/D

Autumn 2015

Special Topics in Experimental Physics: Radiation and Radiation Detectors

Course home page:

depts.washington.edu/physcert/radcert/575website/



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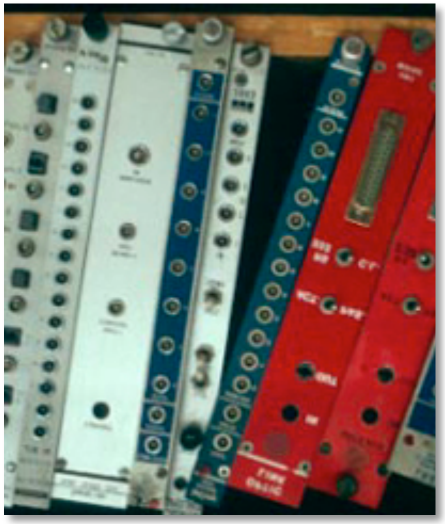


But first...Orientation for new students

UW Professional MS in Physics (PMSP) program

- Whom do I contact with questions? ...also GNM, Certificate students
  - **Any academic question or issue, advising, selecting courses:**

    Physics faculty coordinator: THAT'S ME!

    Jeffrey Wilkes, B-303 Physics-Astronomy, (206) 543-4232

    emsp@uw.edu*
  - **Any question or problem with admissions, degree requirements, rules and regulations of Graduate School or UW :**

    Physics program administrator/advisor

    Catherine Provost, office C-139B Physics-Astronomy, (206) 543-2488

    emsp@u.washington.edu*

    * Catherine and I *both* get all mail sent to emsp@u, so either one of us may reply
  - **Anything to do with course registration or tuition payment:**

    Professional & Continuing Education (PCE)

    Chantelle Vollmer, PCE Program Administrator, (206) 685-9586, cvolmer@pce.uw.edu

Courses and credits

MS only: You must register for credit each regular term to stay in the program!

- If you don’t want to register for credits in autumn, winter, or spring, you **must** request on-leave status for that term
  - Submit an online Request for On-Leave Status via MyGrad, or go to http://www.grad.washington.edu/policies/general/leave.shtml
  - Otherwise you will have to re-apply (and pay another app fee)!
  - **Summer terms excepted** - no requirement to register for Summer

- How do I register for classes?
  - MS and GNM students will get email from PCE with registration forms each term
    - If you haven’t received registration info within 2 weeks of end of this term, contact Chantelle Volmer, (cvollmer@PCE.UW.EDU)
  - You can register with PCE by email (uweoreg@pce.uw.edu), mail or phone
- What if I need a few more credits to qualify for financial aid?
  - Register for 1 or 2 credits of PHYS 600 with me or any other faculty member – see http://sharepoint.washington.edu/phys/grad/EMSP/ and click on ‘course offerings’

Other requirements for MS students

- Graduate School rules require “satisfactory performance and progress toward completion of their graduate degree”
  - Apply for on-leave status if you need to take time off
- A minimum cumulative 3.0 GPA is required for a graduate degree and for every quarter of course work
  - If your GPA drops below 3.0 any quarter you will go on academic probation
  - You must bring your GPA up to 3.0 to remain in the degree program
- You must complete all degree requirements within six years
  - If you enroll as GNM before matriculating for the MS degree, time spent as GNM counts toward the 6 year limit!
  - Extensions may be possible under special circumstances

Orientation for new students

Resources for PMSP students

- Who's my adviser?
  - For new students, I am ! wilkes@uw.edu
    - Or, ask Larry Sorensen, seattle@uw.edu
  - For those doing independent study: your faculty mentor
- Funding resources: see sharepoint.washington.edu/phys/grad/EMSP/Pages/Opportunities.aspx
- Where can I hang out / study before class?
  - Physics study center, mezzanine level (in the A-wing, go down the spiral staircase one floor)

    PCs, with net access and printers

    Meeting/work area with tables and blackboards
  - Suzzallo / Allen (graduate) library, Odegaard Undergraduate library, and Engineering Library have many study spaces

Don’t forget to use your UW NetID

- Your UW NetID gives you email + access to resources
  - Check UW mail regularly or set *YournetID@uw.edu* to forward
- UW Library has huge print resources, but also wide variety of online resources
  - Browse www.lib.washington.edu/
  - Libraries have many PCs for student use
  - Your UW NetID gets you off-campus access to online journals, newspapers and magazines, e-books, and many media collections and e-resources
    - See www.lib.washington.edu/help/connect.html for off-campus access
  - Visit any library and ask a librarian for a guide

Plan for coursework

- Lecture/discussion Tuesday evenings
  - Attend in person if possible; online via Adobe Connect
    - We will do a demonstration session tonight
  - Slides will be posted on website before class
    - Will be available at 6 pm each meeting night
    - Adobe session recordings available ~1 day later
- Hands-on work in lab on 2 Thursday evenings
  - Demonstration of phenomena, experimental methods
  - Chance to work with lab equipment, analyze real data
    - NO lab reports or grading: lab work is for your own benefit
    - Take careful notes to get the most out of the opportunity
- Working together is encouraged!
  - Get together with other students; use study space in PAB

Plan for coursework

- No exams (unless you demand one)
- Homework: student reports
  - Select a relevant topic of interest to you (or see next slide)
  - Prepare a 15 min or longer presentation, and a term paper
    - Written progress report due mid-term, by email
    - Paper and presentation due at last class meeting
  - Class grade = Report grade
    - Comments on progress report will indicate how you are doing
    - Assumption: everyone is here to learn for their own benefit, grades are not a primary concern…
- Resources: UW library, web sites
  - Please do NOT depend entirely on web references – some print media too, please

Report topic suggestions

(but your original ideas are most welcome!)

- Photodetectors – contemporary solid-state devices
- New ideas to replace cyclotrons and/or synchrotrons
- Dosimetry devices
- New designs for fission reactors
- Will we ever have a fusion reactor?
- Gamma ray astrophysics detectors and their capabilities
- Ultra-high energy (ground-based) cosmic ray detectors
- "Classical" models for nuclei (liquid drop, shell, etc)
- Contemporary models for nuclei (see papers by UW nuclear theorists!)
- Magnetic spectrometers
- Low energy gamma rays and their absorption
- Enrico Fermi's amazing range of contributions
- Cherenkov detectors
- Background radiation levels – low BG labs, spacecraft, homes…

Textbook (available at U. Bookstore)

- Knoll, Glenn F.,

Radiation Detection and Measurement, Wiley, 4th ed., 2012

I' ll use the 4th edition; 3rd edition is ok

- Read assigned sections *before* class
- Typically 1 or 2 chapters assigned per week
  - If more are assigned, it means we will not go into material in as much detail as in textbook – study *main points* of topics
  - for some topics text does not cover material as deeply as I will, so class slides and handouts will be primary source

- Knoll is on reserve at the Odegaard Undergraduate Library (NW corner of Red Square) Reserve Desk. You can check it out for 4 hrs – library is open 24 hrs M--Th. You will need your Husky ID Card to get in after 7pm.

Course calendar

Tonight

week	date	day	topic	text
1	10/1/15	Thurs	Introduction, review of basics, radioactivity, units for radiation and dosimetry	Ch. 1, notes
2	10/6/15	Tues	Radioactive sources; decay processes;	Ch. 1, notes
3	10/13/15	Tues	Photomultiplier tubes and scintillation counters; Counting statistics	Chs. 3, 8, 9 (I-V)
3	10/15/15	Thurs	**LAB: Room B248** Scopes, fast pulses; PMTs and scintillation counters; standard electronics modules	Chs. 4, 9, 16, 17
4	10/20/15	Tues	Overview of charged particle detectors	Ch. 4
4	10/22/15	Thurs	**LAB: Room B248** Coincidence techniques; nanosec time measurement, energy from pulse area	Chs. 17, 18
5	10/27/15	Tues	Interaction of charged particles and photons with matter	Ch. 2
6	11/3/15	Tues	Other photodetectors; gas and solid-state detectors	Chs. 5, 6, 7 Chs. 11, 12, 13
7	11/10/15	Tues	Detecting neutral particles; Data acquisition methods	Ch. 14, 15, 18
8	11/17/15	Tues	Cherenkov detectors; Case studies: neutrino detectors (Super-K)	Ch. 19, Notes
9	11/24/15	Tues	Case studies: classic detectors (cloud and bubble chambers, nuclear emulsion), high energy accelerators	Ch. 19
10	12/1/15	Tues	Case studies: contemporary leading-edge detectors (ATLAS, Auger)	Notes
11	12/8/15	Tues	Student presentations	-
11	12/10/15	Thurs	Student presentations	

Online resources

Course home page

depts.washington.edu/physcert/radcert/575website/

- Calendar, course info, lab handouts, slides from classes
- Check for new material at least weekly – your main info source

Adobe Connect (attend class online) link

uweoconnect.extn.washington.edu/phys575/

- "Room" will be open at 6:15 pm each class night
- No special software, any standard browser should work
- You need a good internet connection, and a microphone if possible

Quick Review of Basics

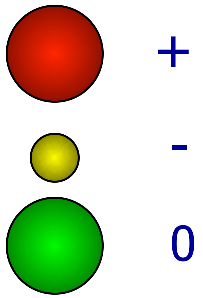
Assume you have seen this (at undergrad level):

- Linear algebra (matrices), complex variables
- *Basic* ideas of E&M
  - 1/r^2 law, Maxwell's eqns, E-M waves, etc
- *Basic* ideas of quantum mechanics, special relativity
  - Wave functions, basis states, Lorentz transforms

We'll go over things you learned (? or were supposed to learn...) in undergrad classes about:

- Microscopic structure of matter
- Types of "radiation"
- Fundamental forces (E&M, strong and weak nuclear)

Atoms Are Themselves Composite

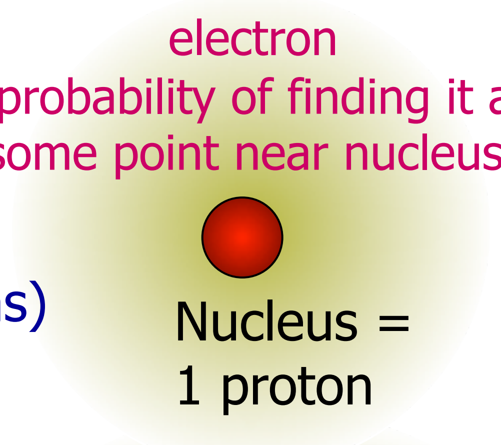


As you learned in high school:

- Protons (+ electric charge), p
- Electrons (– electric charge), e
- Neutrons (no charge), n
- Proton and Neutron have about the same mass
  - Tiny mass, about 10^{-26} kg
  - Tiny "size" too: about 10^{-15} meter (how do we know? Later…)
- Electron is about 2000 times less massive than proton
  - Pointlike - no measurable extent!
  - Electrical Forces produce *attraction* between electrons and protons
    - "opposite charges attract" - more on that later, too
- Atom = *nucleus* (p's+n's), surrounded by cloud of e's
  - "Like charges repel" - so how can p's in nucleus stick together?
    - "Strong force" between nucleons - much stronger than electric force

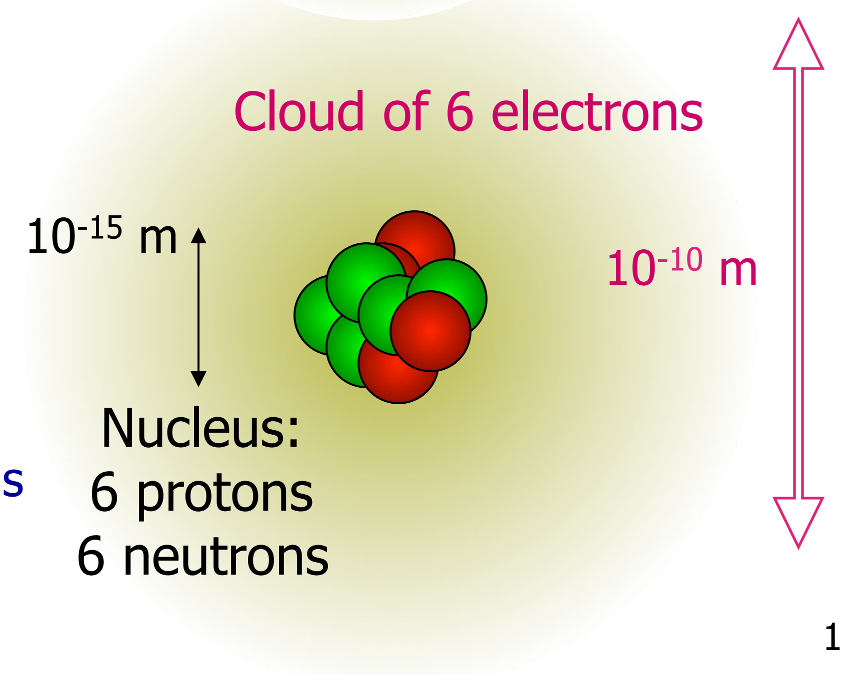
Elements are identified by number of protons in the atom's nucleus: *Atomic Number = Z*

- Hydrogen: Z=1
  - 1 proton & 1 electron
  - Simplest nucleus
- Atomic "weight" A = (#n + #p)
  - hydrogen has A=1 also (no neutrons)
- Carbon has 6 protons
  - Z=6, most commonly A=12



"Cloud" of one electron (probability of finding it at some point near nucleus)

Nucleus = 1 proton



Cloud of 6 electrons

Not to scale! 10^{-15} m

10^{-10} m

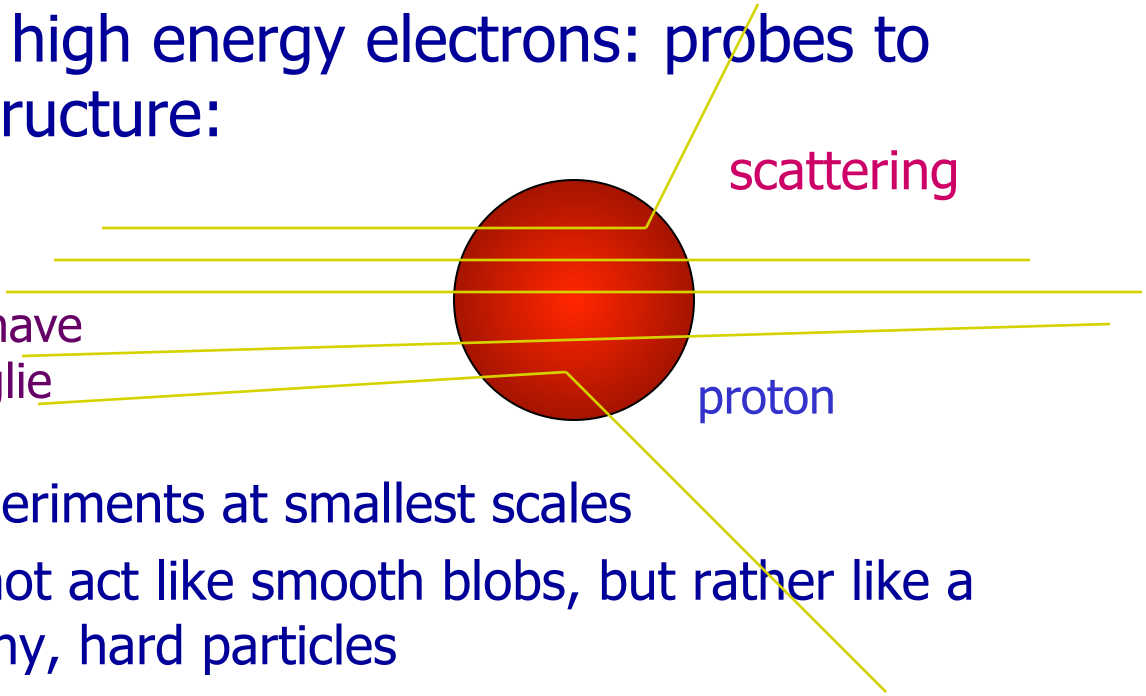
Nucleus: 6 protons 6 neutrons

- this is ^{12}C ("carbon-12")
- rarer *isotopes* exist
  - same Z, more or fewer n's
  - e.g., ^{14}C has 8 n's

10/1/15

...even protons and neutrons have constituents

- Make a beam of high energy electrons: probes to study nucleon structure:



High *momentum* particles have short *wavelengths*: de Broglie

  - "Scattering" experiments at smallest scales
    - Protons do not act like smooth blobs, but rather like a bag full of tiny, hard particles
      - direct evidence for point-like objects making up protons
  - Also: properties of p, n (and other "elementary particles" observed in experiments) have regularities - reminiscent of periodic table!
    - Can "explain" properties of all known "*hadrons"* by assuming they are combinations of 6 *quarks*

Some terminology

- "Elementary particles" = objects that make up atoms (n,p,e), or are produced when atoms are smashed (over 200 identified to date)
  - "elementary" because thought to be fundamental in 1950s
- "Fundamental" particles or constituents of matter
  - Truly no substructure (as of today!)
- *Hadrons* = elementary particles subject to *strong nuclear force* (Greek: *hadros* = strong)
  - protons, neutrons; plus *pions, kaons, lambda* particles...etc
  - now known to be made of fundamental particles: *quarks*
- *Leptons* = elementary particles subject to *weak nuclear force* (Greek: *leptos* = weak)
  - Pointlike, responsible for radioactive decays
  - electrons, plus *muons, taus* and associated *neutrinos*

But that' s not all…

- Antimatter : Each elementary particle has an "antimatter" counterpart

  Electron ~ Antielectron (Positron)

  Proton ~ Antiproton

  Neutron ~ Antineutron

  etc. ~ *anti-etc*.

  Antiparticles have *opposite* electric charge (and other quantum properties), but are otherwise identical

- $E=mc^2$ says matter and energy are interchangeable
  - It's just as easy to make antimatter as matter
  - It happens all the time in nature - and we can do it in labs

- If particle and antiparticle meet – annihilation!

  BIG question today: Why do we live in a universe where there is almost no antimatter?

The “Standard Model” of Particle Physics

Basic ingredients of *matter* are the fundamental particles: quarks and leptons

6 quarks

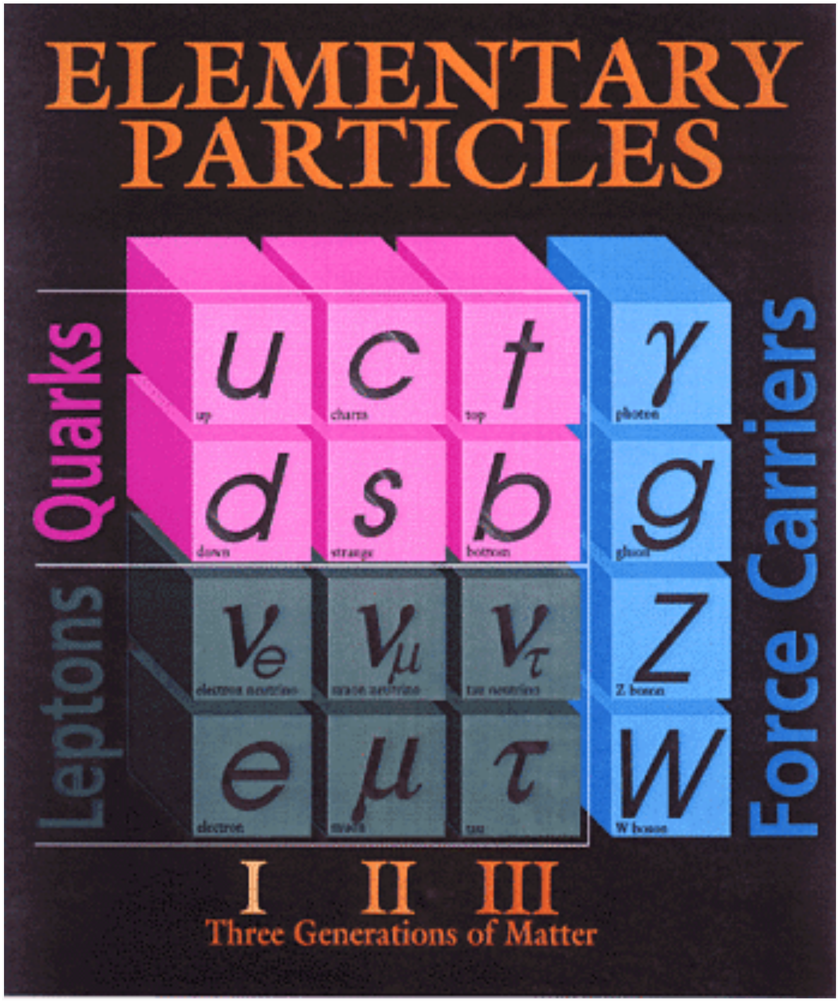
6 leptons

+ their antiparticles

(Symmetry!)

These types of particles are called 'fermions'

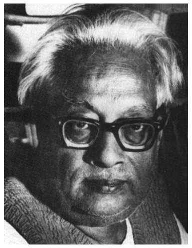
(after
Enrico Fermi)



(from http://www.fnal.gov)

Fundamental *forces* are mediated by photons, gluons, Z’s and W’s

These types of particles are called 'bosons'



(after
Satrendyanath Bose)

Closer look at the Standard Model table

- Fermions fall into 3 groups (*columns* in chart):

	3 generations of quarks ("matter")			Bosons ("force carriers")
Quarks charge mass (MeV)*	up +2/3 3	charmed +2/3 1200	top +2/3 170000	gluon 0 0
	down -1/3 5	strange -1/3 100	bottom -1/3 4200	photon 0 0
Leptons charge mass (MeV)*	ν_e 0 ~ 10^{-7} ?	ν_μ 0 ~ 10^{-7} ?	ν_τ 0 ~ 10^{-7} ?	Z^0 0 91200
	e -1 0.5	μ -1 106	τ -1 1800	$W^{\pm}$ ±1 80400

3 'flavors' of leptons

Protons are made of 3 quarks:
p = uud
n = udd

antiparticles have *opposite* charge

* as of 2015
MeV=million electron volts
Recall: $E=mc^2$
proton mass = 938 MeV

Need big toys to make high energy particles!

(more on this later)

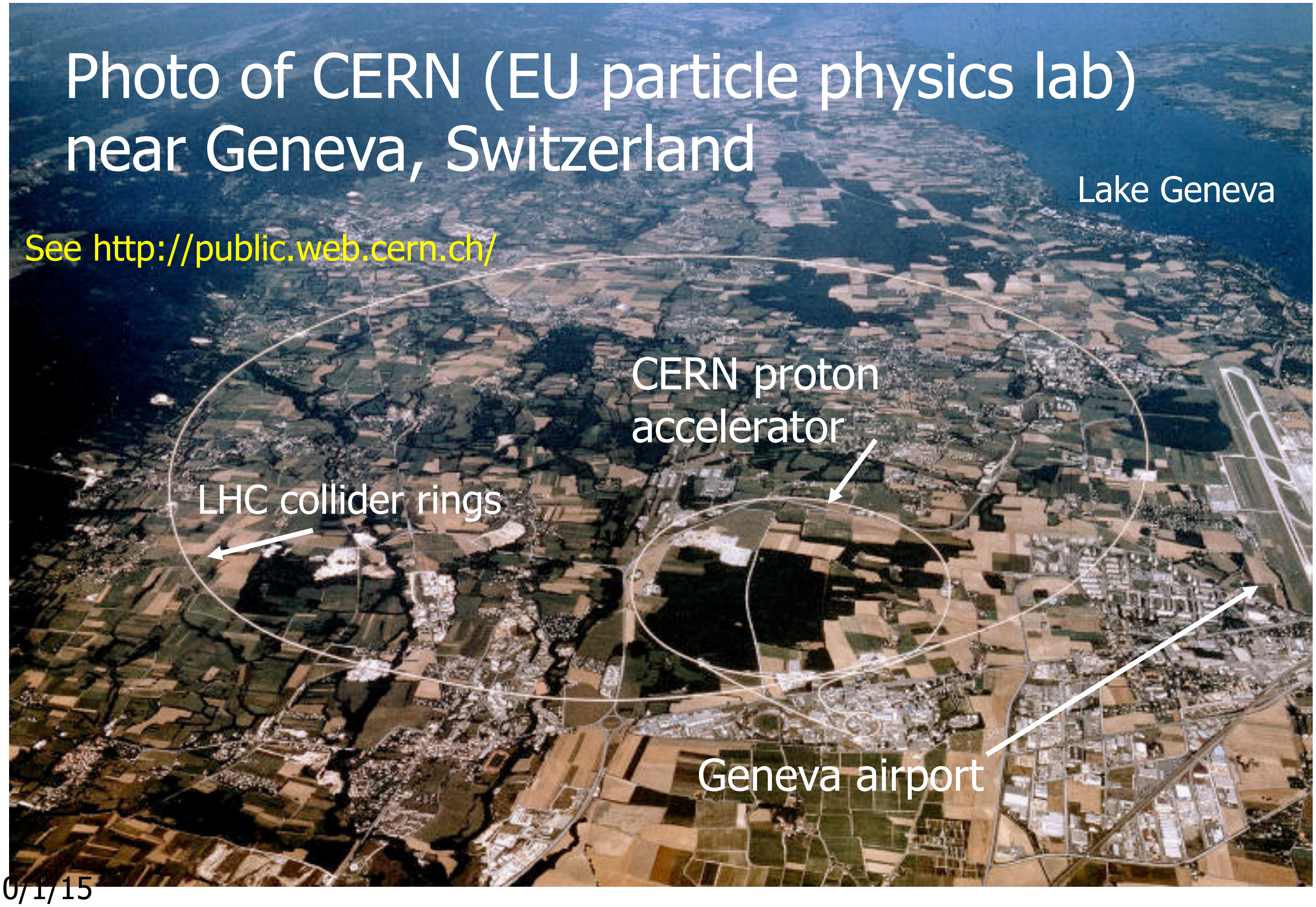


Photo of CERN (EU particle physics lab) near Geneva, Switzerland

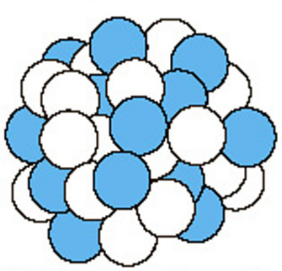
See http://public.web.cern.ch/

Even further substructure?

- Subject of hot debate!
- Could all the particles be different “states” of a more basic entity? "String theory" suggests so.
  - Says: Universe is actually 11-dimensional (!?)
    - All but 3 space dimensions are folded up inside “strings”…
      - Particles correspond to different vibrational modes
  - *The Elegant Universe*, by Brian Greene, describes this view
- One difficulty: inaccessible for experimental tests!
  - “Planck Scale”, 10^{-35} meters, would require *solar-system* sized accelerator!
    - String theorists are safe from experiments, for now…
    - We need new ideas...

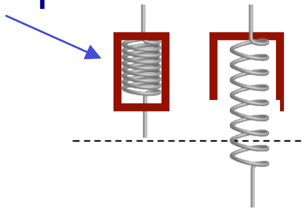
What holds nuclei together?

- Recall structure of nuclei:
  - Nucleus = Z protons (Z="atomic number": 1=hydrogen, 2=helium…) and N neutrons; Z + N = A (atomic mass number)
  - Protons have + charge: repel each other via $1/r^2$ Coulomb's Law
    - Remember nuclear size scale: incredibly small r = huge force



A = atomic *mass* number = total number of protons + neutrons
Z = atomic *number*, # of protons (determines which *element* it is)
N = A – Z =number of neutrons (determines which *isotope* it is)
Isotopes have same Z but different A's.
Example: ${}_6C^{12}$ = "carbon-12", has 6 protons (like all carbon) and 6 neutrons (unlike "carbon-14", which has 8 neutrons)

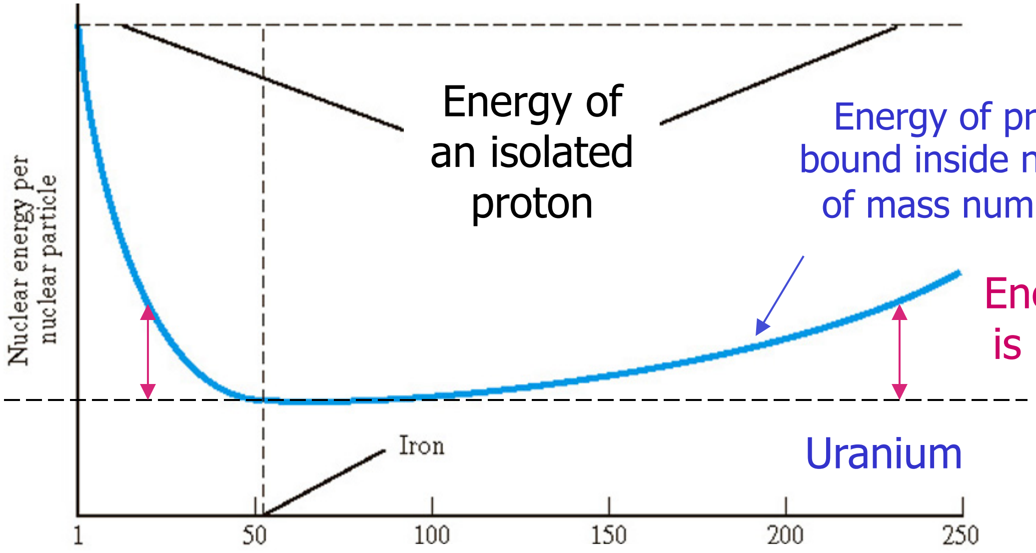
- **Nuclear "glue"** holds protons and neutrons into nuclei
  - "strong nuclear force" is carried by particle called (what else?) ***gluon***
  - Nucleus is like a compressed spring, held together by a rope
    - Cut the rope, and stored "binding energy" is released
  - Energy taken up to bind nucleus is reflected in mass



$E = mc^2$ + conservation of energy

Binding energy curve

- The whole is not equal to the sum of its parts !
  - Mass of helium nucleus (2p+2n) is *less than* 2*M$_{proton}$ + 2*M$_{neutron}$
    - Difference = binding energy (stored energy, like compressed spring)
    - *Fuse* p's and n's to make He, and energy is released: *nuclear fusion*
  - Mass of uranium nucleus is *more than* sum of its p's and n's masses
    - Break uranium nucleus into lighter nuclei and E is released: *nuclear fission*
  - Iron nucleus has *minimum binding energy* per particle: most stable



Energy of an isolated proton

Energy of proton bound inside nucleus of mass number A

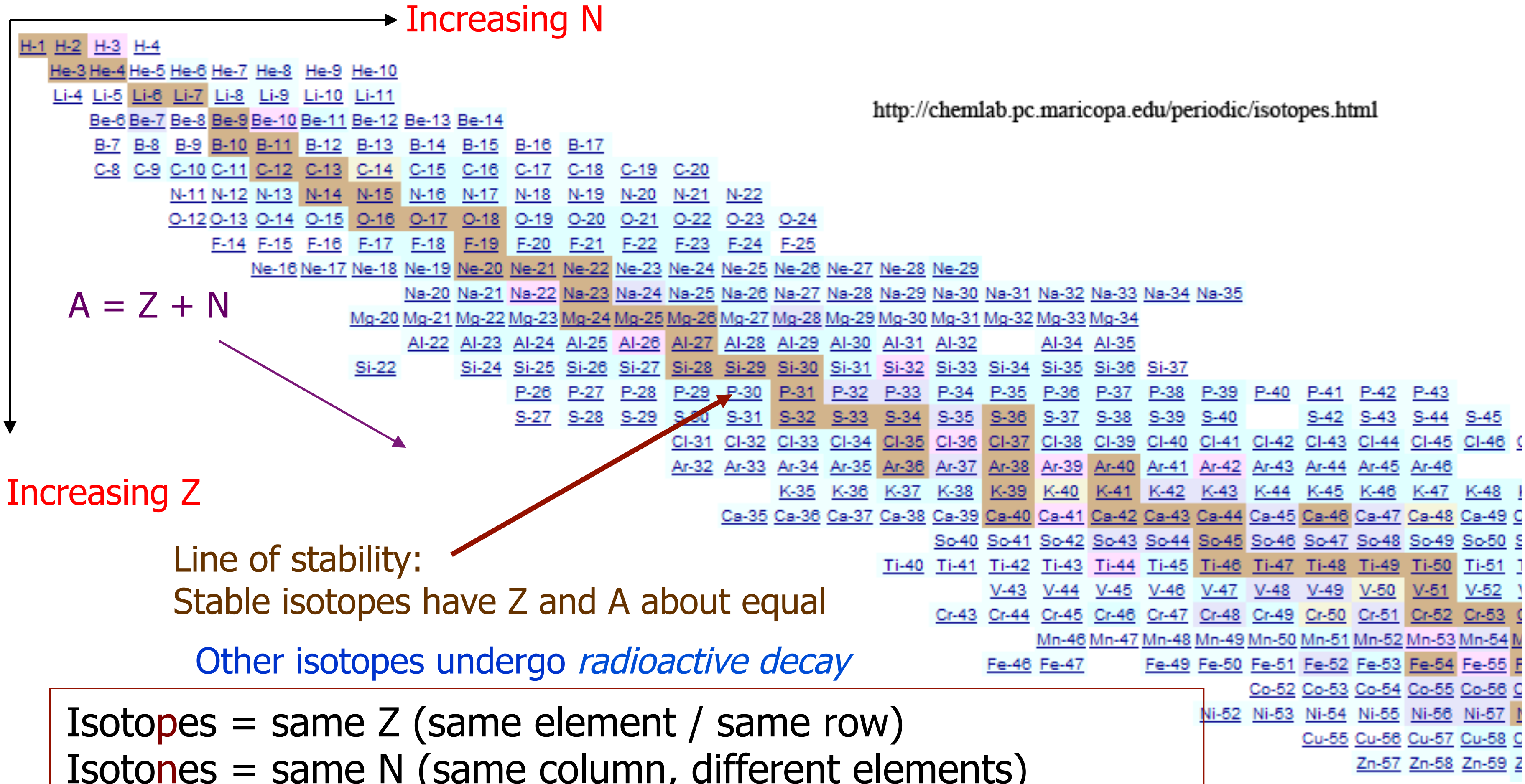
Energy is *released* when heavy nucleus is broken up, OR light nuclei are fused

Uranium

Atomic mass number, A

Radioactivity: instability of nuclei

- Table of *isotopes,* shows all known varieties of elements



Increasing N

H-1 H-2 H-3 H-4
He-3 He-4 He-5 He-6 He-7 He-8 He-9 He-10
Li-4 Li-5 Li-6 Li-7 Li-8 Li-9 Li-10 Li-11
Be-6 Be-7 Be-8 Be-9 Be-10 Be-11 Be-12 Be-13 Be-14
B-7 B-8 B-9 B-10 B-11 B-12 B-13 B-14 B-15 B-16 B-17
C-8 C-9 C-10 C-11 C-12 C-13 C-14 C-15 C-16 C-17 C-18 C-19 C-20
N-11 N-12 N-13 N-14 N-15 N-16 N-17 N-18 N-19 N-20 N-21 N-22
O-12 O-13 O-14 O-15 O-16 O-17 O-18 O-19 O-20 O-21 O-22 O-23 O-24
F-14 F-15 F-16 F-17 F-18 F-19 F-20 F-21 F-22 F-23 F-24 F-25
Ne-16 Ne-17 Ne-18 Ne-19 Ne-20 Ne-21 Ne-22 Ne-23 Ne-24 Ne-25 Ne-26 Ne-27 Ne-28 Ne-29
Na-20 Na-21 Na-22 Na-23 Na-24 Na-25 Na-26 Na-27 Na-28 Na-29 Na-30 Na-31 Na-32 Na-33 Na-34 Na-35
Mg-20 Mg-21 Mg-22 Mg-23 Mg-24 Mg-25 Mg-26 Mg-27 Mg-28 Mg-29 Mg-30 Mg-31 Mg-32 Mg-33 Mg-34
Al-22 Al-23 Al-24 Al-25 Al-26 Al-27 Al-28 Al-29 Al-30 Al-31 Al-32 Al-34 Al-35
Si-22 Si-24 Si-25 Si-26 Si-27 Si-28 Si-29 Si-30 Si-31 Si-32 Si-33 Si-34 Si-35 Si-36 Si-37
P-26 P-27 P-28 P-29 P-30 P-31 P-32 P-33 P-34 P-35 P-36 P-37 P-38 P-39 P-40 P-41 P-42 P-43
S-27 S-28 S-29 S-30 S-31 S-32 S-33 S-34 S-35 S-36 S-37 S-38 S-39 S-40 S-42 S-43 S-44 S-45
Cl-31 Cl-32 Cl-33 Cl-34 Cl-35 Cl-36 Cl-37 Cl-38 Cl-39 Cl-40 Cl-41 Cl-42 Cl-43 Cl-44 Cl-45 Cl-46
Ar-32 Ar-33 Ar-34 Ar-35 Ar-36 Ar-37 Ar-38 Ar-39 Ar-40 Ar-41 Ar-42 Ar-43 Ar-44 Ar-45 Ar-46
K-35 K-36 K-37 K-38 K-39 K-40 K-41 K-42 K-43 K-44 K-45 K-46 K-47 K-48
Ca-35 Ca-36 Ca-37 Ca-38 Ca-39 Ca-40 Ca-41 Ca-42 Ca-43 Ca-44 Ca-45 Ca-46 Ca-47 Ca-48 Ca-49
Sc-40 Sc-41 Sc-42 Sc-43 Sc-44 Sc-45 Sc-46 Sc-47 Sc-48 Sc-49 Sc-50
Ti-40 Ti-41 Ti-42 Ti-43 Ti-44 Ti-45 Ti-46 Ti-47 Ti-48 Ti-49 Ti-50 Ti-51
V-43 V-44 V-45 V-46 V-47 V-48 V-49 V-50 V-51 V-52
Cr-43 Cr-44 Cr-45 Cr-46 Cr-47 Cr-48 Cr-49 Cr-50 Cr-51 Cr-52 Cr-53
Mn-46 Mn-47 Mn-48 Mn-49 Mn-50 Mn-51 Mn-52 Mn-53 Mn-54
Fe-46 Fe-47 Fe-49 Fe-50 Fe-51 Fe-52 Fe-53 Fe-54 Fe-55
Co-52 Co-53 Co-54 Co-55 Co-56
Ni-52 Ni-53 Ni-54 Ni-55 Ni-56 Ni-57
Cu-55 Cu-56 Cu-57 Cu-58
Zn-57 Zn-58 Zn-59

http://chemlab.pc.maricopa.edu/periodic/isotopes.html

A = Z + N

Increasing Z

Line of stability:
Stable isotopes have Z and A about equal

Other isotopes undergo *radioactive decay*

Isotopes = same Z (same element / same row)
Isotones = same N (same column, different elements)
Isobars = same A (diagonal: different elements with same A)

Radioactivity

- Henri Becquerel (1896): discovered radioactivity
  - Sample of mineral containing uranium fogged photographic plate
- Marie Curie (c. 1900): with P. Curie, made many early discoveries (Nobel Prize 1903)
  - "Radiation" takes 3 main forms
    - *Alpha rays* are positively charged, heavy (actually: helium nuclei)
      - Cannot penetrate much matter (paper stops them)
    - *Beta rays* are negatively charged, very low mass (electrons)
      - More penetrating than alphas, but stopped by thin lead sheet
    - *Gamma rays* are uncharged, massless (high energy photons)
      - Tend to penetrate even thick lead sheets
  - Later another form was identified: *neutrons*
    - Uncharged, so not subject to electrical forces: can percolate through matter for a long distance
  - All can be produced by radioactive decay of nuclei

Examples of radioactive decay processes

- Standard way to write isotopes: $_{Z}(\text{Element})^{A}$
- Uranium alpha decay: $_{92}U^{238} \rightarrow {}_{90}Th^{234} + \alpha$
  - Remember, α =helium nucleus = $_{2}He^{4}$
  - Notice the A's and Z's *balance* on both sides of the equation
    - U loses 2 from Z, and 4 from A: becomes thorium
  - However, *exact* masses don't add up: some goes into KE of the α

  M_U =238.051 MeV, M_{Th} = 234.044 MeV, M_α = 4.002 MeV

  U nucleus is heavier than sum of thorium nucleus and alpha
- Carbon-14 beta decay: $_{6}C^{14} \rightarrow {}_{7}N^{14} + \beta$
  - This is an example of *weak nuclear force* in action
    - Neutron *turns into* a proton, emitting an electron
      - More about this process later!
    - carbon gains 1 in Z, but A stays the same: becomes nitrogen
      - Electron has KE, which carries away some energy
      - "invisible" neutrinos carry away additional energy
        - » More about these particles later!

Radioactivity is truly random process

Radioactivity illustrates interesting features of *randomness*

In a sample of (say) 1 billion U^{234} atoms:

- *Probability* of radioactive decay for any individual nucleus is small for any particular 1-second period of time
  - P(decay) = same for *any* second of time: now, tomorrow, year 3015
  - P(decay) is not affected if some *other* nucleus chooses to decay now
    - Decays are *independent* of one another: no "memory"
  - *Total number of decays* counted in any time interval is *proportional to sample size* (total number of U atoms): more atoms → more decays

  This kind of random behavior is called a *Poisson process* (S. Poisson, 1781-1840) and applies in *many other phenomena*
- Once U nucleus decays, it is *no longer uranium!*
  - Taken out of the running… number of candidates available for decay *diminishes* with time
    - ...Unless some other process is *making* uranium too!

Statistics of radioactive decay

- Recall definition:

statistic = a single number, derived from a large body of data, that describes some feature of the *whole* data set

- Mean (average) lifetime T_{avg} of a nucleus is a useful statistic
- Another is the half-life: $T_{1/2}$ = time it takes for *half* of nuclei to decay
- Example: start with 1,000,000 radioactive nuclei with average lifetime 1000 seconds.
  - So each second, any nucleus has probability 1/1000 of decaying
    - For a 10 second interval, P(decay) = 1% -- this means:
      - » after 10 sec, 99% of original nuclei survive: 990,000
      - » after 20 sec, 99% of 99% = 98% remain
      - » after 30 sec, 99% of 98% = 97% remain...etc
  - Make a graph of number of remaining nuclei vs time…

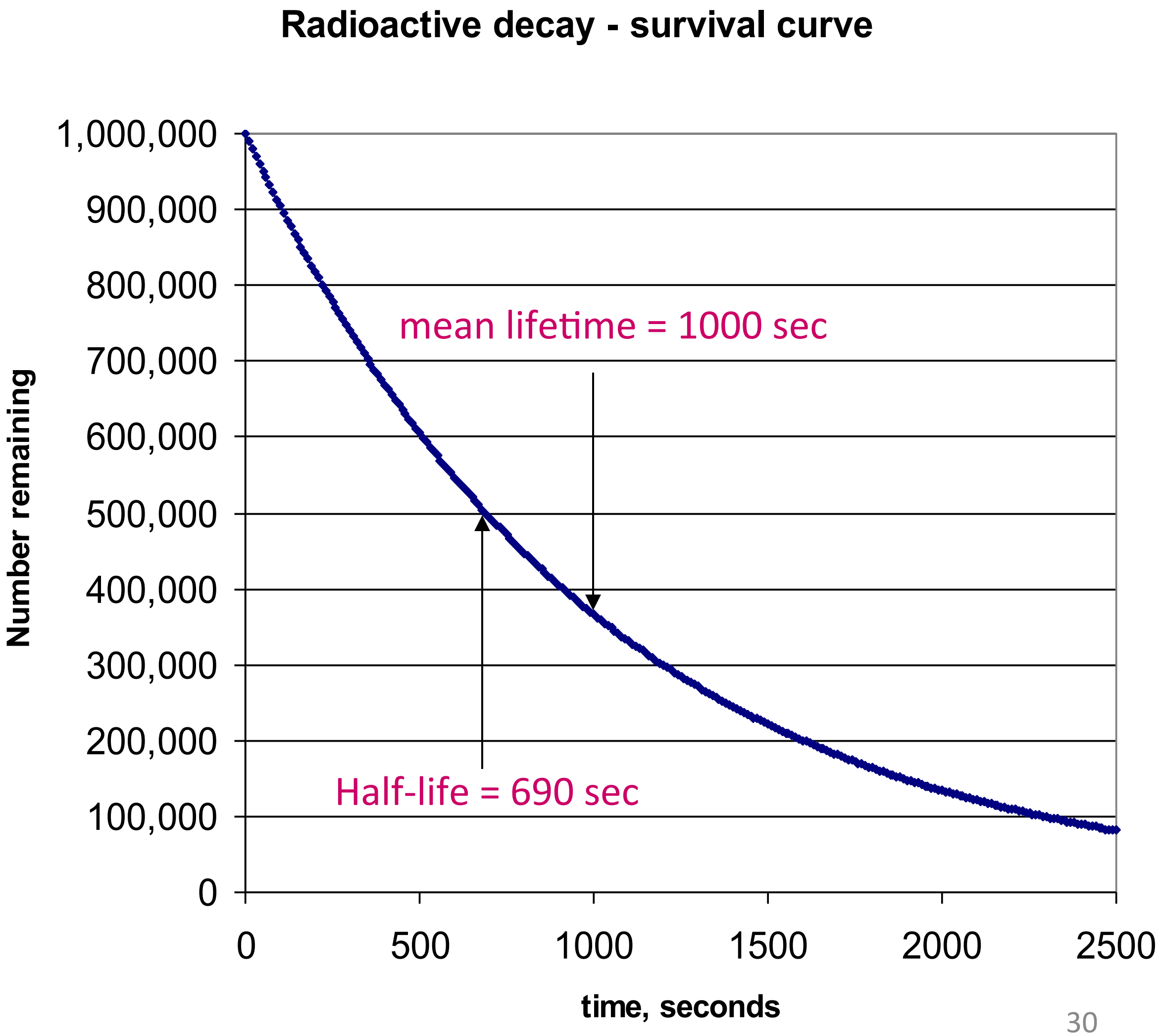
Survival curve

- Number of nuclei remaining (undecayed) vs time:

Example here: decay probability = 0.001 per second

- Every 10 sec, 1% of the *survivors* decay
- Rate of decay is constant *per nucleus,* but number of decays per second (Geiger counter ticks/sec) drops as population diminishes!
- This is an example of ”exponential behavior” - applies to many physical phenomena

Statistics for this example:
- half-life = 690 sec
= time to drop to 500,000
- avg lifetime = 1000 sec.
(Longer than half-life, because a *few* nuclei remain for a *long* time: distribution has a "long tail")



Radioactive decay math

- Radioactive decay law represents the differential equation

$$dN/dt = -\lambda N,$$

where λ *is the decay constant,*

which has the solution

$$N(t) = N_0 \exp(-\lambda t) = N_0 \exp(-t/\tau)$$

- *Where* $\tau = 1/\lambda$ *= Mean lifetime*
- Half-life $T_{1/2}$ = time when $N/N_0 = ½$ → $½ = \exp(-T_{1/2}/\tau)$
- Solve for $T_{1/2} = (\ln 2)\tau = 0.693\tau$
- Units for decay rates:

One becquerel (Bq) = 1 nuclear disintegration per second

One curie (Ci) = 3.7×10^{10} decays per second = 3.7×10^{10} Bq

Radioactive processes and sources

- Energy unit: electron-volt (eV) = 1.6x10^{-19} joule
  - Scale to remember: electron mass ~ ½ MeV, proton mass ~ 1 GeV
- Energy gained by any object with Q = ± 1e falling through 1V potential difference (*regardless* of its mass)

(Table of SI prefixes)

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	µ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y

Name of physics subfield is related to the energy scale studied:

Cosmic rays
(particle astrophysics)

Particle physics
(high-energy physics)

Nuclear physics

Radioactivity terminology

- Nuclide = generic term for a type of nucleus (specific Z, N, A)
- Unit of activity (disintegrations/sec):

  Curie (Ci) = 3.70 x 10^{10} disintegrations/sec (= 1g of ^{226}Ra, c. 1900)

  Typical radioactive sources are mCi (industrial), μCi or even pCi (ours)

  Ci is commonly used, although official SI unit is Bequerel (Bq):

  1 Bq = 2.703 x 10^{-11} Ci (typical sources are kBq~MBq)

- Specific activity (SA) = activity/gram

  $= \lambda N/(N M / N_{AVOG}) = \lambda N_{AV} / M$,

  N=# molecules, M=grams/mole, N_{AVOG}=Avogodro's no.

  for a pure sample (no other substance mixed)

  – So large SA → large λ → small half-life

Dose vs activity

- Activity refers to the radiation *source*
- Dose refers to the *absorber* (eg, organ, whole body, shielding block, detector component)
  - Absorbed dose (energy dose) depends on properties of absorbing material
  - Unit of dose = energy absorbed per unit mass of absorber
- SI unit of dose = 1 gray (Gy) = 1 joule/kg
  - Old unit of dose still used = rad ('radiation absorbed dose')

  1 rad = 100 erg / gram -> 100 rad = 1 Gy

Exposure vs dose

- Exposure (ionization dose) = charge created per unit volume, standardized to dry air, but depends upon air density:

$$I = \frac{1}{\rho_{AIR}} \frac{dQ}{dV} \quad (C / kg)$$

- Unit of exposure = roentgen (R)

  1 R = 2.58×10^{-4} coulomb / kg = $1.61\times10^{+15}$ electrons (or +1e ions) / kg

  Alternatively, 1R = $2.08\times10^{+9}$ ions/cc

  Air has *work function* (energy to ionize) W=33.7 eV, so 1 R = 0.87 rad

- Equivalent dose = effect of radiation on *human tissue*
  - Unit = rem (roentgen equivalent man)

  1 rem = q (1 R)

  q = *quality factor* of radiation type:

  (eg, alphas are 20X as damaging as e's)

  q is now called *radiation weighting factor* W_R

Radiation type	**q**
Electrons, photons	1
Protons, deuterons	2~10
alphas	20

Alpha sources

- α = 2p+2n = He nucleus

  Alphas are very stable; can *tunnel out* of heavier nuclei:

  $^{A}_{Z}X \longrightarrow\ ^{A-4}_{Z-2}Y + \alpha$

- Some alpha-emitters:

MeV	Source	Half-life
4.016	**Th 232**	**1.41 X 10^{10} years**
4.15	**U 238**	**4.47 X 10^{9} years**
4.598	**U 235**	**7.04 X 10^{8} years**
4.602	**Ra 226**	**1,599 years**
4.688	**Th 230**	**8 X 10^{4} years**
4.723	**U 234**	**2.45 X 10^{5} years**
5.143	**Pu 239**	**5.5 X 10^{15} years**
5.305	**Po 210**	**138.4 days (in tobacco)**
5.486	**Am 241**	**432 years**
5.490	**Rn 222**	**3.824 days (in your basement)**
7.687	**Po 214**	**164 microsec (daughter of Rn-222)**

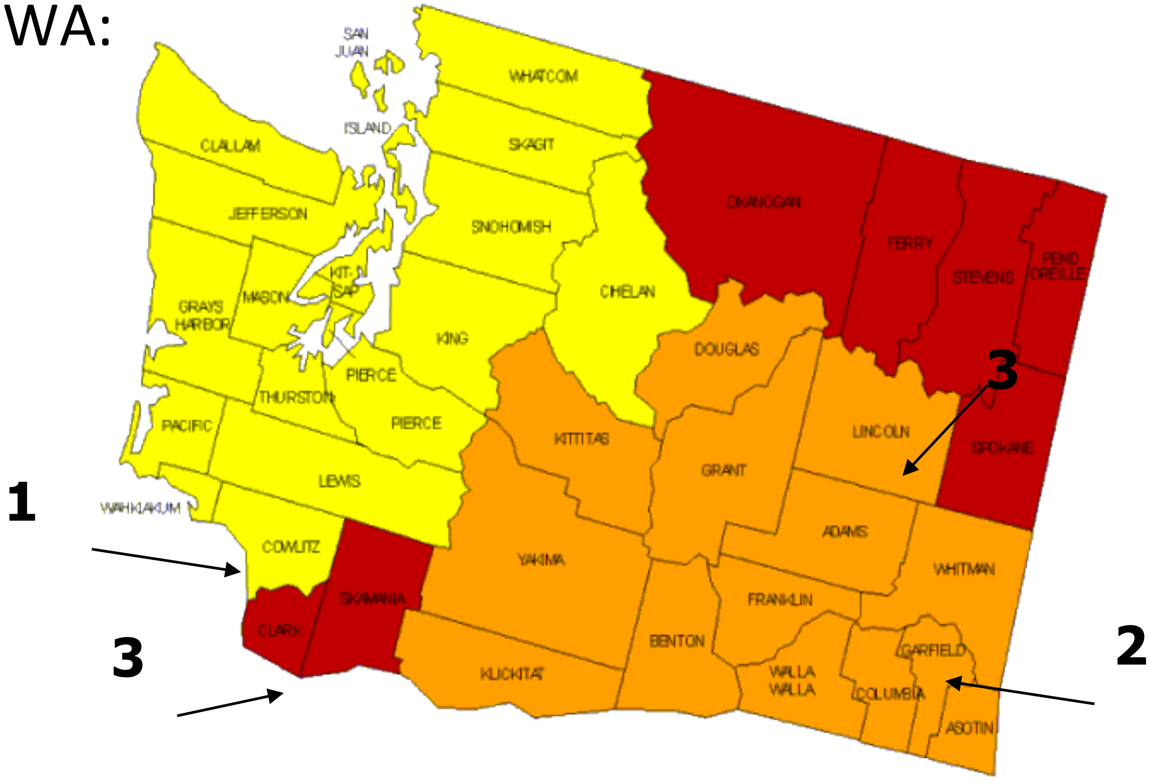
Dangerous alphas: Indoor Radon (Rn)

- Estimated to cause 20,000 cancer deaths/year in USA
- EPA recommends < 4 pCi/liter of indoor air (US avg=1.3 pCi/l)
- Typical levels in WA:

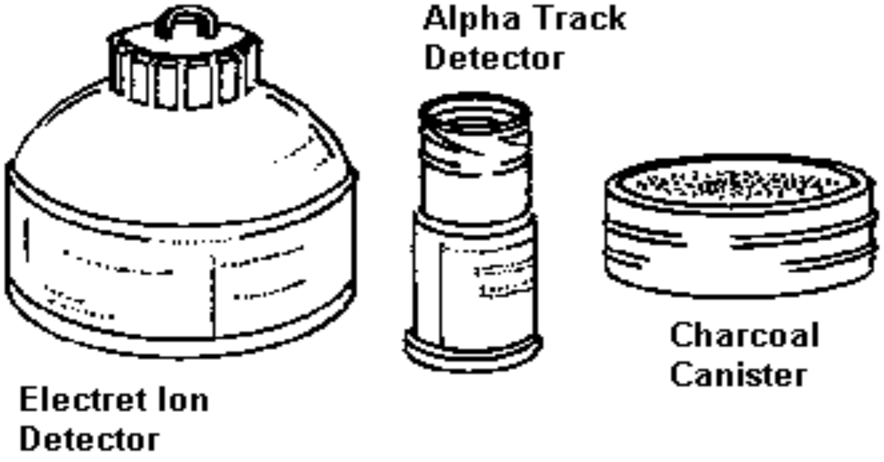
1=<2 pCi/l

2=2~4 pCi/l

3=>4 pCi/l

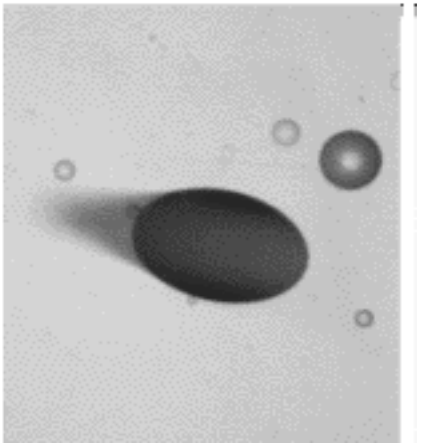


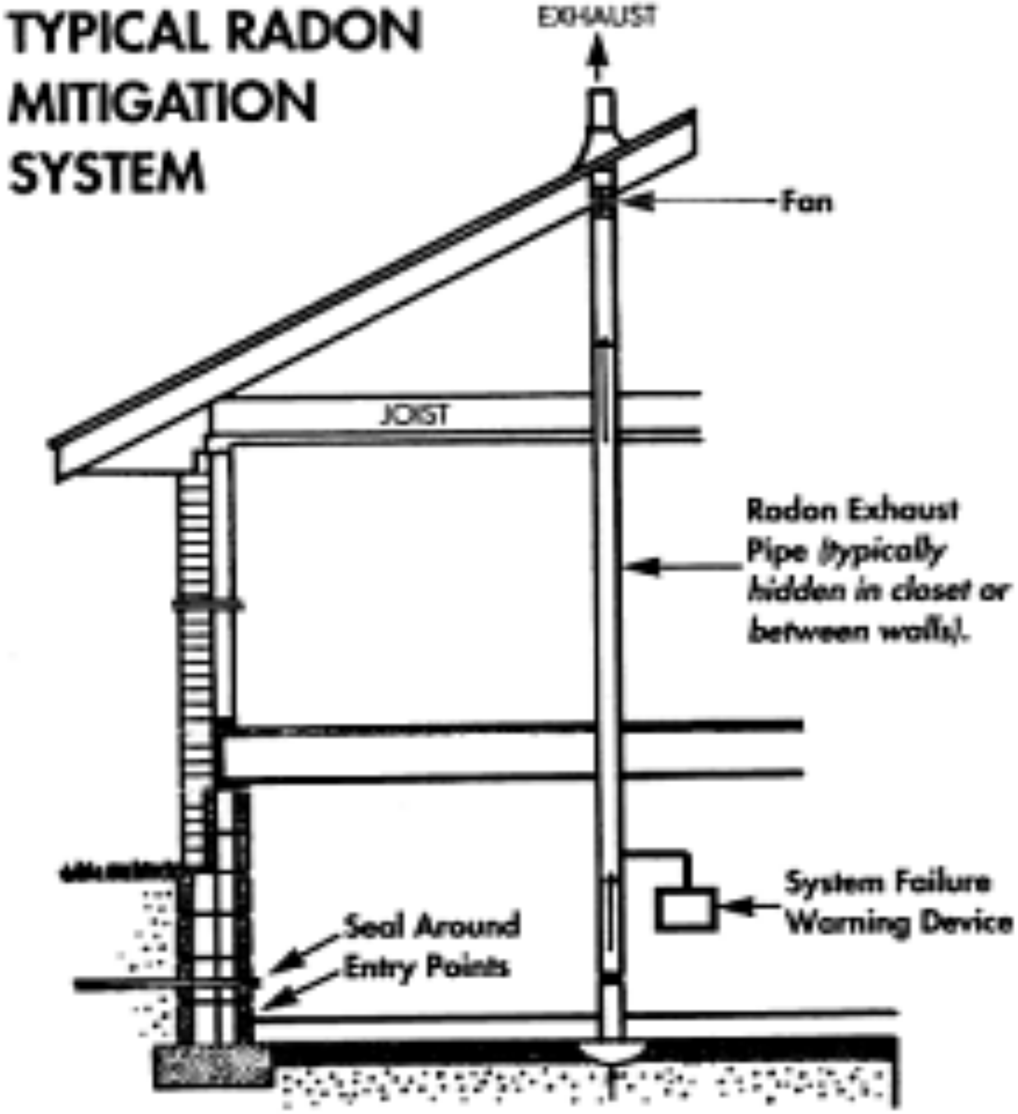
Radon measurement and mitigation



- Charcoal canister detectors contain activated charcoal. Rn and its decay products are absorbed onto the charcoal and are measured by counting with NaI detector or a scintillation counter.
- Alpha track detectors contain a small sheet of plastic that is exposed for a period of 1~3 months. Alpha particles damage the plastic as they strike it. These sheets are then chemically etched and damage pits are counted to determine the radon concentration.
- Electret ion detectors contain an electrostatically charged Teflon disk. Ions generated by the decay of radon strike and discharge the disk. The radon concentration can be calculated from the remaining charge on the disk after exposure.

Conical *etch pits* in plastic (the big one is due to a relativistic cosmic ray Pb nucleus!)



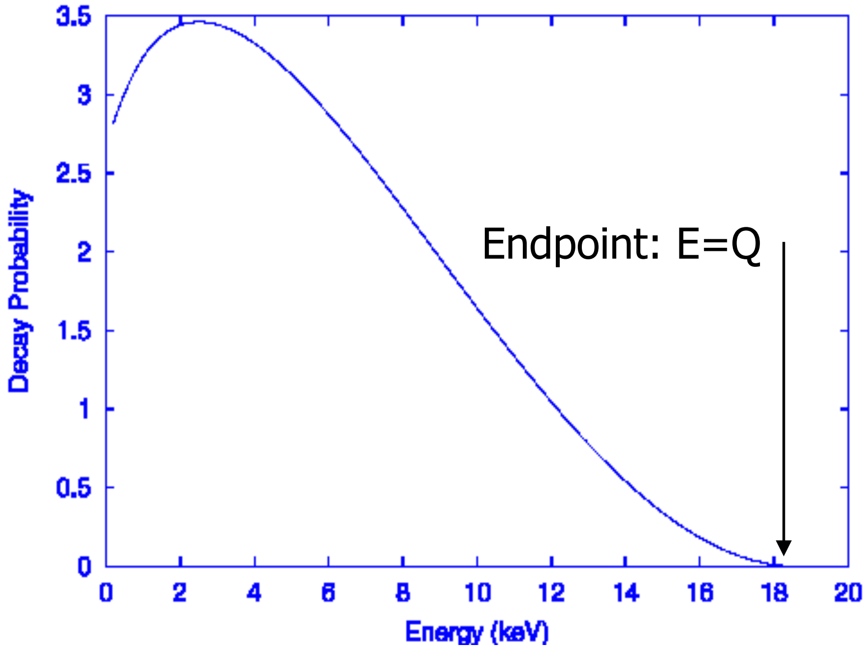


- Newer energy-efficient houses are tightly sealed to conserve heat and have poorer ventilation. Older houses are typically “leaky” and have lower Rn levels.
- Mitigation is mainly done by ensuring adequate air circulation to remove Rn and its products.

Beta sources

Beta particles = electrons (or positrons) from radioactive decays of nuclei

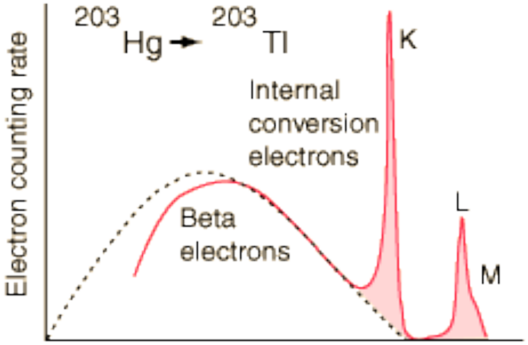
- Direct beta decay: ${}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + e^{-} + \underline{\nu}_{e}$ (or $e^{+} + \nu_{e}$)
  - Neutrinos are required to balance spin and lepton number
  - Kinematics → electron comes off with broad spectrum: endpoint = Q-value of decay (total energy released)



examples of beta-emitters

Nuclide	$T_{1/2}$	Q (MeV)
H-3 (tritium)	12 yr	0.02
C-14	5730 yr	0.156
Cl-36	3.1×10^5 yr	0.714
Sr-90	27.7 yr	0.546

Note long lifetimes: beta decay=weak interaction



- Internal conversion / Auger processes

  A previous decay may leave an excited nuclear state

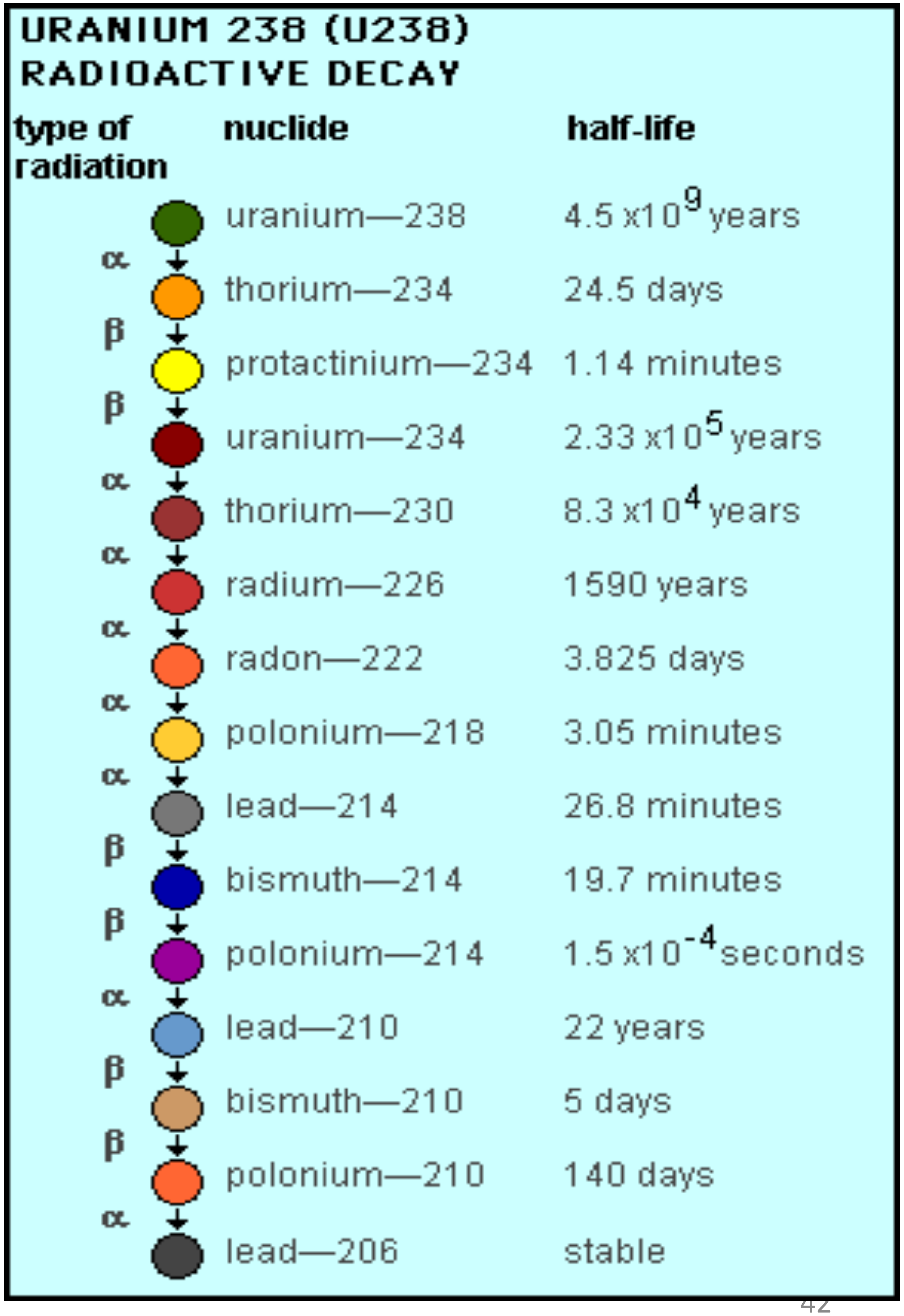
  - De-excitation via gamma emission is most common, but is suppressed by conservation rules for some nuclides
  - Internal conversion = de-excitation by transfer of energy to orbital electron (conversion electron)
  - Sharply defined energy: peaked spectral line, typically keV
  - Auger electrons: same idea but originates from *atomic* rather than nuclear excitation (few keV)

Radioactive decay chains

Example: U-238 →

Each radioactive isotope on the chart emits alpha or beta rays (and sometimes gammas too), transforming itself into the next element down the list.

The chain ends with Pb-208, which is stable.

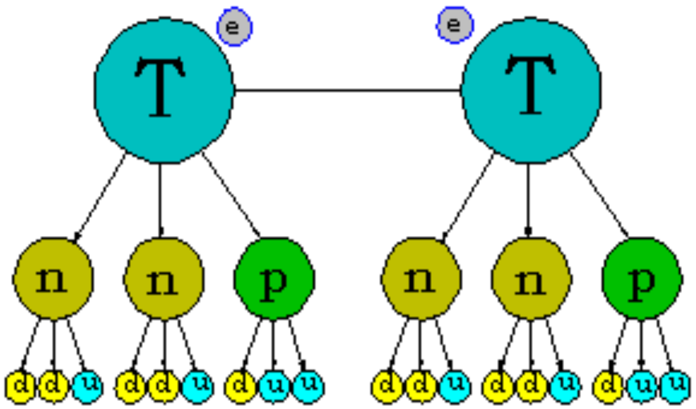


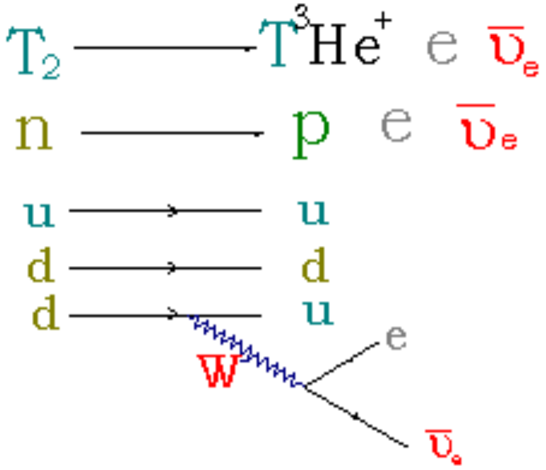
URANIUM 238 (U238)
RADIOACTIVE DECAY

type of radiation	nuclide	half-life
α	uranium—238	4.5 x10^{9} years
β	thorium—234	24.5 days
β	protactinium—234	1.14 minutes
α	uranium—234	2.33 x10^{5} years
α	thorium—230	8.3 x10^{4} years
α	radium—226	1590 years
α	radon—222	3.825 days
α	polonium—218	3.05 minutes
β	lead—214	26.8 minutes
β	bismuth—214	19.7 minutes
α	polonium—214	1.5 x10^{-4} seconds
β	lead—210	22 years
β	bismuth—210	5 days
α	polonium—210	140 days
	lead—206	stable

Digression:
Beta decay and neutrino mass

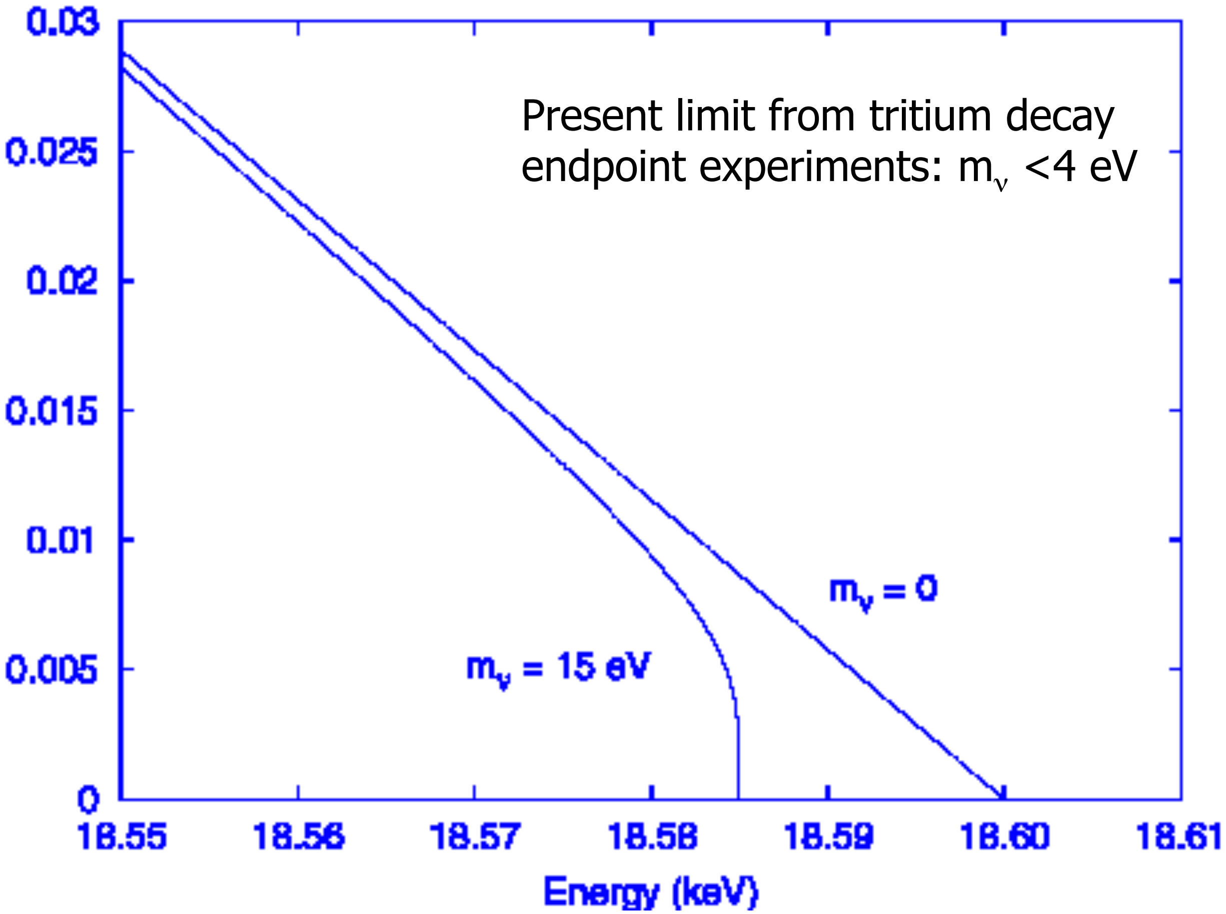
- *Neutrino oscillation* experiments I will describe (neutrino flavor change observations) like Super-Kamiokande cannot measure the mass of the neutrino (only existence of m>0)
- Tritium beta-decay endpoint experiments can
  - More on this later...





One of the neutrons becomes a proton
→ One of its d quarks emits a W^- and becomes a u
→ The W- decays to an electron + e-antineutrino
If the antineutrino has negligible kinetic energy, the electron has max possible energy = $(m_n - m_p) - m_\nu$

neutrino mass



Present limit from tritium decay endpoint experiments: $m_\nu < 4$ eV

Nuclear chemistry:

$T_2 \rightarrow T + {}^3He$

At the particle level:

$n \rightarrow p + e^- + \underline{\nu_e}$

At the quark level

$d \rightarrow u + W^-$

Weak interaction:

$W^- \rightarrow e^- + \underline{\nu_e}$

If neutrino has mass, electron spectrum is distorted near the endpoint

Gamma ray sources

- Gamma emission does not change A or Z by itself
- De-excitation following β^- decay

Example: $^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + \beta^-$, followed by (2-step decay)

$^{60}_{28}\mathrm{Ni}^{**} \rightarrow {}^{60}_{28}\mathrm{Ni} + \gamma$ (2.5 MeV)

$^{60}_{28}\mathrm{Ni}^{*} \rightarrow {}^{60}_{28}\mathrm{Ni} + \gamma$ (1.3 MeV)

- Annihilation radiation following β^+ decay

Example: $^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne}^* + \beta^+$, followed by

$^{22}_{10}\mathrm{Ne}^* \rightarrow {}^{22}_{10}\mathrm{Ne} + \gamma$ (1.27 MeV)

$e^+ + e^- \rightarrow 2\gamma$ (0.511 MeV each, back to back)

Notice 3 gammas are emitted for each Na decay

- Gamma emission following nuclear reactions

Example: $\alpha + {}^{13}_{6}\mathrm{C} \rightarrow {}^{16}_{8}\mathrm{O}^* +$ neutron, followed by

$^{16}_{8}\mathrm{O}^* \rightarrow {}^{16}_{8}\mathrm{O} + \gamma$ (6.1 MeV: note high energy)