PHYSICS 102N
Spring 2022

Week 13 - 14

Nuclear and Particle Physics

The Atomic Nucleus…

- …what do we know so far? Nuclei…
  - are made up from Z protons and N neutrons
  - have total charge = Z*e* (Z = number of protons; “atomic number” - determines element properties)
  - are incredibly tiny (a few 10^{-15} m = fm), 100,000 times smaller than the atom
  - …but contain nearly all of the mass (99.97%): $M \approx A \cdot u = (N+Z) \cdot u$;
    - $u = 1.661 \cdot 10^{-27}$ kg = $M(^{12}C)/12$ = 931.5 MeV/c^2
  - proton = nucleus of simple-most hydrogen atom
  - neutron = proton without charge (slightly more massive, too)
  - most elements come in different isotopes (same Z but different N and therefore different A)

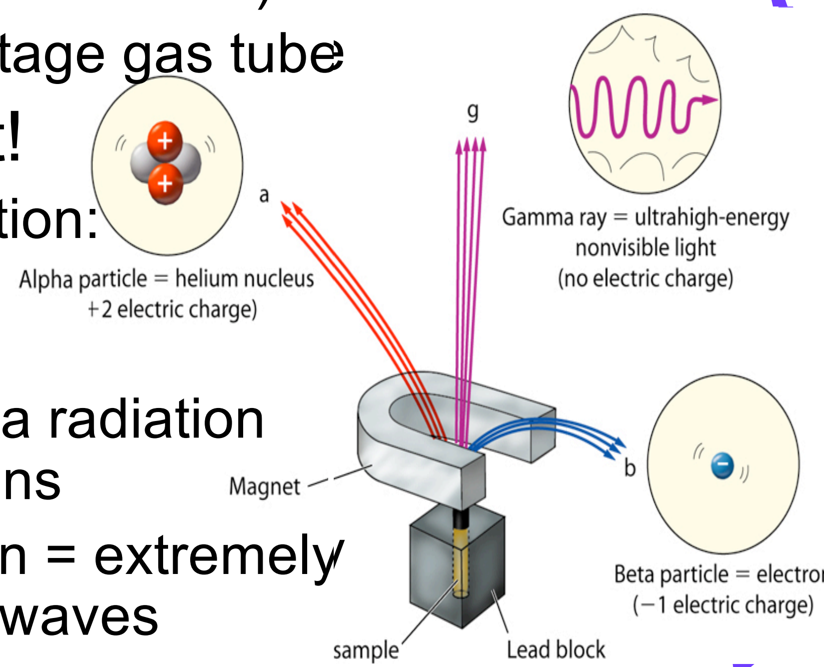
The Atomic Nucleus…

- …what do we (=PHYS102) **not** know yet?
  - Why doesn’t it blow into pieces immediately?
    - protons are all positively charged and repel each other
    - Why not M = A $\cdot$ u exactly ???
    - Why is u < mass of proton $m_p = 1.673 \cdot 10^{-27}$ kg ???
    - Heisenberg sez: $\Delta p \cdot \Delta x \approx h/2\pi$; $\Delta x = 2 \cdot 10^{-15}$ m =>
      $\Delta p \approx h/2\pi\Delta x \approx 0.5 \cdot 10^{-19}$ kgm/s $\approx 1/3\ m_p c$
  - => what kind of force binds protons and neutrons together?
    - electric force ruled out (neutrons are neutral, protons repel)
    - magnetic force present but tiny; gravity infinitesimally tiny *)
  - AND WHY DO THEY SOMETIMES FALL APART AFTER ALL?

*) One loophole: A nucleus with 10^{57} neutrons can be bound by gravity = neutron star.

Radioactivity (Nuclei going “kapoom”)

- Around late 1890s, people noticed that some nuclei emit extremely energetic, penetrating radiation
  - Can darken photographic film
  - Can make scintillators flash (fluorescence!)
  - Can cause discharge in high voltage gas tube
- Several different types to boot!
  - Did already mention alpha radiation: whole ^{4}He nuclei being sent off at a few % of *c*
  - next letter in greek alphabet: beta radiation = extremely high-energy electrons
  - …and of course gamma radiation = extremely high-frequency electromagnetic waves (high energy photons)



Effect of Radiation

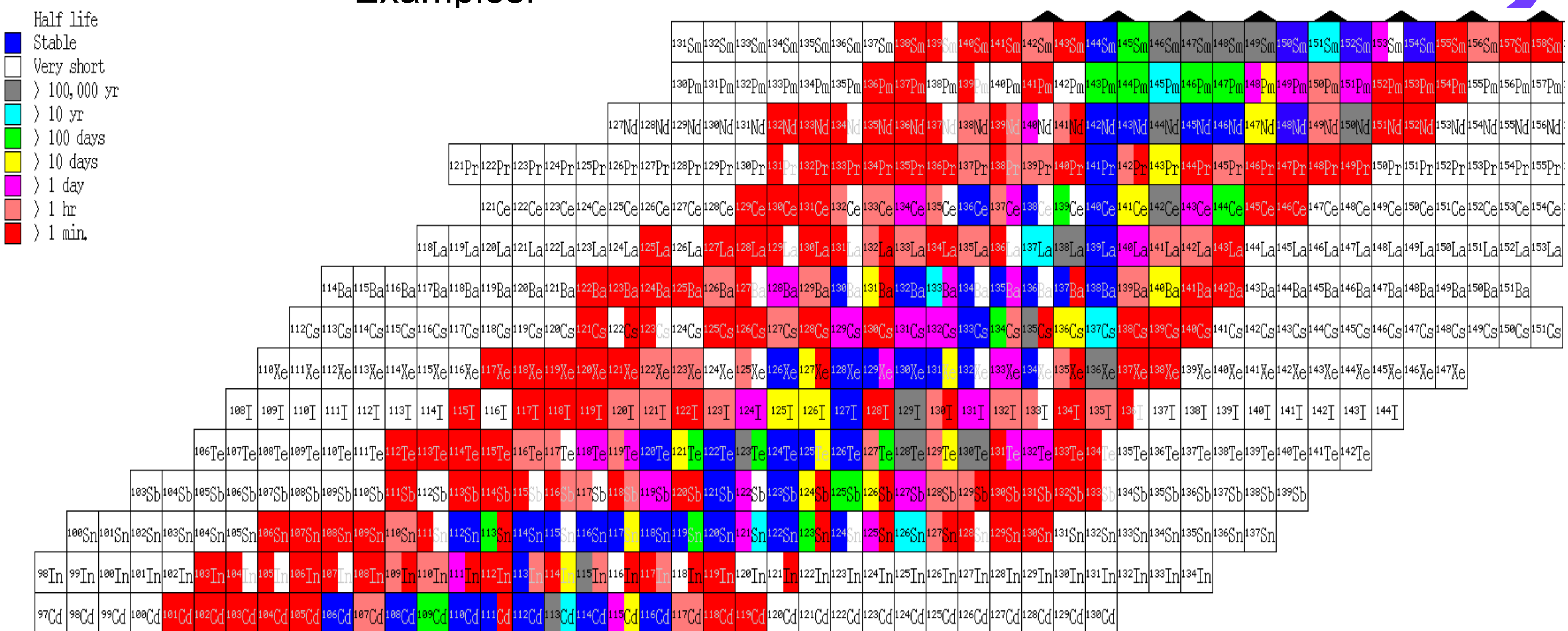
- Nuclear decay products can be very high-energy => penetrating, able to ionize atoms or molecules (ionizing radiation)
  - alpha particles can kick out lots of electrons along their flight path but can be (therefore) stopped easily (don't inhale Radon!)
  - beta particles have less effect, but can travel further
  - Xrays and gammas are most penetrating (don't stop all after the same distance)
- Create "radicals" that can destroy or alter cells and their function
  - possible cause of cancer or genetic modifications…
  - …but can also be used to destroy cancer cells
  - harmful or deadly in large doses…
  - …but can be used to kill germs in food

Some Examples for Radioactive Nuclei

- All Nuclei heavier than lead (Pb):
  - Mostly emit alphas
  - Examples:
    - Polonium, Radium, Radon, Uranium (A = 209…238) all exist naturally in Earth's crust (Radon, as a gas, can seep into houses)
      - Energy liberated in decay warms Earth's interior!
    - Even heavier ones can be created artificially but don't survive very long (Neptunium, Plutonium, Americium… up to A = 292)
  - Reason for decay: get rid of too much charge (electrostatic repulsion)
- Many isotopes throughout the periodic table emit betas:
  - ^{3}H = tritium (artificial), ^{14}C (atmosphere), ^{40}K (your bones)…
  - Reason for decay: re-balance ratio protons/neutrons
- Many nuclear alpha and beta decays are followed by gammas
  - Remove excess energy (just like electron jumping from higher to lower orbit after excitation)

Some Examples for Radioactive Nuclei

- All Nuclei heavier than lead (Pb):
  - Mostly emit alphas
  - Examples:



Half Life

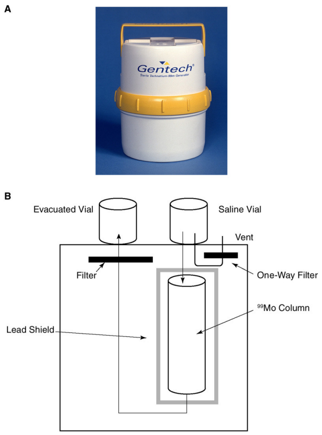
- Decays are **allowed** by energy conservation…
- …**but** still don't proceed instantly – why not?
  - Alpha decay: Barrier
    - Example: Water in a glass - energy lower if instead a puddle on the table; but can't get there
    - Alpha emitter: First have to remove the alpha particle a few fm before electric repulsion can take over (tunneling)
  - Beta decay: New type of interaction involved: WEAK interaction (hence long wait…)
    - Think of a fly pushing a truck - without friction it will move **eventually**
  - Gamma decay: Can be fast or slow - depends on particular energy levels (orbits) involved, just like for atoms

Half Life cont'd

- Quantum Mechanics: Cannot predict WHEN decay will occur, only the probability per unit time
  - Example: Play lottery every week for millions of years - **eventually** you will win, but you cannot predict **when**
- Concept: Half-life = the time that has to elapse before you have a 50-50 chance for a given nucleus to decay
  - If the chance of winning the lottery is 1 in 100 million, you have to play for 50 million weeks to get a 50-50 chance to win
  - Brain teaser: What if you didn't win in the first 50 million weeks? Will you be guaranteed to win in the next 50 million weeks? **NO**, the chances are again only 50-50!
- Start with a large number of identical radioactive nuclei
  - After 1 half-life, about 1/2 will have decayed
    - After 2nd half-life, about 1/4 more (one half of the rest) will be gone
      - After 3rd half-life, only 1/8 left over
        - After 4th half-life, only 1/16 left
          - …

Half Life cont’d

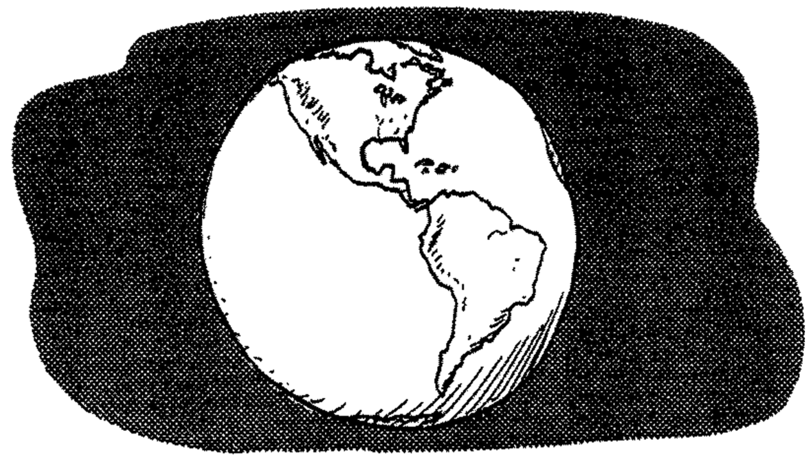
- Measure Half-Life: Count number of nuclei you start with and how many decay in a given time interval
  - Example: Start with 10^6. After 1 hour, 10 have decayed => Half Life must be of order 50,000 hours (69315, to be precise).
- Half-lifes can be all over the map:
  - some beta emitters live only a fraction of a second
  - others (^{40}K) over 1 billion years!
  - ^{14}C in between: 5700 yr
  - Tc has only radioactive isotopes (up to 1 million years)
  - neutron itself lives only 15 min unless bound in nucleus!
  - alpha emitters can live even longer: ^{238}U has $T_{1/2}$ = 4.5 billion years (the age of our solar system!), but the heaviest nuclei live only seconds
- Can use radioactive nuclei to measure age:
  - “Radiocarbon dating”
  - Age of our solar system from U, K



Half Life cont'd

- Example: Technetium
- The U.S. medical community depends on a reliable supply of the radioisotope Mo-99 for nuclear medical diagnostic procedures. Mo-99's decay product, technetium-99m (Tc-99m), is used in over 40,000 medical procedures in the United States each day to diagnose heart disease and cancer, to study organ structure and function, and to perform other important medical applications. For example, patients undergoing a common procedure—the cardiac "stress test"—likely have benefited from Tc-99m.
- Doctors or trained nuclear medicine health professionals will administer Tc-99m radiotracers to patients before a diagnostic test, usually by injection, to help diagnose medical conditions. As the half-life of Tc-99m is only six hours, it does not stay in the human body long. Nuclear medicine scans are safe and are a widely used imaging test.
- Molybdenum: Naturally occurring element, except for Mo-99. The latter can be produced through fission or through neutron capture by Mo-98.
- Because of its relatively short half-life (66 hours), Mo-99 cannot be stockpiled for use. It must be made on a weekly or more frequent basis to ensure continuous availability. The processes for producing Mo-99 and technetium generators and delivering them to customers are tightly scheduled and highly time dependent.
- Tc-99 has a half-life of about 6 hours and emits 140 keV photons when it decays to Tc-99, a radioactive isotope with about a 214,000-year half-life. This photon energy is ideally suited for efficient detection by scintillation instruments such as gamma cameras.

The age of the Earth and the entire solar system is most precisely determined by...

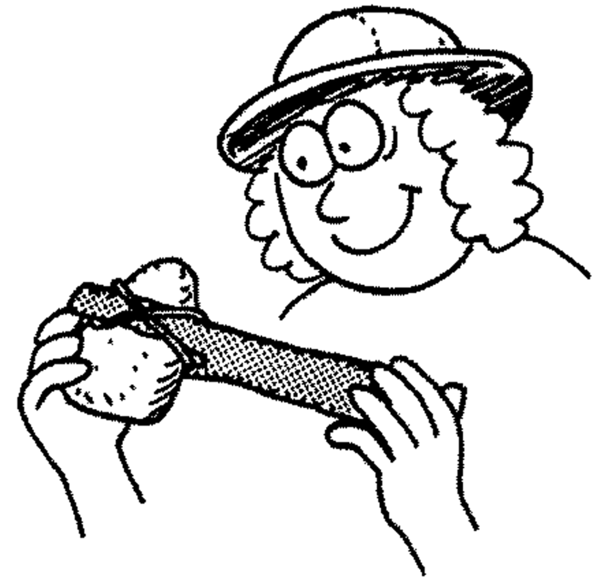


A. careful analysis of ancient written records.

B. fossil analysis.

C. radiometric dating of its oldest rocks and meteorites.

An archaeologist extracts a sample of carbon from an ancient ax handle and finds that it emits an average of 10 beta emissions per minute. She finds that the same mass of carbon from a living tree emits 40 betas per minute. Knowing that the half-life of carbon-14 is 5730 years, she concludes that the age of the ax handle is about...



A. 2865 years.
B. 5730 years.
C. 11460 years.
D. 17190 years.

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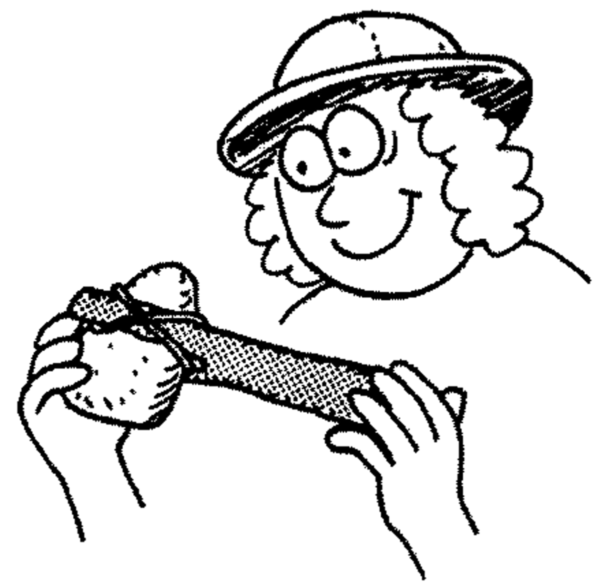

A. 2865 years.
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TWO half-lifes = reduction of acitivity (=number of nuclei) by a factor 1/4

Which of the following types of radiation is not usually emitted by radioactive nuclei?

A. Alpha.
B. Beta.
C. Gamma.
D. Radiowaves

Nuclear Force

- Back to our question: What keeps the nucleus together at all?
  - Answer: A new kind of force unlike any we've discussed so far - The strong nuclear force (duh!)
  - Note: all forces ultimately due to exchange of particles / waves
    - Easy to see for repulsion: Throw basketball back and forth…
    - Also true for attraction: electrostatic force = photon exchange (remember: photons = particles of electromagnetic field)
  - In case of nuclear force: particles exchanged are fundamental building stones of nucleons (yup, ***quarks***) and combinations of quarks (called mesons - pion, rho, omega,…)
    - Ultimately "leftover" from the even stronger, more fundamental force between quarks: Color-"electromagnetism"
    - Force between 2 tiny quarks = 1 ton!
    - Exchange particle? Yup, called "gluon"

Nuclear Force cont'd

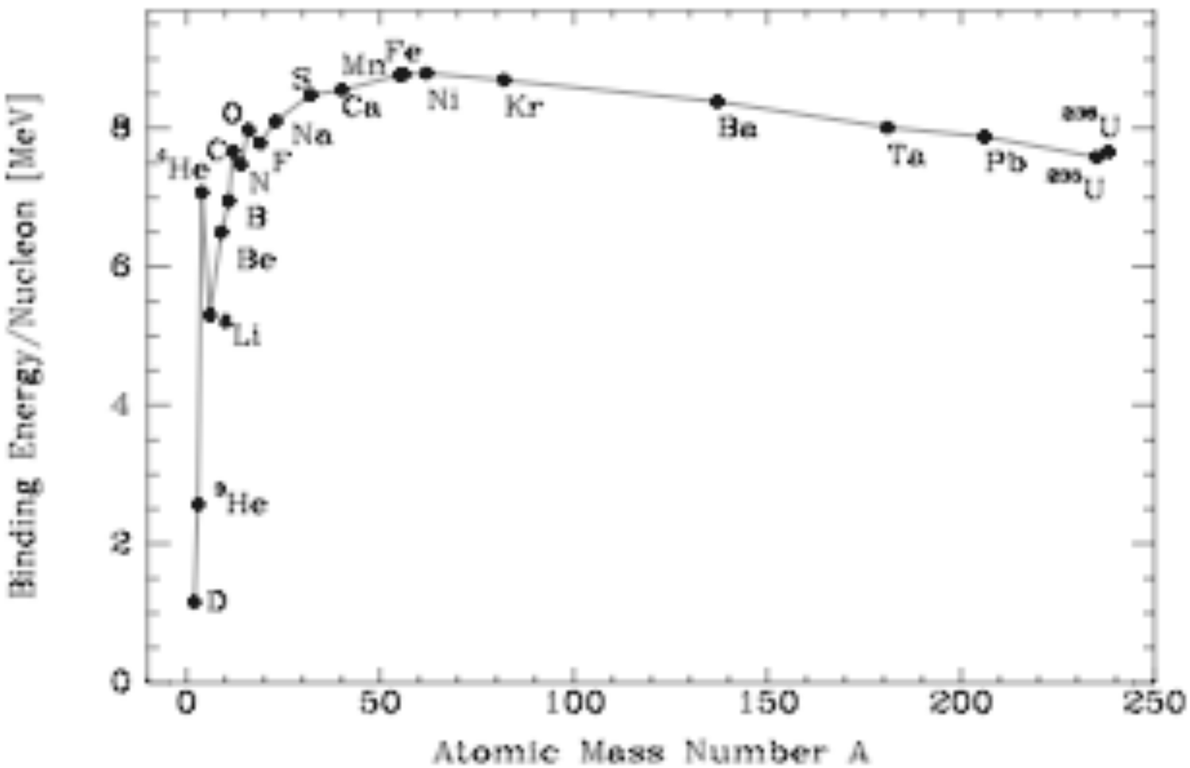
- Net effect: nearby nucleons attract each other
- Further apart: ignore each other (that's why ultimately electrostatic repulsion wins out over nuclear attraction)
- Too close for comfort: repulsion
- => Liquid drop model of the nucleus
- Pauli Exclusion Principle: Want to have roughly equal number of neutrons and protons
- Electrostatic repulsion: Increase number of neutrons over protons
- If out of balance: Change protons <=> neutrons via emission of extra charge = electrons/positrons (beta decay!)
- If too big - shed some extra charge (alpha decay)

  Can even break into two roughly equal parts - fission!

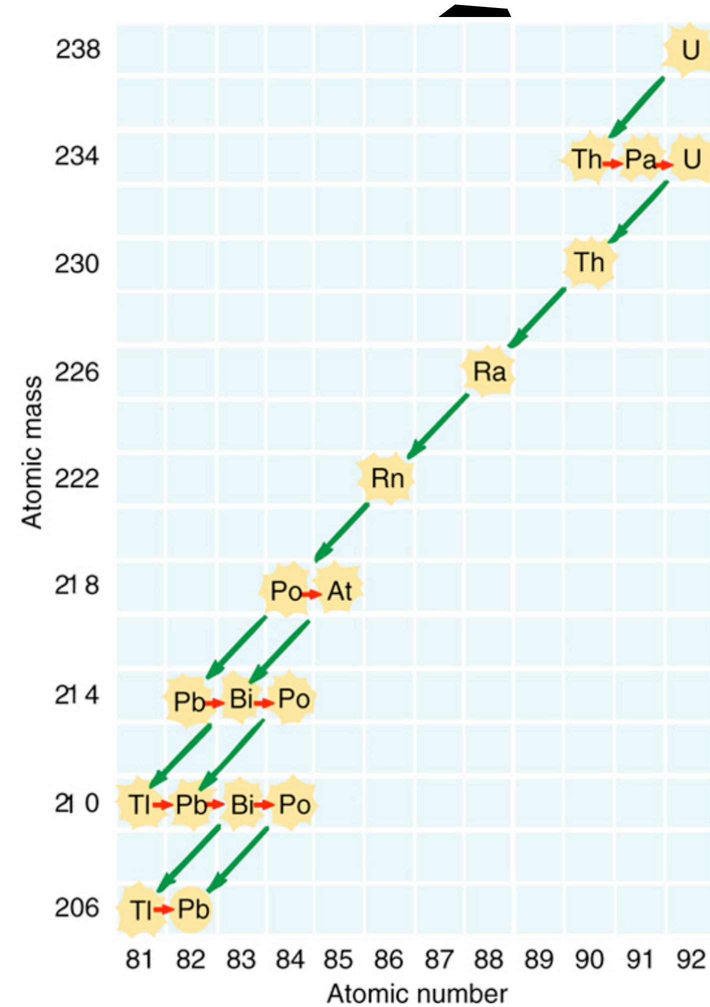
  (very rare form of radioactive decay in nature)

Nuclear energy levels

- Nucleons inside nucleus can have similar "orbits" as electrons in atom
- Similar "preferred" numbers ("magical numbers") => explains abundance of ^{4}He, ^{12}C, ^{16}O,…,^{56}Fe in the Universe
- Can excite nuclei to higher energies => decay via gamma emission (or break apart)
- Analog to photon emission in atoms



Nuclear reactions



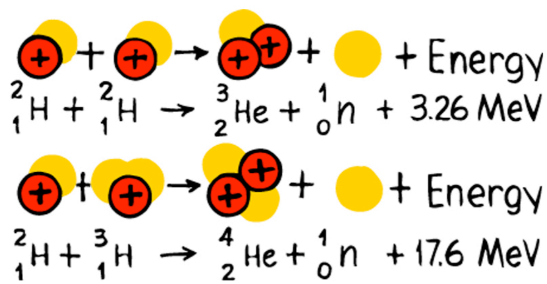
- Alpha decay
  - Changes Z by -2, A by -4 => new element!
- Beta decay (A = const!)
  - β- (electron): Z -> Z+1, N -> N-1
  - β+(positron): Z -> Z-1, N -> N+1
  - Will proceed until optimum Z/N ratio
- Elastic scattering
  - bombard nuclei with all kinds of “probes” (γ ray photons, electrons, nucleons, other nuclei,…) and look for deflection (Rutherford!)
- Inelastic scattering
  - Excite nucleus to higher energy - look for decay products (γ rays, nucleons, …)

Nuclear Reactions cont'd

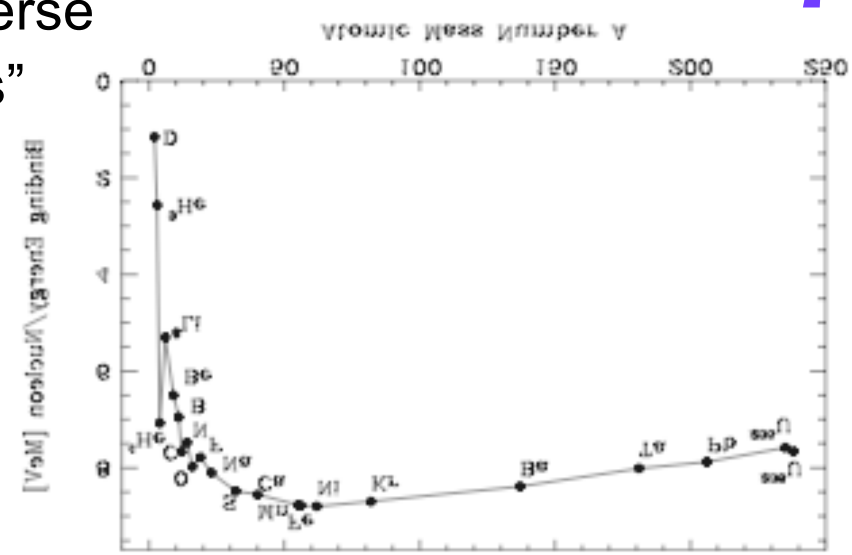
- Transmutation
  - Bombard one nucleus with another, let them exchange some nucleons, end up with 2 different nuclei
    - Example: $^{4}He + ^{14}N \rightarrow ^{17}O + ^{1}H$
    - Can make gold out of lead: Just kick out 3 protons
- Fusion
  - Similar to above; combine 2 nuclei to make a new one (often highly excited)
    - Source of all elements with Z>92: Neptunium, Plutonium, Americium, Curium, Berkelium, …. up to 116
- Fission
  - Bombard nucleus => breaks into pieces…

Nuclear Fusion

- If you combine 2 light nuclei into a heavier one, you get net energy out (each nucleon more tightly bound)
- Consequence: $M_{new} < M_1 + M_2$ ($m = E/c^2$)
- Examples
  - $^2H + ^2H \rightarrow ^3He + n$
  - $^2H + ^3H \rightarrow ^4He + n$
  - $^2H + ^1H \rightarrow ^3He + \gamma$
  - $^1H + ^1H \rightarrow ^2H + e^+ + \nu_e$

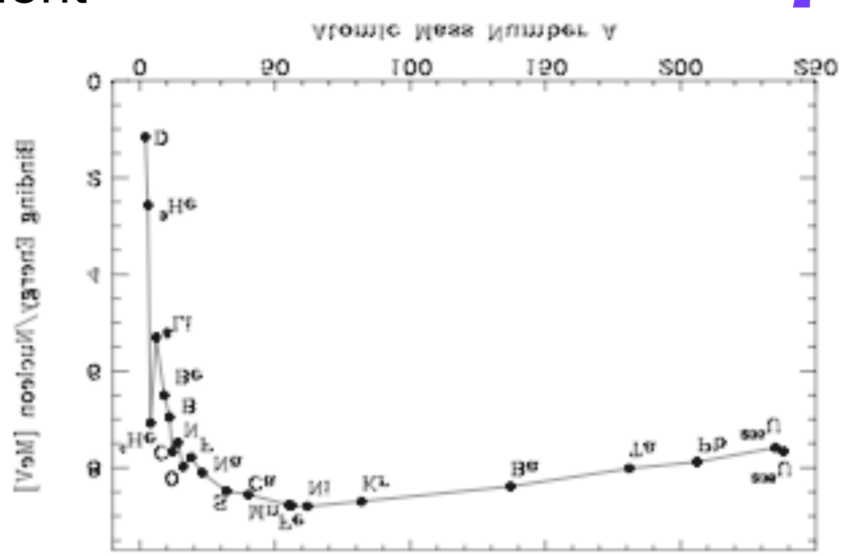


- Source of sun’s energy (and therefore nearly all energy on Earth); source of all elements in Universe
- Source of energy in “hydrogen bombs” (thermonuclear bombs)
- Possible future source of energy (fusion reactor)



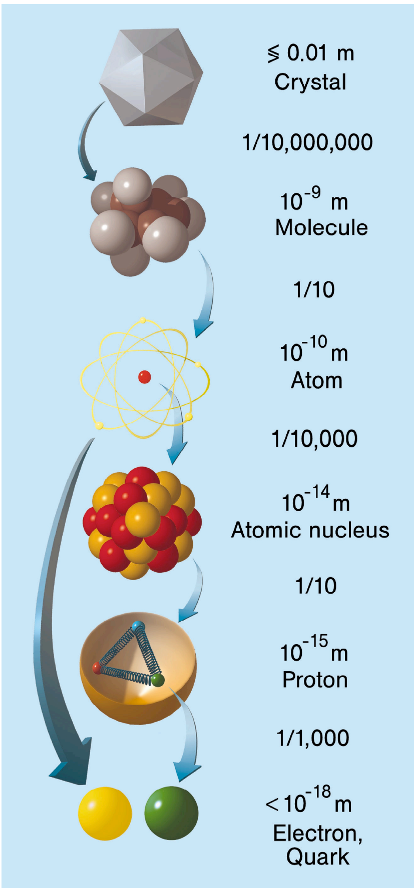
Nuclear Fission

- If you split 1 ultraheavy nucleus into two lighter ones, you get net energy out (each nucleon more tightly bound)
- Consequence: $M_1 + M_2 < M_{initial}$ ($m = E/c^2$)
- Example
  - n + ^{235}U -> Kr + B + n's
  - Requires threshold energy (from n capture)
  - Many possible reaction products (many radioactive)
  - Other fissionable isotopes: ^{233}Th, ^{239}Pu
- Chain reaction, critical mass, enrichment
- Source of energy in "atom bombs" (fission bombs)
- Source of energy (fission reactor)



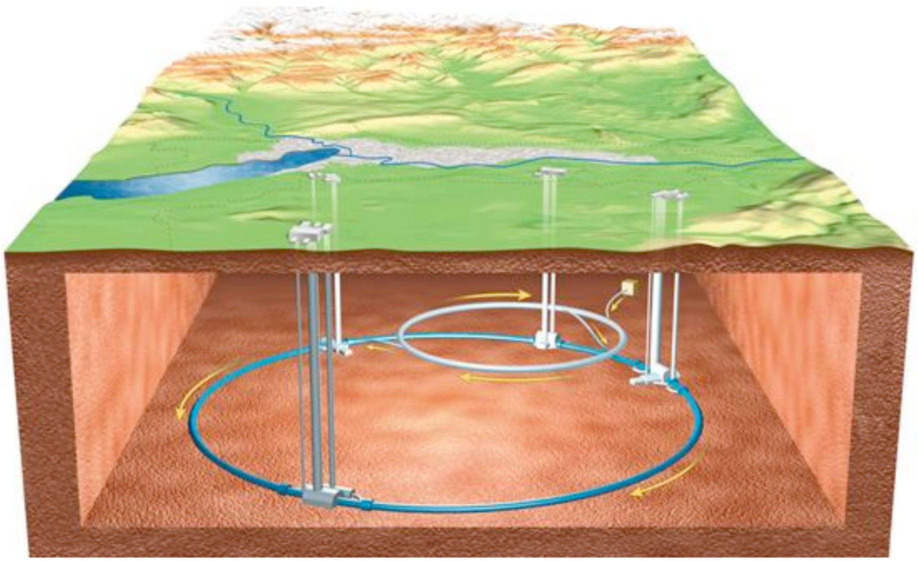
Electrostatic repulsion ->
kinetic energy of fragments ->
heating (of water in power plant)

Particle Physics

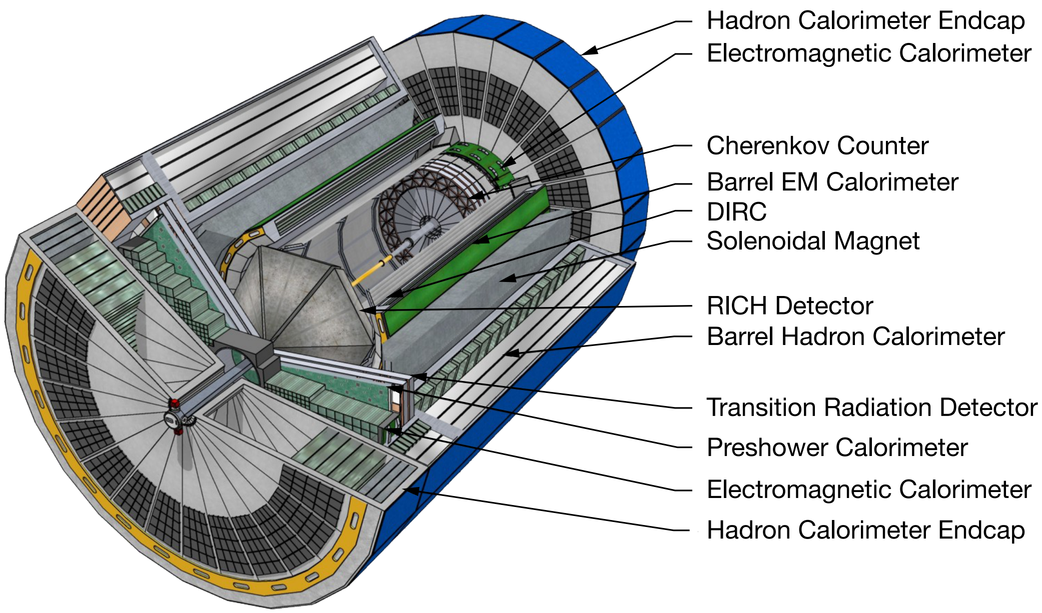


- Everything (matter, waves,…) is ultimately composed of smallest units - particles!
- Have already encountered some particles: Protons, neutrons, electrons, positrons, neutrinos, photons,…
- First 2 are not fundamental - they are made from quarks which are truly point-like (as far as we know)
- Study particles at huge accelerators using big detectors; compare with fundamental theory

“Typical” accelerator (CERN)



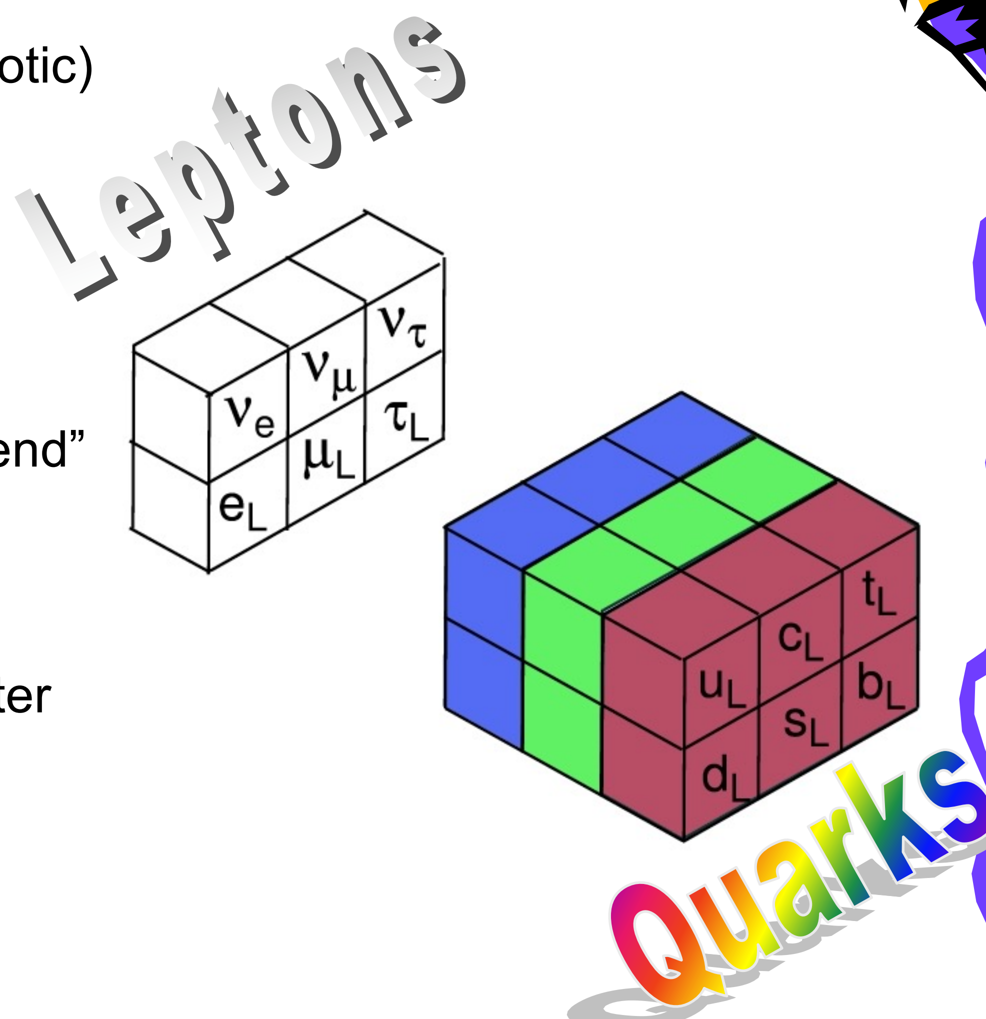
Typical detector (EIC)



The Players:

Fundamental MATTER PARTICLES

- Make up all matter (ordinary or exotic)
- Pointlike ($<10^{-18}$ m), Fundamental *)
- Massive (from < 0.1 eV to 175,000,000,000 eV = 175 GeV)
- Distinct from their antiparticles
- Fermions: Spin = 1/2 $\Rightarrow$ they "defend" their space (Pauli!)
- can only be created in particle-antiparticle pairs
- Can be "virtual", but make up matter mostly as "real"
- "stable" (from ∞ to 10^{-24} s)



x2 for R, x2 for antiparticles

*) Until further notice

The Players:
Gauge Bosons

- Mediate Interactions (Forces) - “Waves”
- Pointlike, Fundamental
- Massless *)
- Some are their own antiparticles (photon, Z^0, graviton)
- Spin 1, 2 -> Bosons (tend to cluster together, can be produced in arbitrary numbers)
- Can be real, but carry forces as virtual particles
- Some are absolutely stable (γ, gluons, gravitons)

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

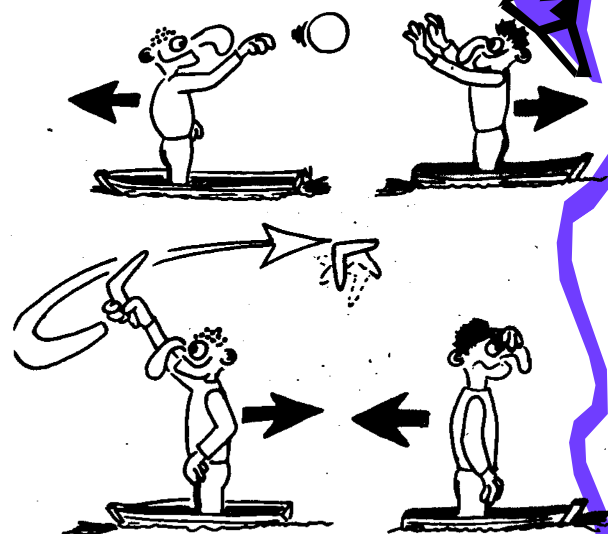
Gravitation spin = 2		
Name	Mass GeV/c^2	Electric charge
g graviton	0	0

*) See next slide

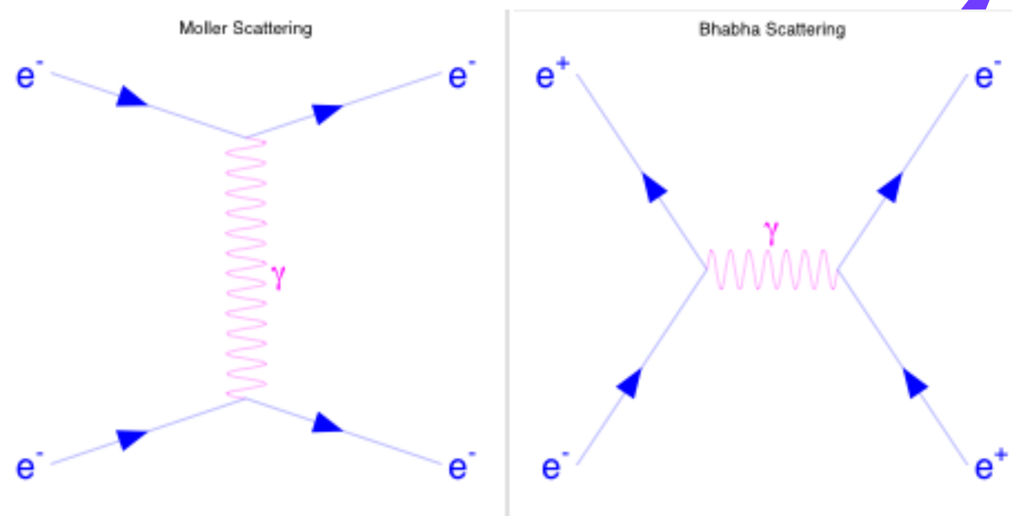
The Players:
Higgs Field

- Create “Drag” on Particles (“Molasses”)
- Origin of Mass
  Makes some gauge bosons very heavy (W’s, Z’s) and therefore short-range (“Weak” interaction)
- Origin of electroweak symmetry breaking
- Pointlike, Fundamental
- Bosons (Spin 0)
- Three massless (“swallowed up” by W’s, Z’s); one very massive (>100 GeV)
- Discovered at the Large Hadron Collider (LHC) at CERN on July 4, 2012

The Play: Feynman Diagrams



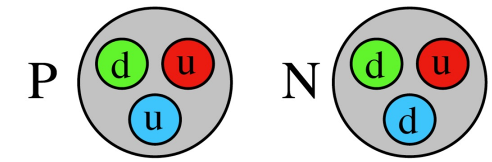
- Matter Particles interact with each other by exchanging Gauge Bosons
- Strength of Interaction determined by coupling ("charge": electromagnetic, weak, color)
- Range of interaction determined by mass of gauge boson and Heisenberg uncertainty principle
- SOME gauge bosons can interact with each other
- Examples:
  - $e^- e^{+/-}$ scattering (E&M)
  - neutron beta decay (weak)
  - quark-quark interaction (strong)
    - Confinement
    - Asymptotic freedom
    - Mesons, baryons…
    - Nπ interaction, NN interaction
  - gluons interacting with gluons -> short range of strong force



The Play: Rules (Conservation Laws)

- Some quantities are absolutely conserved:
  - Momentum p, energy E, angular momentum
  - Electric charge Q, weak hypercharge/isospin, color charge
- Some quantum numbers seem universally conserved by electroweak and strong interaction:
  - Electron lepton number L_e
  - Muon lepton number L_μ
  - Tauon lepton number L_τ
  - Baryon number B
- Some quantum numbers are conserved by strong and electromagnetic interaction
  - Parity, Time Reversal, CP
  - Quark flavor: I_3, S, C, B, T
- Some quantum numbers are only conserved by strong interaction
  - Isospin

Particle Zoo Summary



HADRONS

Family Name	Particle Name	Particle Symbol	Antiparticle Symbol	Composition	Mass	Electric Charge	Lifetime in Seconds
baryon	proton	p or p^+	$\bar{p}$	uud	1,836	+1	stable
	neutron	n or n^0	$\bar{n}$	udd	1,839	0	887
	lambda	Λ^0	$\bar{\Lambda}^0$	uds	2,183	0	2.6×10^{-10}
	lambda-c	Λ^+_c	$\bar{\Lambda}^-_c$	udc	4,471	+1	2.1×10^{-13}
	lambda-b	Λ^0_b	$\bar{\Lambda}^0_b$	udb	11,000	0	1.1×10^{-12}
	sigma	Σ^+	$\bar{\Sigma}^-$	uus	2,328	+1	0.8×10^{-10}
		Σ^0	$\bar{\Sigma}^0$	$\frac{(ud \pm du)s}{\sqrt{2}}$	2,334	0	7.4×10^{-20}
		Σ^-	$\bar{\Sigma}^+$	dds	2,343	−1	1.5×10^{-10}
	xi	Ξ^0	$\bar{\Xi}^0$	uss	2,573	0	2.9×10^{-10}
		Ξ^-	$\bar{\Xi}^+$	dss	2,585	−1	1.6×10^{-10}
	xi-c	Ξ^0_c	$\bar{\Xi}^0_c$	dsc	4,834	0	9.8×10^{-14}
		Ξ^+_c	$\bar{\Xi}^-_c$	usc	4,826	+1	3.5×10^{-13}
	omega	Ω^-	$\bar{\Omega}^+$	sss	3,272	−1	0.8×10^{-10}
	omega-c	Ω^0_c	$\bar{\Omega}^0_c$	ssc	5,292	0	6.4×10^{-14}
meson	pion	π^+	π^-	$u\bar{d}$	273	+1	2.6×10^{-8}
		π^0	π^0	$\frac{(u\bar{u} - d\bar{d})}{\sqrt{2}}$	264	0	8.4×10^{-17}
	kaon*	K^+	K^-	$u\bar{s}$	966	+1	1.2×10^{-8}
		K^0	$\bar{K}^0$	$d\bar{s}$	974	0	8.9×10^{-11} 5.2×10^{-8}
	J/psi	J or Ψ	J or Ψ	$c\bar{c}$	6,060	0	1.0×10^{-20}
	omega	ω	ω	$\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}$	1,532	0	6.6×10^{-23}
	eta	η	η	$\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}$	1,071	0	3.5×10^{-22}
	eta-c	η_c	η_c	$c\bar{c}$	5,832	0	3.1×10^{-22}
	B	B^0	$\bar{B}^0$	$d\bar{b}$	10,331	0	1.6×10^{-12}
		B^+	B^-	$u\bar{b}$	10,331	+1	1.6×10^{-12}
	B-s	B^0_s	$\bar{B}^0_s$	$s\bar{b}$	10,507	0	1.6×10^{-12}
	D	D_0	$\bar{D}_0$	$c\bar{u}$	3,649	0	4.2×10^{-13}
		D^+	D^-	$c\bar{d}$	3,658	+1	1.1×10^{-12}
	D-s	D^+_s	D^-_s	$c\bar{s}$	3,852	+1	4.7×10^{-13}
	chi	χ^0_c	χ^0_c	$c\bar{c}$	6,687	0	3.0×10^{-22}
	psi	Ψ^0_c	Ψ^0_c	$c\bar{c}$	7,213	0	1.5×10^{-20}
	upsilon	Υ	Υ	$b\bar{b}$	18,513	0	8.0×10^{-20}

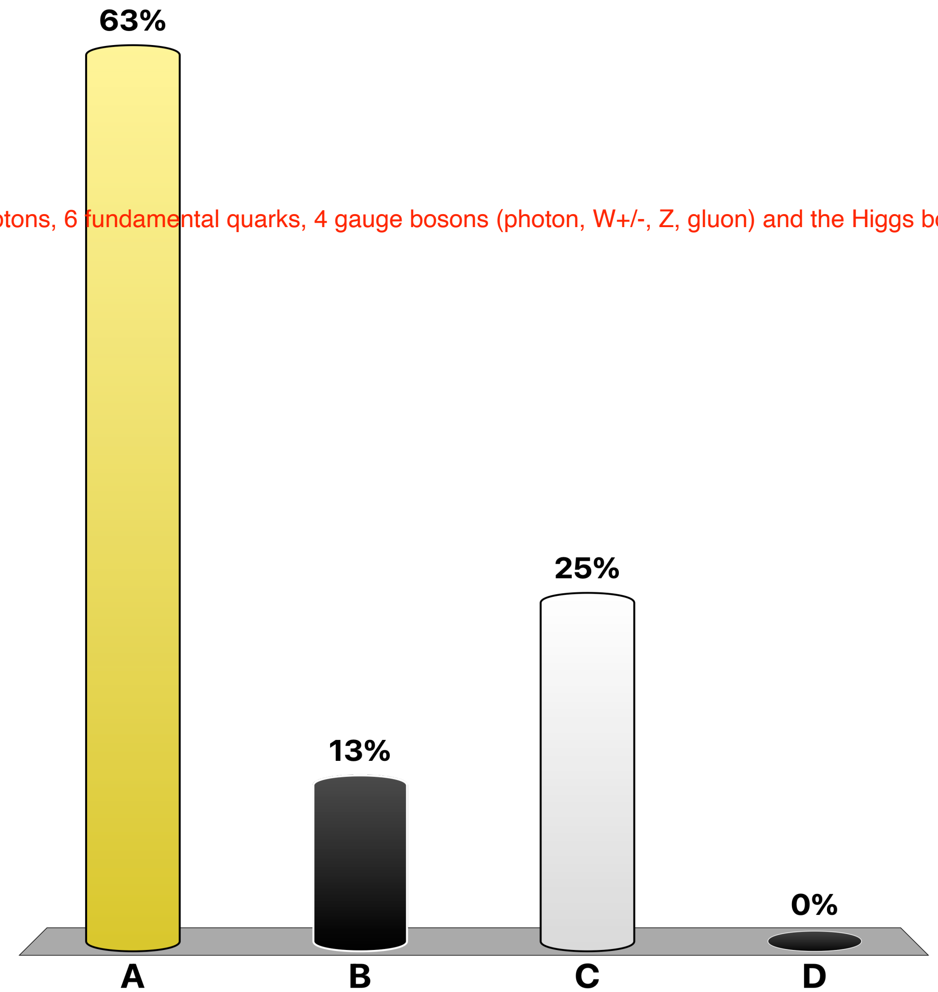
*The neutral kaon is composed of two particles; the average lifetime of each particle is given.

How many different truly ***fundamental*** particles do we know to exist (as of today)?

(Don't count antiparticles as separate particles)

A. 3
B. Less than 20
C. 100's
D. millions

6 fundamental leptons, 6 fundamental quarks, 4 gauge bosons (photon, W+/-, Z, gluon) and the Higgs boson



Which fundamental interaction is **essential** for sun to produce light?

A. The strong nuclear interaction
B. The weak nuclear interaction
C. The electromagnetic interaction.
D. Gravity.

ALL of them!