(2019) PHYS 2260 Nuclear & Particle Physics

WHAT ARE THE FUNDAMENTAL CONSTITUENTS OF NATURE?

[What is everything made out of?
From ancient times, people have asked this question.
By the end of 19th century, most chemists & physicists concluded]

ATOMS (~ 100 different types)

↓ composed of

ELECTRONS and NUCLEI

↓ composed of

PROTONS and NEUTRONS (called nucleons)

↓ composed of

	1st generation	2nd	3rd
QUARKS	u	c	t
	d	s	b
LEPTONS	ν_e	ν_μ	ν_τ
	e^-	μ^-	τ^-

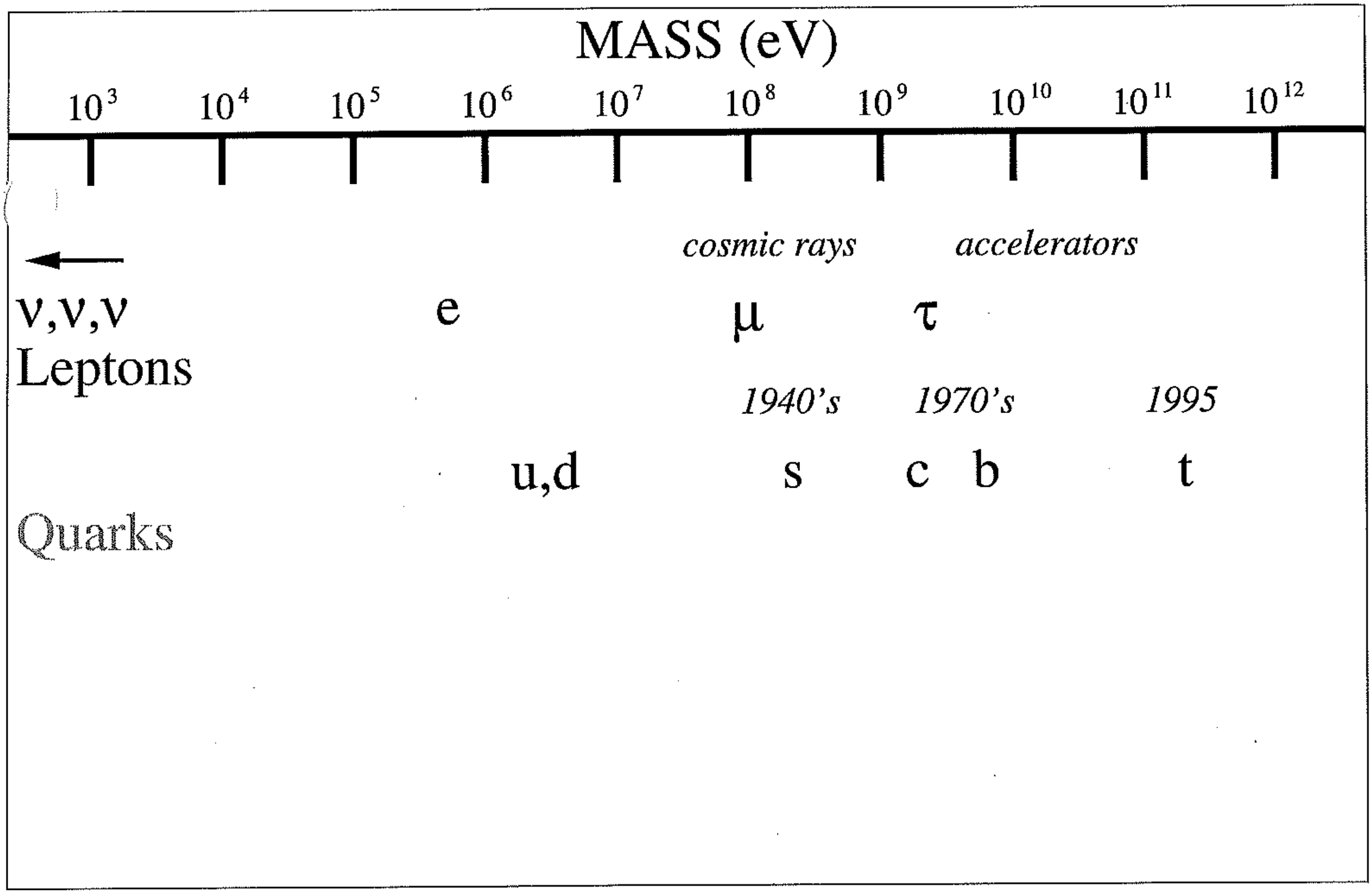
(ELECTRONS → LEPTONS)

⟶ more massive

Neutrinos initially believed to be massless.
They actually have small (but yet unknown) masses.

These 6 Quarks + 6 leptons are believed to be the most fundamental constituents

but ...
more generations?
subquarks & subleptons?
strings?



MASS (eV)
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12
cosmic rays
accelerators
ν,ν,ν
Leptons
e
μ
τ
1940's
1970's
1995
u,d
s
c
b
t
Quarks

[The theoretical framework which describes these particles is]
quantum field theory (QFT), merger of QM and special relativity

QFT ⇒ for each type of particle, there is a corresponding type of antiparticle, w/ same mass + opposite charge

antiquarks	$\bar{u}$	$\bar{c}$	$\bar{t}$
	$\bar{d}$	$\bar{s}$	$\bar{b}$
antileptons	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$
	e^+	μ^+	τ^+

↑ positron (e^+)

[use bars on all xc charged leptons]

Antiparticles are generally much less abundant (despite the theoretical symmetry between pcls + antipcls)

[Why?]

[We characterize different types of particles (both fundamental + composite)
[by their properties

PROPERTIES OF PARTICLES

- MASS
- CHARGE, ELECTRIC + OTHERWISE (eg. quarks also have color charge)
- OTHER CONSERVED (OR ALMOST CONSERVED) ADDITIVE QUANTUM NUMBERS
  (eg. baryon no., strangeness)
- MULTIPLICATIVE QUANTUM NUMBERS
  parity P
  charge conjugation symmetry C
  time reversal invariance T
- SPIN (ie intrinsic angular momentum)
- MAGNETIC DIPOLE MOMENT
- ISOSPIN, and OTHER FLAVOR QUANTUM NUMBERS
- MEAN LIFE and DECAY PRODUCTS, if unstable

These properties are measured experimentally and compiled in the biennial Particle Physics Booklet
[hand out; put up on screen]
↳ μ^-

[We'll try to understand and hopefully calculate these]
[properties from our theoretical models

Most particles are unstable; ~~e.g. all charged 2nd & 3rd generation~~

more massive particles always decay into less massive ones unless forbidden by some conservation law

- All charged 2nd & 3rd generation ptls decay into 1st generation

[wait until later!] [wt is not forbidden is mandatory]

Note: didn't include size

→ all fundamental ptls are ~~[illegible]~~ thought to be point-like

How do we study elementary particles + learn about their properties?

By throwing things at them + seeing what happens.

- sometimes gets deflected or bounces back
- sometimes gets absorbed
- if throw hard enough, produces new particles

Scattering experiments (target and probe)

Probes

- visible light [called "looking at something"]

  gases scatter $\sim \frac{1}{\lambda^4}$ ⇒ Rayleigh scattering

- X-rays [study crystal structure, DNA]

  when scattered from free electrons, scattered X-rays have slightly longer λ ⇒ Compton scattering

- α-particles

  scatters off nuclei → both positively charged ⇒ Rutherford scattering

  induces nuclear reactions

- neutrons - no Coulomb barrier
  - absorbed to create new isotopes or induce fission

- cosmic rays (mostly protons)

  create new elementary particles

- accelerators (charged particles: p or e^-)

  van de Graaff
  cyclotrons
  modern particle accelerators (LHC)

What holds particles together in composite particles?

What causes more massive particles to decay, and conversely what allows them to be produced in collisions?

What causes particles to scatter or absorb incoming probes?

Ans: four fundamental forces / interactions

1) electromagnetic
2) strong nuclear
3) weak nuclear
4) gravity

[Are there more? "Fifth force experiments"]

The strength of the interaction influences

① the binding energy of composites
② the rate of decay, ∴ mean life τ

③ the scattering rate, ∴ cross-section σ

1) electromagnetism

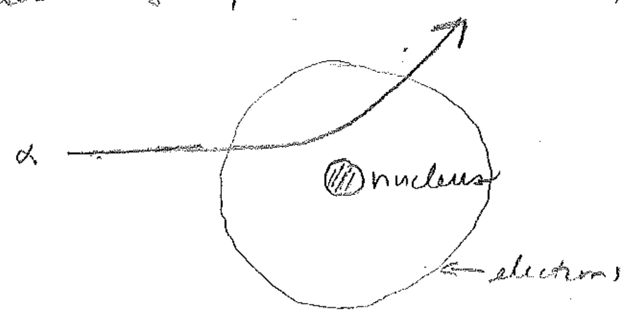
- acts on all electrically charged particles (+ particles w/ magnetic moments)
- binds electrons and nuclei into atoms

- residual force on neutral objects [QM also plays a role]

  binds atoms into molecules

- long-range Coulomb force $F = \frac{KQ_1Q_2}{r^2} = \frac{Q_1Q_2}{4\pi\epsilon_0 r^2}$

  causes charged particles to scatter off unshielded nucleus



strength of interaction $\sim Ke^2$

2) strong nuclear force

- acts on quarks (which have "color charge": R, G, B)

  antiquarks have anticolor $\bar{R}, \bar{G}, \bar{B}$

- binds quarks & antiquarks into mesons ($q\bar{q}$)

  e.g. $\pi^+ = u\bar{d}$ [not as familiar since unstable]

  [many others: PPB]

- binds triplets of quarks into baryons (qqq), one of each color

  ↑ ↑ ↑ → R G B

  e.g. proton $p = uud$

  neutron $n = udd$

  many other combinations, all unstable [see PPB]

- mesons & baryons are "color neutral" or "color singlet"

  $R\bar{R}$, $G\bar{G}$, $B\bar{B}$, RGB

  Color force is so strong that it is believed that only color-neutral objects can exist in isolation

  (confinement of quarks)

[search for free quarks]

• even though nucleons (p, n) are color neutral the (much weaker) residual force can bind them into nuclei

• ∃ other color neutral objects: pentaquarks
$qqqq\bar{q}$ [bound state of baryon & meson]

why not qq or $q\bar{q}\bar{q}$? not color neutral

• strong force is <u>short range</u>, so size of nuclei is limited
~1 fm = femtometer = 10^{-15} m = 1 fermi

<u>Scattering</u> of protons off nuclei
is purely electromagnetic until protons gets close enough to feel strong force

scattering of neutrons ⇒ no Coulomb barrier

<u>weak nuclear interaction</u>

- short range
- primarily responsible for particle decay
  eg β-decay of nuclei
- intergenerational decay (2nd → 1st, 3rd → 2nd, 3rd → 1st)
  always occurs via the weak interaction

→ weak interaction strength → slow decay rate
→ long mean life

<u>gravity</u>

- acts on anything w/ energy (not just mass)
- long-range (inverse square)
  - solar system, galaxies
- always attractive
  - binds hydrogen into stars, stars into galaxies
- very weak on microscopic scale (<< electromagnetic)
  but cumulative so dominant on macroscale
- ignorable for elementary particles

strong

strength ↑ EM

weak

gravity

Interactions ⟶ more particles

Electromagnetic force: due to electromagnetic fields governed by Maxwell eqns

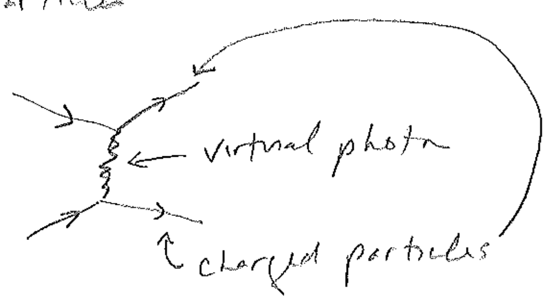
[These eqns have wavelike solns
EM waves travel at speed of light ⇒ they are light]

Apply quantum mechanics to these fields ⇒ QFT

Quanta are massless particles called photons (Einstein, 1905)

QFT ⇒ Exchange of virtual photons mediates EM force between charged particles

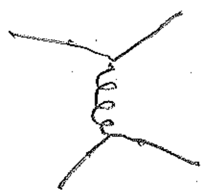
Feynman diagram



strong nuclear force due to QCD field
(quantum chromodynamics)
governed by a nonlinear version of Maxwell's eqns
(Yang-Mills eqns)

When quantized ⇒ 8 types of gluons (massless)

Exchange of gluons mediates color force between quarks



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weak nuclear force is similar

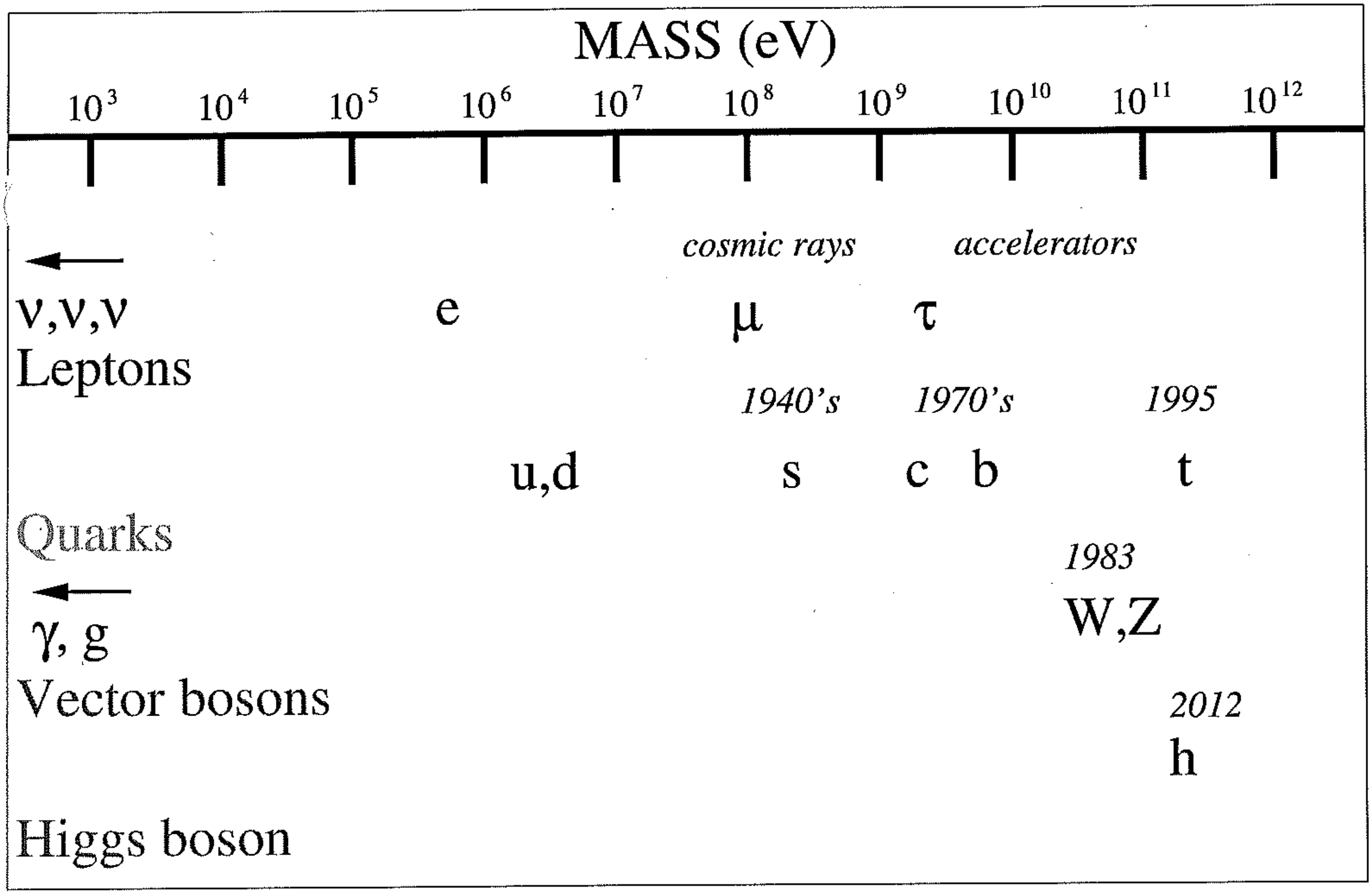
When quantized ⇒ 3 massive particles (W^+, W^-, Z^0)
which mediate the weak interaction

(actually, electroweak)

The particles are massive due to symmetry-breaking
by another field called Higgs field ⇒ Higgs boson (massive)

[show chart of masses] [also flip thru PPB together]

The strong and electroweak interactions,
together w/ the quarks + leptons, make up the
standard model of particle physics,
which is our current understanding and very well tested.
This course is about how we came to know this.



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accelerators
ν,ν,ν
e
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τ
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1970's
1995
u,d
s
c
b
t
Quarks
1983
γ, g
W,Z
Vector bosons
2012
h
Higgs boson

gravity, mediated by gravitational fields
governed by Einstein's equations of GR.

[These eqns have wavelike solutions
⇒ gravitational waves discovered by LIGO]

We <u>expect</u> that quantum mechanics ⇒ gravitons
but single gravitons are not yet detectible.

Also quantum theory of gravity is not yet satisfactory

Fortunately, gravity is irrelevant on the scale of
elementary particles

<u>BSM?</u>

- massive neutrinos
- dark matter
- quantum gravity (string theory?)

- more forces (GUT)
- supersymmetry