

Particle physics: lecture 1

Biplab Dey

Eötvös Loránd University (ELTE)
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LECTURER AND COORDINATES



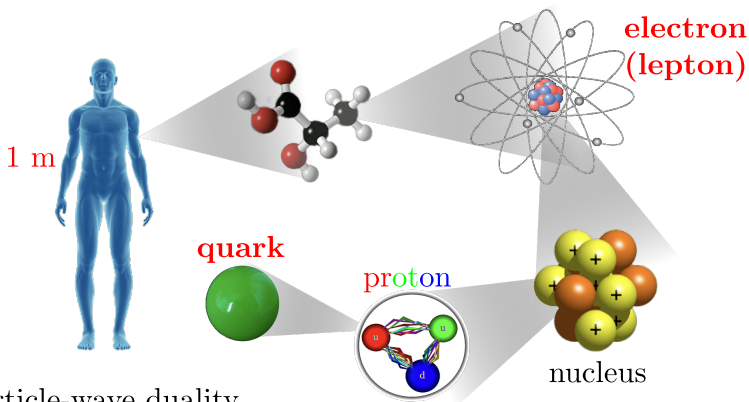
- I am a high energy particle experimentalist working at the Large Hadron Collider (LHC) at CERN, near Geneva.
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- Office: Dept. of Atomic Physics, 3.81

SCHEDULE AND REFERENCES

- Course page:
<http://bodri.elte.hu/~giordano/partphys/index.html>
- This week's schedule:
 - Lecture 1 (13th Sept): introduction to elementary particles
 - Lecture 2 (15th Sept): introduction to particle detectors
 - Lecture 3 (16th Sept): relativistic kinematics and exercises
- Introductory books:
 - D. Griffiths, *Introduction to Elementary Particles*
 - D. H. Perkins, *Introduction to High Energy Physics*

WHAT IS ELEMENTARY PARTICLE PHYSICS?

- Fundamental/indivisible constituents of matter.
- Understand their interactions \Rightarrow biology, chemistry (in principle!).



particle-wave duality

top quark probes physics at $\sim 10^{-21}$ m

SCALES AND ELEMENTARITY

- What is “elementary” depends on the energy/length scale you are probing. Uncertainty principle: $\Delta x \sim \hbar/\Delta p$
 - Newtonian planetary motion: earth is point-like
 - Nuclear physics (NP): protons and neutrons
 - High energy physics (HEP): quarks and leptons (no known sub-structure yet)
- We will revisit the concept of effective-elementarity/range-of-interaction/degrees-of-freedom several times during this course.
- Nice website for a perspective: <https://scaleofuniverse.com>

NATURAL UNITS

- In HEP, it's convenient to use *natural units*, that set the values of physical constants to unity:

$$\hbar = c = \varepsilon_0 = k = 1$$

- Redefine all other units in terms of energy.
- Electron volt (eV): energy acquired by an electron accelerated over a potential of 1V. (MeV, GeV, TeV, ...).
- Mass and momentum $\propto E$ ($E = mc^2$).
- Length and time $\propto E^{-1}$ ($E = h\nu$).

NATURAL UNITS (CONT.)

- Connection with SI units: $\hbar c \sim 197 \text{ MeV}\cdot\text{fm}$.
- 1 Fermi (proton radius) $\sim 10^{-15} \text{ m} \sim \frac{1}{5} \text{ GeV}^{-1}$.
- Proton/neutron masses $\sim 1 \text{ GeV}$.
- Electron mass is $\sim 0.5 \text{ MeV}$.
- Charge (Coulomb) is redefined by choosing $\epsilon_0 = 1$.
- Fine-structure constant $\alpha = \frac{1}{137} = \frac{e^2}{4\pi\epsilon_0\hbar c} = \frac{e^2}{4\pi}$. Charge is dimensionless ($e = \sqrt{4\pi\alpha} \sim 0.3$).
- Temperature: $kT = E$ (Boltzmann const.). $1 \text{ GeV} \sim 1.16 \times 10^{16} \text{ K}$.

BRIEF HISTORY: BIRTH OF PARTICLE PHYSICS

- What are we made of: a philosophical question for the ages.
- First scientific breakthrough was early 19th century chemist, John Dalton's "law of multiple proportions".
- One unit carbon and one unit oxygen makes CO. Two units of oxygen makes CO₂, ... theory of atoms ("indivisible" in Greek).

PERIODIC TABLE

- Mendeleev's periodic table (1869): each element has an integral atomic number (Z) and non-integral atomic weight (A).

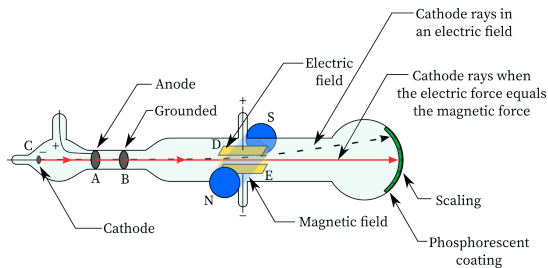
Periodic Table of the Elements

1 H Hydrogen 1.01																	2 He Helium 4.00												
3 Li Lithium 6.94	4 Be Beryllium 9.01											5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18												
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.95												
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.99	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.38	31 Ga Gallium 69.72	32 Ge Germanium 72.63	33 As Arsenic 74.92	34 Se Selenium 78.97	35 Br Bromine 79.90	36 Kr Krypton 84.00												
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.95	43 Tc Technetium 98.91	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.6	53 I Iodine 126.90	54 Xe Xenon 131.29												
55 Cs Cesium 132.91	56 Ba Barium 137.33	Lanthanides		72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222.02											
87 Fr Francium 223.02	88 Ra Radium 226.03	Actinides		104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 263	107 Bh Bohrium 264	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Ds Darmstadtium 267	111 Rg Roentgenium 268	112 Cn Copernicium 269	113 Nh Nihonium 270	114 Fl Flerovium 271	115 Mc Moscovium 272	116 Lv Livermorium 273	117 Ts Tennessine 274	118 Og Oganesson 274											
89-103	104-108	109-112	113-118	119-120	121-122	123-124	125-126	127-128	129-130	131-132	133-134	135-136	137-138	139-140	141-142	143-144	145-146	147-148											
57 La Lanthanum 138.91	58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium 144.91	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.05	71 Lu Lutetium 174.97	89 Ac Actinium 227.03	90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium 237.05	94 Pu Plutonium 244.06	95 Am Americium 243.06	96 Cm Curium 247.07	97 Bk Berkelium 247.07	98 Cf Californium 251.08	99 Es Einsteinium 254	100 Fm Fermium 257.10	101 Md Mendelevium 258.10	102 No Nobelium 259.10	103 Lr Lawrencium 262

Alkali Metal
Alkaline Earth
Transition Metal
Lanthanide
Actinide

- Pattern linked to the fact that atoms are very much “divisible”, with internal structure.

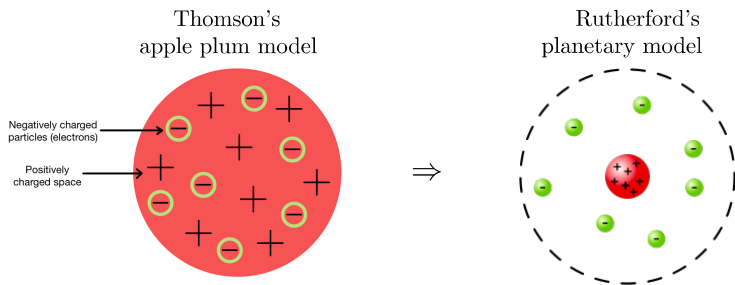
ELECTRON: FIRST SUB-ATOMIC PARTICLE



- 1897 *electron* (e), J. J. Thomson
- Cathode rays: negatively charged.

- Using perpendicular crossed electric and magnetic fields, tuned so that the stream was undeflected, $v/c = E/B$
- From the deflection in the presence of the electric field only, determined their charge-to-mass ratio
- Further, m/e less than thousand times smaller than hydrogen ions.

INSIDE THE NUCLEUS



- **1908-1917:** *proton* (p), E. Rutherford, H. Geiger, E. Marsden *et al.*
- planetary model of the atom: electrons orbiting around a positively charged *nucleus* containing almost all the mass
- each positive charge = one hydrogen nucleus = proton
- **1932:** *neutron* (n), J. Chadwick
- mismatch between mass and charge of the nucleus
- fixed by neutron: neutral but essentially same mass as proton

MEANWHILE...RADIATION

1905: *photons* (γ), M. Planck, A. Einstein, *et al.*

- In subatomic processes, EM radiation comprises neutral, massless particles.
- Birth of quantum theory: $E \propto$ radiation frequency (photons)
- Only way to explain photoelectric effect (Einstein, 1905) and the scattering of light on particles at rest (Compton, 1926)
- *EM interaction* \sim exchange of a stream of photons between electrically charged objects.

STRONG INTERACTIONS: π -MESON OR PION

- Recall: Rutherford's gold-foil experiments showed a densely packed nuclear core.

Q. How do protons (and neutrons) stay together in nuclei?

A. *Strong interaction*: strong (overcome EM repulsion among protons), short-ranged (no macroscopic effects)

1934, H. Yukawa: strong interaction mediated by a new particle – the π -meson – in analogy with EM and the photon

- proton and neutron \in *baryons*; baryons and mesons \in *hadrons*
- estimate of mass from range of force $\sim 1/6$ of proton mass

1936: new particle, right mass found in cosmic rays by Anderson & Neddermeyer... but *not* Yukawa's meson!...

MUONS: “WHO ORDERED THAT?”

1946-47 Powell, Lattes, Occhialini: *two* new particles in cosmic rays

- heavier one, shorter lifetime, disintegrated almost entirely in the upper atmosphere – the *pion* (π), the true Yukawa meson
- lighter one, longer lifetime, originally identified with the meson but interacts little with nuclei – the muon (μ), into which the pion decays
- muon was not expected (I. Rabi: “Who ordered that?”): sort of heavier electron, grouped with it in the family of *leptons*

ANTIPARTICLES

Theory:

1928-1931, P. A. M. Dirac: relativistic quantum mechanics predicts that to each particle corresponds its *antiparticle*: same mass but opposite electrical (and other) charge(s).

1928-1931, W. Pauli: AHAHAHAH LOL

Experiment:

- 1932: *positron*, C. D. Anderson
- 1955: *antiproton*, E. Segrè & O. Chamberlain
- 1955: *antineutron*, B. Cork

Some particles, like the photon, are their own antiparticles; electric neutrality is however a necessary but not sufficient condition

WEAK DECAYS: THE GHOSTLY NEUTRINO(S)

- Unstable nuclei undergo radioactive β -decay: $n \rightarrow p + e^- (+X)$.
- Problem was, this seemed to break momentum conservation.
- W. Pauli in 1930: additional neutral, very weakly interacting, almost massless particle is also emitted \Rightarrow neutrino.
- Very hard to detect. 1956 Reines & Cowan: first observation
- 1950s-1960s: several experiments show
 - neutrino (ν) \neq antineutrino ($\bar{\nu}$)
 - two types of neutrinos, one corresponding to the electron (ν_e), one corresponding to the muon (ν_μ), and respective antineutrinos ($\bar{\nu}_e, \bar{\nu}_\mu$)

STRANGENESS AND THE HADRON “ZOO”

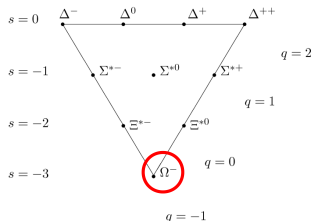
1947: kaon (K), G. D. Rochester & C. C. Butler

- Hadron of the meson subfamily, mass intermediate between π and p
- “Strange” particle: created via strong interactions, decays slowly via weak interactions
- **pre-1960**: Hundreds of strongly interacting hadrons (strange and non-strange) found experimentally in the following years: the hadron “zoo”
- Clear that they were not all elementary, but underlying pattern unclear.

THE QUARK MODEL

1964, Gell-Mann, Zweig: *quark model*

- Mesons and baryons not elementary but bound states of *quarks* and *antiquarks* – “more fundamental” particles
 - meson = quark+antiquark,
 - baryon = three quarks, antibaryon = three antiquarks
- Three types: *up* (u), *down* (d), and *strange* (s). Fractional charges. Has a property called “color”.
- Neatly accommodates the hadron zoo spectra, predicts the Ω^- baryon (obs. 1964).
- Quarks as real objects (and not just a model) accepted only after discovery of the fourth quark: 1974, J/ψ meson and *charm* quark (c), B. Richter *et al.*; S. Ting *et al.*



THE STANDARD MODEL: MATTER

From here on:

- **1975**: tau lepton (τ), M. Perl *et al.*, corresponding neutrino immediately theorised
- **1977**: *bottom* or *beauty* quark (b), L. Lederman *et al.*, sixth quark immediately theorised
- **1995**: *top* or *truth* (t) quark, CDF and DØ experiments at Fermilab
- **2000**: ν_τ , DONUT experiment at Fermilab

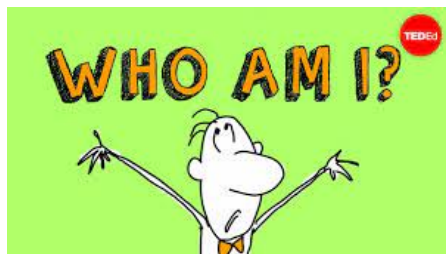
Six quarks, six leptons and corresponding antiparticles = *matter particles*

THE STANDARD MODEL: INTERACTIONS

Weak and strong interactions modeled like the photon for EM.

- Mediator role of pion taken over by *gluons* (g), interactions described by Quantum Chromodynamics (QCD)
- Weak interactions mediated by *intermediate vector bosons*: W (charged) and Z (neutral), (1983, UA1 and UA2 experiments at CERN)
- Remaining problems fixed by *Higgs boson* (H), (2012, ATLAS and CMS experiments at CERN)
- Weak interactions unified with EM: Glashow-Salam-Weinberg model
- GSW+QCD= *Standard Model* of particle physics

SPIN AND PARITY

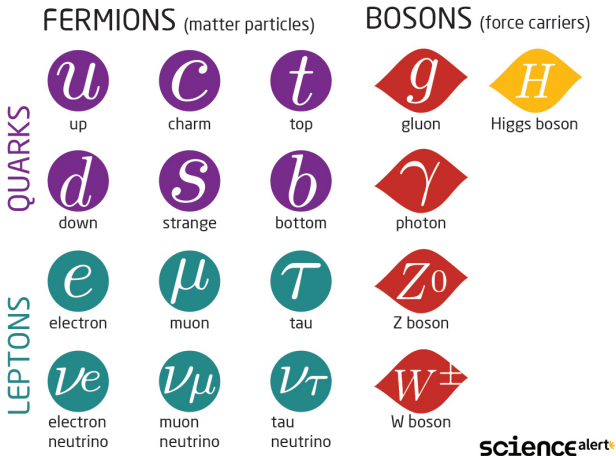


- What properties uniquely identify particles – both elementary (electron) or composite (proton).
- Mass, type of interaction (strong, weak, EM) and charge
- + need several other “quantum numbers”, in particular spin and parity. Lead to selection rules for decays.

SPIN AND PARITY

- Spin (\vec{S}): rotational symmetry; Parity (P): mirror symmetry.
- Note: weak interaction breaks parity symmetry. Strong interaction preserves parity.
- Half-integer spin particles are called fermions (quarks + leptons).
- Spin-statistic theorem, 1940, W. Pauli: no two identical fermions can occupy the same quantum state. Holds up neutrons stars.
- Integer-spin particles are called bosons (photons). Identical particles can form Bose-Einstein Condensates.

The Standard Model of Particle Physics



- Other than gravity (a big problem!)...SM includes everything we currently understand about Nature.

MATTER PARTICLES: FLAVOR SECTOR

- All spin- $\frac{1}{2}$ fermions: *quarks* (interact strongly) and *leptons* (e, μ, τ and neutrinos, do not interact strongly)
- To each particle \rightarrow antiparticle with same mass and spin, and
 - opposite charge for charged particles (quarks, e, μ, τ)
 - opposite helicities (spin component in the direction of motion) for ν
- Three *families* (or *generations*): hierarchical from lighter to heavier $[(u, d); (e, \nu_e)], [(c, s); (\mu, \nu_\mu)], [(t, b); (\tau, \nu_\tau)]$
- Masses span five orders of magnitude: $m_e = 0.5$ MeV, $m_t = 170$ MeV (and possibly more, since m_ν are small but yet unknown)
- Understanding *why* we have this structure: “flavor problem”

INTERACTION PARTICLES: GAUGE SECTOR

- All spin-1 bosons
- photon, γ : $m_\gamma = 0$, electrically neutral (i.e., it does not self-interact); mediates the electromagnetic interactions
- IVB, W^\pm and Z : $m \neq 0$, W s electrically charged while Z neutral; mediate the weak interactions;
- gluons, g : $m_g = 0$, electrically neutral; mediate the strong interactions
- IVB interact with each other and self-interact; g interact with each other and self-interact; IVB and g do not interact with each other

Bonus particle: Higgs boson H

- spin 0, massive, electrically neutral
- essentially provides mass to all other elementary particles
- interacts with IVB but not with the photon or with the gluons (hence these are massless)

Graviton (G): hypothetical quantum of gravitational interactions, not observed yet

BUILDING UP HADRONIC MATTER

- Quarks are coloured objects. So $|u\rangle \Rightarrow |u\rangle + |u\rangle + |u\rangle$.
- Color confinement: stable objects (hadrons) are colour neutral. We never see free quarks in Nature.
- Note: antiquarks have opposite colour and parity, as quarks. Quark-antiquark \Rightarrow colorless.
- Multi-particle system also has an orbital angular momentum (\vec{L}).
- Total angular momentum $\vec{J} = \vec{L} + \vec{S}$.
- All hadrons will have some value of J^P that identifies it.

BUILDING UP HADRONS: MESONS

$$\boxed{\text{Meson} \approx q\bar{q}}$$

- lightest mesons (also lightest hadrons): pions π^-, π^0, π^+
 - $m_\pi \approx 140$ MeV ($m_{\pi^0} < m_{\pi^\pm}$)
 - built from lightest quarks and antiquarks: u, d, \bar{u} and \bar{d}
 - bound states with total quark spin $S_q = 0$ and orbital angular momentum $L_q = 0 \rightarrow$ pion spin $J = 0$
- meson state depends on S_q and L_q of $q\bar{q}$, so same quark content $\not\Rightarrow$ same meson
 - ρ mesons have the same quark content of the pions, but in a combination with $S_q = 1$ and $L_q = 0 \rightarrow \rho$ spin $J = 1$
- meson state depends on quark content
 - kaons K (contain a strange quark)
 - J/ψ ($|c\bar{c}\rangle$ state)

BUILDING UP HADRONS: BARYONS

$$\text{Baryon} \approx qqq$$

- lightest baryons: proton (uud), neutron (udd)
 - $m_{p,n} \approx 1 \text{ GeV}$, $m_n > m_p$, with $|m_n - m_p|/m_p \ll 1$
 - n decays into p via β decay, p is stable
- p is stable since lightest baryon: *baryon number* (number of baryons minus number of antibaryons) is conserved, p cannot decay into anything \rightarrow stability of ordinary matter
- no conserved meson number; in fact, even the pion is not stable and decays (mostly) into a muon and a muonic antineutrino
- heavier baryons exist with the same quark content but in different spin/orbital angular momentum states, and/or with different quark content
 - Δ^+ and Δ^0 have same quark content as p and n but $J = \frac{3}{2}$
 - $\Lambda = |uds\rangle$

meson	quark content	spin	charge	mass
π^+	$u\bar{d}$	0	+1	135MeV
π^-	$d\bar{u}$	0	-1	140MeV
π^0	$u\bar{u}, d\bar{d}$	0	0	140MeV
ρ^+	$u\bar{d}$	1	+1	775MeV
ρ^-	$d\bar{u}$	1	-1	775MeV
ρ^0	$u\bar{u}, d\bar{d}$	1	0	775MeV
K^+	$u\bar{s}$	0	+1	494MeV
K^-	$s\bar{u}$	0	-1	494MeV
K^0	$d\bar{s}$	0	0	498MeV
\bar{K}^0	$s\bar{d}$	0	0	498MeV
J/ψ	$c\bar{c}$	1	0	3.1GeV

baryon	quark content	spin	charge	mass
p	uud	$\frac{1}{2}$	+1	0.938GeV
n	udd	$\frac{1}{2}$	+1	0.940GeV
Δ^+	uud	$\frac{3}{2}$	+1	1.232GeV
Δ^0	udd	$\frac{3}{2}$	+1	1.232GeV
Λ	uds	$\frac{1}{2}$	0	1.1GeV

PARTICLE DATA GROUP (PDG)

- Most up-to-date reference: <https://pdglive.lbl.gov>

Gauge & Higgs Bosons reviews γ gluon graviton W Z H^0 Neutral Higgs Bosons, Searches for Charged Higgs Bosons ($H^\pm, H^{\pm\pm}$) Heavy Bosons Axions	Leptons reviews e μ τ Heavy Charged Lepton Neutrino Properties Number of Neutrino Types Double β -Decay Neutrino Mixing Heavy Neutral Leptons	Quarks reviews Light quarks (u, d, s) c b t b' t' Free quark
Mesons reviews Light Unflavored Strange Charmed Charmed, Strange (incl. possibly non- $q\bar{q}$ states) Bottom Bottom, Strange Bottom, Charmed $c\bar{c}$ (incl. possibly non- $q\bar{q}$ states) $b\bar{b}$ (incl. possibly non- $q\bar{q}$ states) Other Mesons	Baryons reviews N Baryons Δ Baryons Λ Baryons Σ Baryons Ξ Baryons Ω Baryons Charmed Baryons Doubly-Charmed Bottom Baryons Exotic Baryons	Other Searches reviews Magnetic Monopole Supersymmetric Particles Technicolor Quark and Lepton Compositeness Extra Dimensions WIMPs Other Particle Searches Conservation Laws reviews Discrete Space-Time Symm. Number Conservation Laws