Unit 26 · Recent Trends in Physics

STUDY NOTES

WHAT NEB'S GRADE 11 EXAM ASKS

- **CDC's grid (2077):** Modern Physics (Units 24–26 together): 9 of 75 marks
- **The paper:** 11 MCQs × 1 · 8 short × 5 · 3 long × 8; 3 hours; 1 mark per expected point
- **MCQ (1 mark)**
  - fermions have half-integer spin (CDC's model paper); bosons whole-number spin
  - which particle is not fundamental; quarks of a proton, a baryon, a meson
  - charge of a quark combination; an antiparticle's charge
  - Hubble's law: 3 × as far, 3 × as fast; Schwarzschild radius ∝ mass
- **Short (5 marks, in parts)**
  - hadrons, baryons, mesons, leptons, exchange particles, with examples
  - antiproton: same and different from the proton; its quarks
  - redshift and recession speed; Hubble's law, H_0, the age $1/H_0$
  - Big Bang and its evidence; cosmological principle; Olbers' paradox
  - black holes, event horizon, R_S; dark matter and dark energy; gravitational waves

Key terms

Antiparticle: same mass, opposite charge (and other quantum numbers); positron, antiproton.

Annihilation: particle + antiparticle → energy (photons).

Fundamental particle: not made of anything smaller (quarks, leptons, bosons).

Standard Model: 6 quarks, 6 leptons, the gauge bosons and the Higgs.

Fermion: half-integer spin (½, ³⁄₂…); obeys the Pauli exclusion principle.

Boson: whole-number spin (0, 1, 2…); any number can share a state.

Hadron: made of quarks; feels the strong force. **Baryon**: three quarks. **Meson**: quark + antiquark.

Lepton: doesn't feel the strong force (e, μ, τ and their neutrinos).

Exchange (gauge) particle: boson carrying a force (photon, gluon, W, Z).

Baryon number (B): quark $+\frac{1}{3}$, antiquark $-\frac{1}{3}$; baryon $+1$, meson 0.

Cosmology: study of the universe as a whole.

Redshift (z): fractional lengthening of a spectrum's wavelengths.

Hubble constant (H_0): recession speed per unit distance.

Cosmological principle: universe homogeneous, isotropic, same laws everywhere.

Cosmic microwave background: Big Bang's light, now microwaves at 2.7 K.

Light year: 9.46×10^{15} m. **Parsec**: distance with 1″ parallax, 3.09×10^{16} m. **AU**: 1.50×10^{11} m.

Black hole: region nothing escapes; **event horizon** at the Schwarzschild radius; **singularity** at the center.

Dark matter: unseen mass known by gravity. **Dark energy**: what speeds up the expansion.

Gravitational waves: ripples in space-time.

Formulas

$z = \dfrac{\Delta\lambda}{\lambda_0} \approx \dfrac{v}{c}$	$v \ll c$ **Use:** redshift
$v = H_0 d$	$H_0 \approx 70$ km/s per Mpc $\approx 2.3 \times 10^{-18}$ s^{-1} **Use:** Hubble's law
$T_0 = \dfrac{1}{H_0}$	H_0 in s^{-1} **Use:** age of the universe
$d = \dfrac{1}{\varphi}$ pc	φ in seconds of arc **Use:** parallax
$R_S = \dfrac{2GM}{c^2}$	$v_{esc} = c$ **Use:** Schwarzschild radius

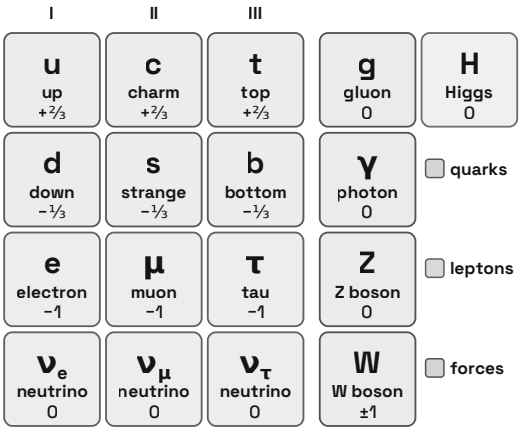
Particles and antiparticles

- positron 1932 (+e, electron's mass); antiproton 1955 (−e)
- positron stable alone; meets an electron → annihilates into photons
- made in nuclear reactions and collisions when enough energy is there

Fermions and bosons (by spin)

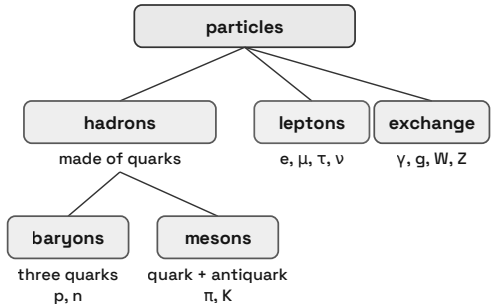
- **fermions**: half-integer spin; Pauli: no two identical in one state; leptons, quarks, baryons
- **bosons**: whole-number spin, odd or even; photon, gluons, W, Z (spin 1), Higgs (0), mesons
- graviton, if it exists, spin 2

The Standard Model



Six quarks and six leptons in three generations, and the bosons; each quark and lepton has an antiparticle.

- once fundamental: p, n, e; then a "zoo" from cosmic rays and accelerators
- produced by cosmic rays, accelerators (LHC, 13.6 TeV), nuclear reactors (antineutrinos)

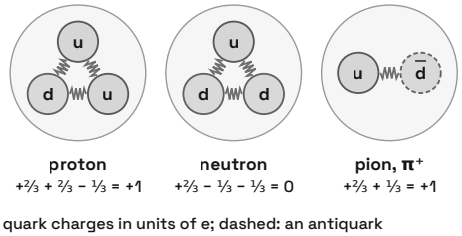


Hadrons (baryons, mesons), made of quarks; leptons and exchange particles fundamental.

- neutron **not** fundamental: three quarks

Quarks

- Gell-Mann and Zweig, 1964; six **flavors**; top found last, 1995
- u, c, t: $+\frac{2}{3}e$; d, s, b: $-\frac{1}{3}e$; every quark $B = +\frac{1}{3}$; antiquark opposite
- never found alone: pulling apart makes new quarks; held by gluons
- tetraquarks, pentaquarks (LHCb, 2015); the 2003 "theta pentaquark" was not confirmed



quark charges in units of e; dashed: an antiquark

Proton uud (+1), neutron udd (0), π^+ u$\bar{\text{d}}$ (+1).

- $Q_p = \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$; $Q_n = \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$
- baryon $B = +1$, antibaryon -1, meson 0, leptons and bosons 0
- **charge and baryon number conserved** in every reaction
- e.g. u$\bar{\text{u}}$ 0; uss 0; sdd -1; b$\bar{\text{u}}$ -1
- $p + p \to p + n + \pi^+$: π^+ +e, B 0 $\to$ u$\bar{\text{d}}$
- antiproton: same mass and spin; charge $-$e, B -1; $\bar{u}\bar{u}\bar{d}$
- neutron's zero charge $\to$ quark charges can't all be one sign

Leptons

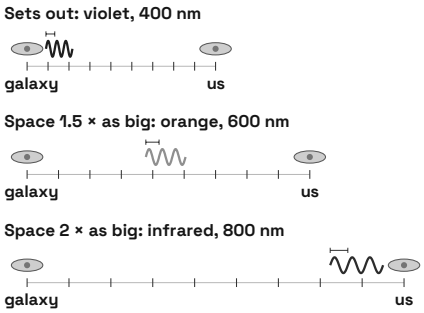
- don't feel the strong force; exist alone; fundamental
- e^-, μ^- ($\approx 207\ m_e$), τ^- ($\approx 3500\ m_e$), each $-$e; with ν_e, ν_μ, ν_τ, charge 0
- neutrinos: mass < a millionth of the electron's
- lepton number per family conserved; but neutrinos **oscillate** between families
- electron vs positron: same mass, spin; opposite charge, lepton number

Models of the universe

- **Newtonian**: infinite, unchanging $\to$ **Olbers' paradox**: every line of sight ends on a star, so the night sky should be bright
- **Big Bang**: began 13.8 billion years ago, hot and dense; finite age and expansion explain the dark sky

Redshift and Hubble's law

- each element's lines; galaxy moving away $\to$ lines to **longer** wavelengths; frequency falls
- e.g. 656.3 $\to$ 662.9 nm: $z = 0.010$, $v \approx 3.0 \times 10^6$ m/s
- Hubble (late 1920s): almost all galaxies redshifted; farther $\to$ faster
- **Hubble's law**: recession speed $\propto$ distance; straight line through the origin; slope H_0
- $3\times$ as far $\to$ $3\times$ as fast
- e.g. 1.51×10^{24} m $\to$ 3.5×10^6 m/s; its 486 nm line $\to$ 492 nm



Space stretches while the light crosses it, and every wave stretches with it.

- redshift from **space itself** expanding, not galaxies flying through space
- balloon activity: dots twice as far apart move twice as much; no center
- **cosmological principle**: homogeneous (on hundreds of millions of ly), isotropic, same laws $\to$ no center, no edge

The Big Bang

- not an explosion from a point: space itself began expanding, everywhere
- $\approx 10^{32}$ K at first; 1 s: 10^{10} K, p, n, e formed
- first minutes: $\approx$ 75% H, 25% He by mass (measured today)
- 380,000 years, $\approx$ 3000 K: first atoms, universe transparent
- that light now **cosmic microwave background**, 2.7 K (found 1965)

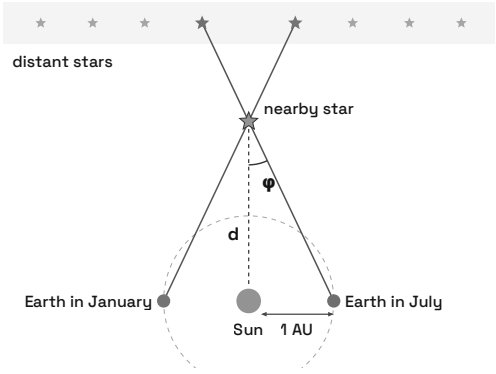
Age

1. galaxy at d_0, speed v_0, same speed since T_0 ago
2. $T_0 = d_0/v_0$
3. $H_0 = v_0/d_0 \rightarrow T_0 = 1/H_0$, the same for every galaxy

- $H_0 = 71$ km/s per Mpc $\rightarrow 4.33 \times 10^{17}$ s $\approx$ 13.7 billion years (speed not really constant)

Distances

- 1 AU $= 1.50 \times 10^{11}$ m; 1 ly $= 9.46 \times 10^{15}$ m; $1' = 60''$, $1^\circ = 60'$

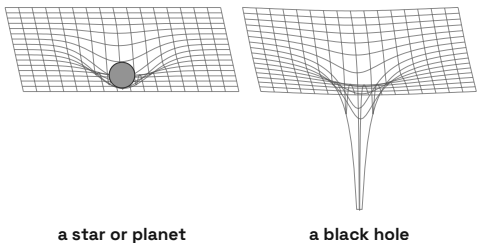


Seen six months apart, a near star shifts against far stars; parallax angle φ.

- $d = 1/\varphi$ pc; 1 pc $= 3.09 \times 10^{16}$ m $= 3.26$ ly; 1 Mpc $= 3.09 \times 10^{22}$ m
- e.g. $6.0 \times 10^{-5\,\circ} = 0.216'' \rightarrow 4.6$ pc $= 15$ ly

Black holes

- escape velocity $\sqrt{2GM/R} = c \rightarrow R_S = 2GM/c^2$
- general relativity: mass **curves space-time**; light bent 1.75″ by the Sun (Eddington, eclipse)

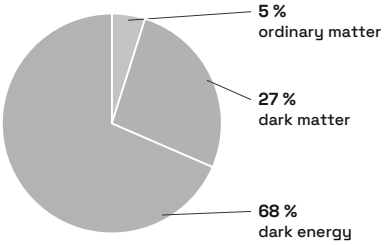


Space-time as a rubber sheet: curved by a mass, steeply by a black hole.

- event horizon: no signal from inside ever reaches us; singularity at $r = 0$ (uncertain)
- known from outside only by mass, spin, charge
- Sun $\rightarrow \approx 3$ km; $R_S \propto M$: 20 $M_\odot$ twice 10 $M_\odot$
- seen by: stars orbiting it (galaxy's center, 16-year orbits); X-rays from a binary; its shadow (Event Horizon Telescope, 2019); gravitational waves
- supermassive ones at most galaxies' centers

Dark matter and dark energy

- galaxies spin too fast for their visible mass $\rightarrow$ **dark matter** (gravity only)
- candidates: MACHOs (dim stars, brown dwarfs, black holes), WIMPs, neutrinos ($< \approx 1\%$)
- expansion **speeding up** $\rightarrow$ **dark energy**



Planck (2018): ordinary matter $\approx$ 5%, dark matter $\approx$ 27%, dark energy $\approx$ 68%.

Gravitational waves

- Einstein, 1916: ripples of space-time from violent events (merging black holes, neutron stars)
- stretch one way, squeeze the other; a 4 km arm by a tiny fraction of a proton's width
- first caught by **LIGO**, 14 September 2015 (two merging black holes); 2017 neutron stars seen in waves and light

COMMON MISTAKES

✗ bosons have even spin
✓ **whole-number** spin; photon 1.

✗ fermions have whole-number spin
✓ **half-integer**.

✗ neutron is fundamental
✓ three quarks, udd.

✗ meson = two quarks
✓ a quark and an **antiquark**.

✗ quark charges ±1
✓ $+\frac{2}{3}e, -\frac{1}{3}e$.

✗ leptons feel the strong force
✓ they **don't**.

✗ redshift: galaxies flying through space
✓ **space** stretching.

✗ Big Bang an explosion from a point
✓ expansion of space everywhere.

✗ $T_0 = 1/H_0$ in km/s per Mpc
✓ convert H_0 to s^{-1} first.

✗ parsec from parallax in degrees
✓ in **seconds** of arc.