Unit 26

# Answers: Recent Trends in Physics

## Quick checks

**1 b** An antiparticle has the same mass as its particle and the opposite charge (and other opposite quantum numbers). So an antiproton has the proton's mass, $1.67 \times 10^{-27}$ kg, and a charge of $-e$.

**2 c** The neutron is a baryon, made of three quarks (udd). The electron and muon are leptons and the photon an exchange particle: all three are fundamental.

**3 b** A quark and an antiquark make a meson. The charge: $+\frac{2}{3}e + \frac{1}{3}e = +e$ (the antistrange quark has $+\frac{1}{3}e$). This is the positive kaon, $K^+$.

**4 c** The muon is a lepton, a heavier cousin of the electron. The pion (a meson) and the proton (a baryon) are hadrons; the gluon is an exchange particle.

**5 c** Hubble's law, $v = H_0 d$: speed is proportional to distance, so three times as far means three times as fast.

**6 b** $R_S = \dfrac{2GM}{c^2}$ is proportional to $M$: twice the mass, twice the radius (about 30 km and 59 km).

**7 b** Dark matter neither gives out nor absorbs light, so it can only be detected by its gravity: the outer stars of galaxies move too fast to be held by the visible matter alone, and clusters of galaxies bend the light passing them more than their visible matter could.

**8 b** A proton is a baryon made of three quarks (uud). The electron and the neutrino are leptons; quarks are fundamental themselves.

**9 b** $+\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$: uud. (udd is the neutron; uuu and ddd are the $\Delta^{++}$ and $\Delta^-$ baryons, with charges +2 and −1.)

**10 d** A baryon is three quarks (ucd); a meson is a quark and an **anti**quark ($c\bar{u}$). Two quarks with no antiquark (cu), or a quark and an antiquark called a baryon, aren't possible.

**11 b** The protons and neutrons are hadrons, and all of them are baryons: 11 + 12 = 23. There are no mesons in an atom. The 11 electrons are leptons.

4. a. A hadron is made of quarks, so it **feels the strong nuclear force** (the strong interaction).

   b. A meson is **a quark and an antiquark**.

   c. A baryon is **three quarks** (an antibaryon three antiquarks).

   d. **Similar:** the same mass ($1.67 \times 10^{-27}$ kg), and the same spin. **Different:** opposite charge (the proton $+e$, the antiproton $-e$), and opposite baryon number (+1 and −1).

   e. (i) **−e**. (ii) $\bar{u}\bar{u}\bar{d}$: two up antiquarks and a down antiquark, charge $-\frac{2}{3}e - \frac{2}{3}e + \frac{1}{3}e = -e$.

5. a. Lepton: **electron** (or muon). Hadron: **proton** (or neutron, or pion).

   b. Hadrons feel the strong nuclear force and are made of quarks; leptons don't feel the strong force and are fundamental (no quarks inside).

   c. A baryon is made of **three quarks**; a meson of **a quark and an antiquark**.

   d. Baryon: **proton** (or neutron). Meson: **pion**.

6. a.

| Particle | Quark structure | Baryon or meson | Charge |
|---|---|---|---|
| pion, $\pi^+$ | $u\bar{d}$ | meson | $+e$ |
| neutron, n | udd | baryon | 0 |
| kaon, $K^+$ | $u\bar{s}$ | meson | $+e$ |

   b. The **proton**, uud, and the **antiproton**, $\bar{u}\bar{u}\bar{d}$. (Others: $\Sigma^-$, sdd, and the anti-$\Sigma^-$, $\bar{s}\bar{d}\bar{d}$.)

   c. **Same:** mass ($9.11 \times 10^{-31}$ kg), or spin ½. **Different:** charge, $-e$ for the electron and $+e$ for the positron (or lepton number, +1 and −1).

8. a. **−e** ($-1.6 \times 10^{-19}$ C)

   b. **0**

   c. $+\frac{2}{3}e$

   d. **+e**

   e. $-\frac{1}{3}e$

   f. $-\frac{1}{3}e$

9. **Similarity:** they have the same mass (and the same spin). An electron and a positron each have a mass of $9.11 \times 10^{-31}$ kg.

   **Difference:** they have opposite charges (and other opposite quantum numbers, such as lepton number or baryon number). The electron has $-e$, the positron $+e$. When they meet, they annihilate.

10. No experiment has found any structure inside a quark. When electrons of very high energy are scattered off protons, they bounce off small point-like charges inside, the quarks, but the quarks themselves behave as points even at the highest energies reached (in experiments at CERN, down to sizes about $10^{-19}$ m, a ten-thousandth of a proton's size). And the Standard Model, which treats them as having no parts, predicts the results of experiments extremely well.

11. a. **Muon**.
    b. **Proton, neutron and pion** (all made of quarks).
    c. **Muon and photon**.
    d. **Pion**.
    e. **Photon** (it carries the electromagnetic force).

12. A **fundamental** particle is not made of anything smaller: as far as experiments show, a quark has no parts. A neutron is **not** fundamental because it is made of smaller particles: three quarks, one up and two down (udd), held together by the strong force. (And a free neutron falls apart, in about 15 minutes on average, into a proton, an electron and an antineutrino: one of its down quarks turns into an up quark.)

13. a.

| Particle | Charge | Quarks |
|---|---|---|
| proton | $+1\ (e)$ | uud |
| neutron | 0 | udd |

b. The neutron is made of three quarks and has **zero** charge. If all the quarks had charges of the same sign, three of them could never add up to zero. So at least one quark must be positive and another negative: the up quark $+\frac{2}{3}e$, the down quark $-\frac{1}{3}e$, so that udd gives $\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$, while uud gives the proton's +1.

14. a. 1. $d = 1.6 \times 10^8 \times 9.46 \times 10^{15} = 1.51 \times 10^{24}$ m.
$v = H_0 d = 2.3 \times 10^{-18} \times 1.51 \times 10^{24} = 3.48 \times 10^6$ m/s $\approx$ **$3.5 \times 10^6$ m/s**.
2. $\dfrac{\Delta\lambda}{\lambda_0} = \dfrac{v}{c}$, so $\Delta\lambda = 486 \times \dfrac{3.5 \times 10^6}{3.0 \times 10^8} = 5.7$ nm.

The galaxy is moving away, so the line is shifted to a **longer** wavelength: $486 + 5.7 =$ **492 nm**.
b. The spectra of distant galaxies show the same patterns of lines as elements in the laboratory, but shifted to longer wavelengths: they are **redshifted**, so the galaxies are moving away from us. The farther away a galaxy is, the greater its redshift (Hubble's law, $v = H_0 d$). Galaxies in every direction are moving away, faster the farther they are, which is what happens when space itself is expanding.

15. a. **The recessional speed of a galaxy is directly proportional to its distance from us**: $v = H_0 d$, where $H_0$ is the Hubble constant.

b. Each element gives out and absorbs light of its own exact wavelengths. In a galaxy's spectrum, astronomers find the line patterns of known elements (hydrogen, calcium…) and measure how far each line is shifted from its laboratory wavelength. A shift to longer wavelengths, a redshift, means the galaxy is moving away. The fractional shift gives the speed: $\frac{\Delta\lambda}{\lambda_0} = z \approx \frac{v}{c}$, so $v = zc$ (for speeds much less than $c$).

c. (i) Nearly all galaxies are redshifted, in every direction, and the redshift is proportional to the distance. The same pattern is seen from any galaxy when the space between all of them stretches, so space itself is expanding.

ii. If the galaxies are moving apart now, they were closer together in the past. Running the expansion backwards, everything we see was packed together, extremely hot and dense, about $1/H_0 \approx 14$ billion years ago: the Big Bang. (The cosmic microwave background, the cooled afterglow of that hot early universe found in every direction at 2.7 K, and the amounts of hydrogen and helium in the oldest, least-changed gas, are further evidence.)