

Episode 533: The particle zoo

Protons, neutrons and electrons are familiar particles of matter. However, students are likely to have heard of other particles, and this episode introduces some of these.

Summary

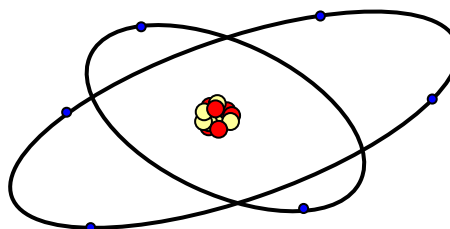
Discussion: Establishing prior knowledge. (15 minutes)

Discussion: Conservation of charge and mass. (20 minutes)

Discussion: Units of mass. (10 minutes)

Student activity: Classification of hadrons. (30 minutes)

Student activity: Research task. (30 minutes)



Discussion:

Establishing prior knowledge

Brainstorm to review prior knowledge. What's in an atom, and how do we know?

Establish with the students that the atom contains: -

- electrons (discovered by J J Thomson in 1897, Cavendish Lab, Cambridge, though he called them negative corpuscles, the name electron was 'coined' by G. Johnstone Stoney in 1891)
- nuclei (Rutherford, Geiger and Marsden, 1911)
- it was soon realised that nuclei contained multiples of the nuclei of hydrogen atoms (i.e. protons; Rutherford suggested the name proton in 1920)
- that the simple picture was completed with Chadwick's discovery of the neutron (predicted by Rutherford) in 1932.

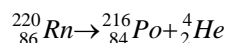
At this point, you may find it useful to ask how students think how a neutral particle such as a neutron may be detected. You can tell them that sub atomic particle detection in 1932 relied on ionisation (as in a GM tube, or in a photographic film), and that this only detects charged particles. They should realise that the neutron must do something to some other matter that then produces some ionising radiation. (For Chadwick, the ionising radiation consisted of protons emitted from paraffin wax when neutrons hit the nuclei of hydrogen atoms. The neutrons came from beryllium that had been bombarded with alpha particles. [J Chadwick, The Existence of a Neutron, *Proceedings Royal Society of London*, 1932])

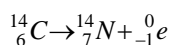
Discussion:

Conservation of charge and mass

Use alpha and beta decay to show conservation of charge and baryon number (see below).

Use the equations for one example of each, e.g.:





to show conservation rules in action: the fact that the bottom numbers add to give the same total each side shows conservation of charge, while the fact that the top numbers do likewise shows that the number of nucleons (neutrons and protons) is also conserved. Introduce the term **baryon** (heavy particle) for these two particles, so that these processes also conserve baryon number. It is worthwhile giving each student an example to do, as this is confidence building, and it is a simple skill that is often examined.

Discussion:

Units of mass

It may help your students, before embarking on a discussion of the various families of particles, if they have an idea of the different units used for mass. All those powers of 10 are very inconvenient; hence, it is easier to work in energy units, particularly the MeV (mega electron volt).

Although it is useful to have met $E=mc^2$, this is not essential. All that is needed here is that students appreciate that mass and energy can be inter-converted in nuclear reactions (such as fission and fusion, which students should be familiar with), and that the energy that would be released if the entire mass of a particle were transferred into energy is used as a measure of its mass in particle physics. Rather than define an electron-volt in terms of charge and pd, you may prefer to state that it is a convenient 'atomic size' energy unit where $1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J}$ equivalent to $1.783 \times 10^{-30} \text{ kg}$. It is useful to have a poster in your lab/ teaching room with different mass units on it.

TAP 533-1: Mass units for particle physics

Student activity:

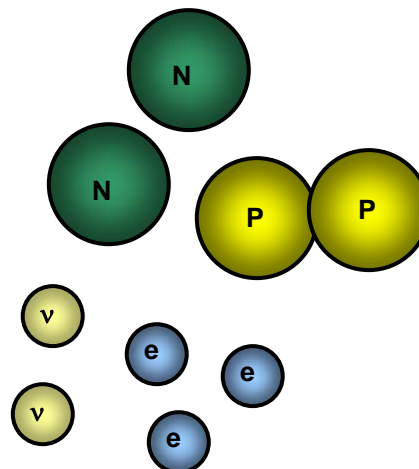
Classification of hadrons

Hadrons, is a collective term for both **mesons** and **baryons**; mesons are less massive than baryons.

This activity is a card-sorting exercise. Helpfully, this slows down the pace compared with teacher exposition or question and answer. Introduce the activity by explaining that, following the discovery of the neutron, many other particles were discovered, including some strange ones: these seemed to be created in pairs, encouraging the physicist Murray Gell-Mann to allocate 'strangeness numbers' to some of these particles. In these reactions, strangeness was conserved.

This is a kinaesthetic exercise using cards for a collection of hadrons. It is best to print up several sets of the two hadron card sheets, on card rather than paper. There is a similar sheet of lepton cards – they can be added to or simplified as you wish. It is best to use a different colour for the lepton cards. You may consider laminating them.

For the first exercise, use the first sheet of hadron cards (omitting some mesons and all anti-baryons), cut into individual cards.



Ask your students to sort particles by mass and to note the charge and baryon number. Mesons are those hadrons, mostly of lower mass, which have baryon number of 0.

Later, the cards can be used, together with genuine particle reactions, to check on conserved quantities.

TAP 533-2: Hadron cards

TAP 533-3: Lepton Cards

Student activity:

Research task

Conclude this episode with some questions for students to research, leading to the next episode:

- What is a positron?
- Who suggested it must exist?
- Who discovered it?
- What is a muon?
- When was it discovered?
- Who said, 'Who ordered that?'
- What is a neutrino?
- Who suggested it must exist?
- Who discovered it?

TAP 533-4: Positron, muon, neutrino

TAP 533- 1: Mass units for particle physics

Atomic mass unit: $u = 1.661 \times 10^{-27} \text{ kg}$

MeV/c² $1 \text{ MeV}/c^2 = 1.783 \times 10^{-30} \text{ kg}$

Some rest masses

| | mass (kg) | mass (u) | mass (MeV/c²) |
|----------|-------------------------|------------------------|---------------------------------|
| electron | 9.109×10^{-31} | 5.486×10^{-4} | 0.5110 |
| proton | 1.673×10^{-27} | 1.009 | 938.3 |
| neutron | 1.675×10^{-27} | 1.007 | 939.6 |

TAP 533- 2: Hadron cards

| neutron | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| n | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 939.6 | 0 | +1 | 0 | 0 |

| pi minus | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| π^- | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 140 | -1 | 0 | 0 | 0 |

| K plus | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| K^+ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 494 | +1 | 0 | 0 | +1 |

| lambda | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| Λ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1116 | 0 | +1 | 0 | -1 |

| pi plus | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| π^+ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 140 | +1 | 0 | 0 | 0 |

| sigma plus | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| Σ^+ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1189 | +1 | +1 | 0 | -1 |

| omega minus | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| Ω^- | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1673 | -1 | +1 | 0 | -3 |

| xi minus | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| Ξ^- | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1321 | -1 | +1 | 0 | -2 |

| delta minus | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| Δ^- | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1232 | -1 | +1 | 0 | 0 |

| proton | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| p | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 938.3 | +1 | +1 | 0 | 0 |

| K zero | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| K^0 | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 498 | 0 | 0 | 0 | +1 |

| sigma minus | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| Σ^- | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1198 | -1 | +1 | 0 | -1 |

| sigma zero | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| Σ^0 | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1192 | 0 | +1 | 0 | -1 |

| K minus | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| K^- | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 494 | -1 | 0 | 0 | -1 |

| delta zero | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| Δ^0 | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1232 | 0 | +1 | 0 | 0 |

| delta plus | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| Δ^+ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1232 | +1 | +1 | 0 | 0 |

| pi zero | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| π^0 | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 106 | 0 | 0 | 0 | 0 |

| xi zero | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| Ξ^0 | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1315 | 0 | +1 | 0 | -2 |

| eta zero | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| η^0 | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 549 | 0 | 0 | 0 | 0 |

| phi zero | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| ϕ^0 | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1020 | 0 | 0 | 0 | 0 |

| anti-sigma minus | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| $\bar{\Sigma}^-$ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1198 | +1 | -1 | 0 | +1 |

| anti-lambda | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| $\bar{\Lambda}$ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1116 | 0 | -1 | 0 | +1 |

| J/psi | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| J/ψ^0 | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 3097 | 0 | 0 | 0 | 0 |

| anti-delta minus | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| $\bar{\Delta}^-$ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1232 | +1 | -1 | 0 | 0 |

| anti-neutron | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| \bar{n} | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 939.6 | 0 | -1 | 0 | 0 |

| anti-proton | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| \bar{p} | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 938.3 | -1 | -1 | 0 | 0 |

| anti-K zero | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| \bar{K}^0 | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 498 | 0 | 0 | 0 | -1 |

| anti-sigma zero | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| $\bar{\Sigma}^0$ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1192 | 0 | -1 | 0 | +1 |

| rho minus | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| ρ^- | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 770 | -1 | 0 | 0 | 0 |

| anti-xi zero | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| $\bar{\Xi}^0$ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1315 | 0 | -1 | 0 | +2 |

| anti-omega minus | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| $\bar{\Omega}^-$ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1673 | +1 | -1 | 0 | +3 |

| anti-xi minus | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| $\bar{\Xi}^-$ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1321 | +1 | -1 | 0 | +2 |

| anti-delta zero | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| $\bar{\Delta}^0$ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1232 | 0 | -1 | 0 | 0 |

| anti-sigma plus | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| $\bar{\Sigma}^+$ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1189 | -1 | -1 | 0 | +1 |

| anti-delta plus | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| $\bar{\Delta}^+$ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 1232 | -1 | -1 | 0 | 0 |

| rho plus | | | | |
|----------------------------|------------|---------------|---------------|---------------|
| ρ^+ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 770 | +1 | 0 | 0 | 0 |

TAP 533-3: Lepton Cards

| electron | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| e^- | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 0.511 | -1 | 0 | +1 | 0 |

| electron neutrino | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| ν_e | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 0 | 0 | 0 | +1 | 0 |

| positron | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| e^+ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 0.511 | -1 | 0 | -1 | 0 |

| electron anti-neutrino | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| $\bar{\nu}_e$ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 0 | 0 | 0 | -1 | 0 |

| anti-muon | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| μ^+ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 106 | +1 | 0 | -1 | 0 |

| muon | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| μ^- | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 106 | -1 | 0 | +1 | 0 |

| muon neutrino | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| ν_μ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 0 | 0 | 0 | +1 | 0 |

| muon anti-neutrino | | | | |
|-------------------------------|---------------|------------------|------------------|------------------|
| $\bar{\nu}_\mu$ | | | | |
| Mass (MeV/c ²) | Charge (e) | Baryon number | Lepton number | Strange -ness |
| 0 | 0 | 0 | -1 | 0 |

TAP 533- 4: Positron, muon, neutrino

Practical advice:

This is just an outline. Your students will probably be much more forthcoming. They should be encouraged to put ideas into their own words rather than copy chunks from websites. (Some chunks are below.) It is good practice for them to fully reference their sources. It is possible that there is some conflict with different web sources; an example is given with the muon answers. Episode 534 gives the basic outline that all students should have.

Outline answers

What is a positron?

Anderson saw an example of anti-electrons, "positrons" in photographs of cosmic rays passing through a cloud chamber.

(Pictures are provided at the site below)

The discovery of the positron

<http://www.physics.ubc.ca/~waltham/p400/presentation/asgeirsson.pdf> [Accessed 14 October 2005]

Who discovered it?

A direct quote from Anderson's 1933 paper: -

"On August 2 1932 during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber (magnetic field 15,000 gauss) designed in the summer of 1930 by Prof R A Millikan and the writer the track shown in fig 1 was obtained which seemed to be interpretable only on the basis of a particle carrying a positive charge but having the same mass of the same order of magnitude as that normally possessed by a free electron."

Anderson Carl D, The positive electron, Physical Review, Vol 43 pp 491-494 15 March 1933

<http://www.hep.man.ac.uk/babarph/babarphysics/positron.html> puts the discovery as 1933 but as Anderson's paper shows the observations were made in 1932

Who suggested it must exist?

"In the 1920's, Paul Adrien Maurice Dirac, a British physicist, developed a quantum-mechanical wave equation which was able to explain the origin of the electrons magnetic moment and spin. There was only one problem, the relativistic equation would only be satisfied if there were solutions for it which corresponded to negative energy states, and in the case of the electron, an electron with a positive charge."

The above is quote from: <http://www.upei.ca/~phys221/mmh/>

Another suitable source is: <http://www.infoplease.com/ce6/sci/A0804257.html>

"The existence of antiparticles for electrons was predicted in 1928 by P. A. M. Dirac's relativistic quantum theory of the electron. According to the theory both positive and negative values are possible for the total relativistic energy of a free electron. In 1932, Carl D. Anderson, while studying cosmic rays discovered the predicted positron, the first known antiparticle."

Or

"Paul Dirac:

Relativity and antiparticles

Paul Dirac set himself the task of repairing the big problem with Schrödinger's wave theory: that it didn't agree with the theory of relativity. What he found in 1928 was totally unexpected. If relativity was included the theory necessarily predicted that every particle must have a 'mirror image' particle, exactly the same but opposite in all properties except mass. These pairs of particles could annihilate one another. This interpretation wasn't clear at first to Dirac, but it gradually became a second cornerstone of quantum physics. If particles can be created or destroyed they have to come in such pairs. Otherwise quantities like electric charge won't be conserved. Soon afterwards, in 1933, the creation of pairs of electrons and antielectrons was observed by Carl Anderson. By the way, as a bonus, Dirac's theory explained the existence of spin too."

Advancing Physics chapter 18 40T

Anderson was given 1936 Nobel Prize for Physics for this discovery

What is a muon?

The muon is a lepton that decays to form an electron or positron. It carries a charge of the same size as that on an electron but is much more massive, more than 2000 times that of an electron

When was it discovered?

"The muon was discovered in 1937 by J. C. Street and E. C. Stevenson in a cloud chamber. The discovery was published in "New Evidence for the Existence of a Particle Intermediate Between the Proton and Electron", Phys. Rev. 52, 1003 (1937)."

<http://hyperphysics.phy-astr.gsu.edu/hbase/particles/muonhist.html>

However

"Muons were discovered 60 years ago, by Carl Anderson and Seth Neddermeyer at Caltech. Muons live for about 2.2 microseconds, and often survive to ground level, before changing into electrons and invisible neutrinos.

In 1947, ten years after the muon discovery, Cecil Powell's group at Bristol University discovered that the muons are produced by other particles - pions - which live for only a few hundredths of a microsecond. In this image, pions fly out from a collision in the streamer chamber."

<http://www.cs.wisc.edu/~kaxiras/decay.html>

But muons had been predicted by Yukawa:

Yukawa Hideka, On the Interaction of Elementary Particles 1, *Proceedings of the Physico-Mathematical Society of Japan* (3) 17, 48, pp 139-148 (1935). (Read 17 Nov 1934)

"It seems natural to modify the theory of Heisenberg and Fermi in the following way. The transition of a heavy particle from neutron state to proton state is not always accompanied by the emission of light particles. The transition is sometimes taken up by another heavy particle".

Who said, 'Who ordered that?'

The muon was discovered accidentally in 1936-1937 in the hunt for a particle predicted by Yukawa. At the time it seemed to serve no purpose in particle physics. I I Rabi asked, "Who ordered that?", when he was told of it.

http://www.everything2.com/index.pl?node_id=92185&displaytype=printable&lastnode_id=92185

What is a neutrino?

"Three types of neutrinos are known; there is strong evidence that no additional neutrinos exist, unless their properties are unexpectedly very different from the known types. Each type or "flavour" of neutrino is related to a charged particle (which gives the corresponding neutrino its name). Hence, the "electron neutrino" is associated with the electron, and two other neutrinos are associated with heavier versions of the electron called the muon and the tau (elementary particles are frequently labelled with Greek letters, which confuses the layman)".

"Neutrinos are similar to the more familiar electron, with one crucial difference: neutrinos do not carry electric charge".

Who suggested it must exist?

"1931 - A hypothetical particle is predicted by the theorist Wolfgang Pauli. He based his prediction on the fact that energy and momentum did not appear to be conserved in certain radioactive decays. Pauli suggested that this missing energy might be carried off, unseen, by a neutral particle which was escaping detection.

1934 - Enrico Fermi develops a comprehensive theory of radioactive decays, including Pauli's hypothetical particle, which Fermi coins the neutrino (Italian: "little neutral one"). With inclusion of the neutrino, Fermi's theory accurately explains many experimentally observed results"

Who discovered it?

1959 - Discovery of a particle fitting the expected characteristics of the neutrino is announced by Clyde Cowan and Fred Reines.

Source for the above: <http://www.ps.uci.edu/~superk/neutrino.html>