Episode 535: Particle reactions

This episode considers both hadrons and leptons in particle reactions. Students must take account of both conservation of lepton number and conservation of baryon number.

Summary

Student activity: Applying conservation rules. (20 minutes)

Discussion: Identifying conservation rules. (10 minutes)

Student questions: Questions on conservation rules. (30 minutes)

Student activity:

Applying conservation rules

Students should first check on the conservation of (electric) charge, baryon number, lepton number and strangeness in real reactions. They should also note that the mass/energy of products should be less/equal to the mass/energy of reactants.

Use the first sheet of hadron cards from the previous episode and the four leptons from the 'lepton cards' document to decide which particle is needed to complete several reactions.

TAP 535-1: Applying conservation of baryon and lepton number

You should expect some ambiguity as to which neutrino or antineutrino is involved: after all, this ambiguity was not resolved until recently. Ask students what they would expect, from symmetry, in each case.

Now add the second sheet of cards from the 'hadron cards' document, containing all the anti-baryons and some more mesons.

TAP 535-2: Particle card student activities

A quick sort of all cards should reveal that all baryons and leptons have their anti-particles, all with obvious names except electron/positron.   Tell students that all mesons – those with baryon number and lepton number of zero – have antiparticles, but that some are their own anti-particles; they can then sort out which is which.

Students are now able to check whether reactions can proceed according to the conservation rules met so far.

Discussion:

Identifying conservation rules

Invite students to sum up what they now know about particles and particle reactions. Look for the following points.

Baryon number is always conserved

(Electric) charge is always conserved

Lepton number is always conserved

Mass on the left hand side of the equation must be bigger than the mass on the right hand side.

Strangeness may be conserved, but not always. (In weak interactions it can change by 1).

Student questions:

Questions on conservation rules

Here are some suggestions for questions that could be given as student exercises at this point.

TAP 535-3: Things that don't change

Questions about creation and annihilation (but note that this question uses $E = mc^2$; however, you may find that more mathematical students will accept mass values quoted as e.g. 939.6 MeV/c^2 once they have done a calculation of this sort.

TAP 535-4: Creation and annihilation

Questions about creation from annihilation. (To reduce the demand, you may wish to delete all the text from 'Exotic forms of matter can occur fleetingly…' and dropping questions 7 to 11.)

TAP 535-5: Creation from annihilation

TAP 535- 1: Applying conservation of baryon and lepton number

Use the hadron and lepton cards to decide which particle is needed to complete each of the following reactions.

Assume that electric charge, baryon number and lepton number are all conserved in each reaction, and that the mass of the reactants cannot be less than the mass of the products.

1. $n \rightarrow p + e^{-} + \ldots\ldots$

2. $\ldots\ldots + n \rightarrow \ldots\ldots + e^{-}$

3. $\pi^{+} \rightarrow \mu^{+} + \ldots\ldots$

4. $p \rightarrow n + \nu_{e} + e^{+}$

Answers and worked solutions

1. $n \rightarrow p + e^- + \bar{\nu}_e$

   allow any antineutrino.

2. $\nu_e + n \rightarrow p + e^-$

   allow any antineutrino, and of course the scattering

   $e- + n \rightarrow n + e^-$ is also a correct answer!

3. $\pi^+ \rightarrow \mu^+ + \nu_\mu$

   allow any antineutrino

4. $p \rightarrow n + \nu_e + e^+$

   allow μ^+

TAP 535- 2: Particle card student activities

1. Sorting particles and anti-particles.

    Apart from the positron, all the anti-particles of baryons and leptons have obvious names. Not so for mesons! The mesons have baryon number 0 and lepton number 0. Some of them are anti-particles of others, but three of the mesons in these cards are their own anti-particles. Can you identify all these?

2. Decay reactions.

    (a) Use the particle cards to check that the following decay reactions are all possible. The rules are:

    -   Mass/energy is conserved. In practice, this means that the mass on the left hand side of the equation must be more than the mass on the right hand side if the reaction is to go.

    -   (Electric) charge is conserved

    -   Baryon number is conserved

    -   Lepton number is conserved

    -   Strangeness may be conserved, or may change by 1

    (The symbol γ refers to a gamma photon.)

    $$K^+ \rightarrow \mu^+ + \nu_\mu$$

    $$\Lambda \rightarrow p + \pi^-$$

    $$\mu^- \rightarrow e^- + \nu_e\text{-bar} + \nu_\mu$$

    $$\Omega^- \rightarrow \Xi^0 + \pi^-$$

    $$\Sigma^0 \rightarrow \Lambda + \gamma$$

    (b) Here are some impossible decay reactions. For each one, use the particle cards to find why the reaction is not possible.

    $$n \rightarrow p + e^- + \nu_e$$

    $$\Delta^+ \rightarrow \pi^+ + \pi^0$$

    $$\Xi^0 \rightarrow p + \pi^0$$

    $$\Sigma^+ \rightarrow p + K^0$$

Answers and worked solutions

1.   The particle – antiparticle pairs are: (π^+, π^-), (K^+, K^-), $(K^0, K^0\text{-bar})$, (ρ^+, ρ^-) and the particles which are their own antiparticles are: π^0, η^0, ϕ^0 and J/ψ^0.

2. (b)

$n \rightarrow p + e^- + \nu_e$ lepton number not conserved

$\Delta^+ \rightarrow \pi^+ + \pi^0$ baryon number not conserved

$\Xi^0 \rightarrow p + \pi^0$ charge not conserved

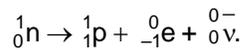$\Sigma^+ \rightarrow p + K^0$ mass/energy not conserved

TAP 535- 3: Things that don't change

Checking on conserved quantities

Try these questions, which require you to notice quantities that are conserved.

Change, and no change

Here is the equation for the reaction in which a neutron decays to a proton p, an electron e and an antineutrino $\bar{\nu}$:

$$_0^1 n \rightarrow {}_1^1 p + {}_{-1}^0 e + {}_0^0 \bar{\nu}.$$

1.   How does the equation show that the total number of nucleons remains the same?

2.   How does the equation show that the total electric charge remains the same?

3.   Which symbols show that the electron and antineutrino are not nucleons, but leptons with zero nucleon number?

4.   An electron is a lepton. An antineutrino is an antilepton. Explain how in this reaction the lepton number is conserved, even though it creates two leptons.

Here is the equation for an electron interacting with a proton to produce a neutron and a neutrino:

$$_{-1}^0 e + {}_1^1 p \rightarrow {}_0^1 n + {}_0^0 \nu.$$
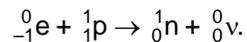
5.   How does the equation show that the total number of nucleons remains the same?

6.   How does the equation show that the total electric charge remains the same?

7.   How does the equation show that the total lepton number remains the same? Why is this neutrino not an antineutrino?

The stable iron nucleus is $^{56}_{26}$Fe; 'lightweight' iron $^{49}_{26}$Fe decays emitting a positron and a neutrino. 'Heavyweight' iron $^{62}_{26}$Fe decays emitting an electron and an antineutrino. Here are the reactions:

$$^{49}_{26}\text{Fe} \rightarrow \, ^{49}_{25}\text{Mn} + \, ^{0}_{1}\text{e} + \, ^{0}_{0}\nu$$

$$^{62}_{26}\text{Fe} \rightarrow \, ^{62}_{27}\text{Co} + \, ^{0}_{-1}\text{e} + \, ^{0}_{0}\bar{\nu}.$$

8.   In the first equation, what values show that the nucleon number stays the same?

9.   In the second equation, what values show that the nucleon number stays the same?

10.   How can you see from the first equation that charge is conserved?

11.   How can you see from the second equation that charge is conserved?

12.   In the first equation, the positive electron (positron) is an antilepton. How does the equation show that total lepton number is unchanged even though two are produced?

13.   In the second equation, why is an antineutrino emitted?

14.   In both equations, how does the reaction change the chemical element involved?

Practical advice

These are intended as simple practice questions, on conservation principles for particles. The most difficult point is that an antielectron plus a neutrino or an electron plus an antineutrino do not change the total number of leptons (a lepton and an antilepton in each case).

Social and human context

Particle physics involves creating meaningful categories, such as 'lepton' and 'nucleon', to form families. These come from thought, not 'directly' from experiment.

Answers and worked solutions

1. The upper numbers (nucleon number) add up to the same on the left and right: 1 = 1 + 0 + 0.

2. The lower numbers (charge number) add up to the same on the left and right: 0 = 1 + (– 1) + 0.

3. The upper (nucleon) number is zero for both (even though an electron has some mass).

4. The reaction produces one lepton and one antilepton. The electron has lepton number 1. The antineutrino has lepton number – 1. Together, they add to zero. The total lepton number is zero before and after.

5. The upper numbers (nucleon number) add up to the same on the left and right: 0 + 1 = 1 + 0.

6. The lower numbers (charge number) add up to the same on the left and right: – 1 + 1 = 0 + 0.

7. An electron (a lepton) vanishes on the left. A neutrino (also a lepton) is created on the right. The total lepton number remains equal to 1. If the neutrino were an antineutrino the lepton number would go from + 1 to – 1, and not be conserved.

8. The total nucleon number 49 remains constant: 49 = 49 + 0 + 0.

9. The total nucleon number 62 remains constant: 62 = 62 + 0 + 0.

10. The electric charge on the nucleus is decreased, the charge being carried away by the positron: 26 = 25 + 1 + 0.

11. The positive electric charge on the nucleus increases, a negative charge being carried away by the electron: 26 = 27 + (– 1) + 0.

12. A lepton–antilepton pair is produced, so the lepton number does not change.

13. The antineutrino 'cancels' the increase in lepton number due to producing an electron.

14. The charge on the nucleus changes. So the number of electrons around the nucleus changes, altering the chemical properties of the atom

External reference

This activity is taken from Advancing Physics chapter 17, 10S

TAP 535- 4: Creation and annihilation

Using $E_{rest} = m\,c^2$

These questions give practice in using $E_{rest} = m\,c^2$ to calculate photon energies and masses of particles created or annihilated.

Energy and mass

The energy of a particle at rest is all due to its mass. This energy is called the rest energy. The rest energy in joules of a particle with mass m measured in kilograms is given by $E_{rest} = m\,c^2$, where c is the speed of light in metres per second. An energy in joules can be converted to electron volts by dividing by 1.60×10^{-19} J eV^{-1}.

The mass of an electron or positron is 9.11×10^{-31} kg. The speed of light is 3.00×10^8 m s^{-1}.

1. Show that the rest energy of an electron is 8.2×10^{-14} J.

2. Use the answer to question 1 to show that the rest energy of an electron is 0.51 MeV.

3. Write down the rest energy of a positron (antielectron).

4. An electron and a positron which meet annihilate one another. By how much does the rest energy decrease in total? Express the answer in MeV.

5. The annihilation of an electron and a positron at rest produces a pair of identical gamma ray photons travelling in opposite directions. Write down in MeV the energy you expect each photon to have

6. A single photon passing near a nucleus can create an electron–positron pair. Their rest energy comes from the energy of the photon. Write down the smallest photon energy that can produce one such pair.

7. Cosmic rays can send high-energy photons through the atmosphere. What approximately is the maximum number of electron–positron pairs that a 10 GeV photon can create?

8. The isotope $^{24}_{12}\text{Mg}$ is stable. The light isotope $^{22}_{12}\text{Mg}$ emits positrons and gamma rays including a photon of energy 1.28 MeV. How can decays of this nucleus result in both annihilation and creation of electron–positron pairs?

9. A photon can create particle–antiparticle pairs of greater mass than electrons and positrons. Approximately what energy must a photon have to create a proton–antiproton pair? (The mass of a proton is 2000 times the mass of an electron).

10. Why do the photons from the annihilation of an electron–positron pair not themselves go on to create new electron–positron pairs?

Practical advice

These are intended as simple practice calculations on energy changes in particle–antiparticle creation and annihilation.

Alternative approaches

You might start in the context of PET scans, which use positron annihilation.

Social and human context

The existence of the creation and annihilation of matter makes for a profound shift in the way the world has to be imagined. Its permanence is undermined.

Answers and worked solutions

1.

$$E_{rest} = mc^2$$
$$E_{rest} = 9.11 \times 10^{-31} \text{ kg} \times \left(3.00 \times 10^8 \text{ms}^{-1}\right)^2$$
$$= 8.2 \times 10^{-14} \text{ J}.$$

2. Energy in eV is energy in joules divided by 1.60×10^{-19} J eV^{-1}:

$$\frac{8.2 \times 10^{-14} \text{ J}}{1.60 \times 10^{-19} \text{ J eV}^{-1}} = 5.1 \times 10^5 \text{ eV} = 0.51 \text{ MeV}$$

3. 0.51 MeV since electrons and positrons have identical mass.

4. 1.02 MeV. Two particles, each of rest energy 0.51 MeV, are annihilated.

5. 0.51 MeV each. The two photons share the total 1.02 MeV.

6. 1.02 MeV. The photon has to create the rest energy of two particles, each 0.51 MeV.

7. Approximately 10^4 pairs. Each pair requires approximately 1 MeV = 1×10^6 eV and 10 GeV = 10×10^9 eV is available.

8. The 1.28 MeV photon has enough energy to create an electron–positron pair. The positron from the decay can annihilate with any nearby electron.

9. Approximately 2 GeV. The rest energy of a proton–antiproton pair is 2000 times greater than the roughly 1 MeV rest energy of an electron–positron pair.

10. Their 0.51 MeV energy is too small (minimum 1.02 MeV).

External references

This activity is taken from Advancing Physics chapter 17, 30S

TAP 535- 5: Creation from annihilation

Colliding electrons and positrons

The passage below is from *The New Physics*, edited by Paul Davies. Read the passage, in which some phrases or words are highlighted in bold. Write a fuller explanation of what is meant by each highlighted word or phrase. Questions to guide you are offered, but you can go further if you wish.

Electron–positron annihilation

Electrons colliding with **positrons** provide one of the most exciting ways of learning about bizarre varieties of matter…. The key feature is that positrons are the **antiparticles** of electrons. When matter and **antimatter** meet, they can **mutually annihilate**. The energy in their masses has been unlocked: $E_{rest} = mc^2$ at work.

What is the point of this?

Destroying the electrons and positrons is just the start. The aim is to watch what happens when their energy 'recongeals' into new forms of matter and antimatter. **It can return whence it came, into electron and positron**, but more interestingly it may produce new forms of matter with their corresponding antimatter. The hunt is on for those occasions when new forms of matter, not previously seen on Earth, **emerge from the encounter**. Exotic forms of matter can occur fleetingly in **the heat of stars**, and when we **temporarily simulate that heat** on Earth, so that we can capture these new varieties in earthbound laboratories.

This continuous destruction of matter and antimatter was common in the brief heat of the **primordial Big Bang. By annihilating electrons and positrons in the laboratory** we are reproducing conditions similar to those that occurred a split second after the Big Bang. We can create matter and antimatter, built for example of quarks and antiquarks, to order.

1.   **Positrons**: what are they?

2.   **Antiparticles**: what's the relation between a particle and antiparticle?

3.   **Antimatter**: what is antimatter? Where can it be found?

4.   **Mutually annihilate**: what happens? What vanishes and what does not vanish?

5. $E_{rest} = mc^2$: give an example of how to use this equation.

6.   **It can return whence it came, into electron and positron**: what is happening here?

7.   **Emerge from the encounter**: what emerges?

8.   **The heat of stars**: why does it matter how hot the stars are?

9.   **Temporarily simulate that heat**: how is this temporary simulation done? By heating stuff up?

10.   **Primordial Big Bang**: what is this?

11.   **By annihilating electrons and positrons in the laboratory**: how?

Practical advice

This passage comes from a book intended for a wide audience, but an audience with considerable knowledge of physics. Suggest to students that they should write enough to help a friend who is not studying physics at A-level at least to make sense of the passage. Remind them that this often means saying the same thing in one or two other ways. Examples always help, too, so encourage that.

Alternative approaches

You could choose a different passage, for example from a text about medical applications of particle physics.

Social and human context

New ideas often need new words. Learning physics is sometimes like learning a new language.

Example answers

1.   Positrons: are antiparticles of electrons, they have the same mass but positive charge.

2.   Antiparticles include the fact that antiparticles have all properties except mass opposite to those of their particle counterparts.

3.   Antimatter: is made of antiparticles. No bulk antimatter is known in the Universe, but antiparticles can be produced in accelerators.

4.   Mutually annihilate: the opposite properties of particle and antiparticle all cancel, and the rest energy (mass) goes into kinetic energy of a photon (which has zero mass).

5. $E_{rest} = mc^2$: you could show that the mass of an electron corresponds to 0.5 MeV approximately. Or give an example from nuclear reactions.

6.   It can return whence it came, into electron and positron: a photon (near a nucleus) can create an electron–positron pair.

7.   Emerge from the encounter: pairs of particles and antiparticles emerge.

8.   The heat of stars: because the stars are hot, particles have a lot of random thermal energy per particle. This may be enough to cause an event in a collision.

9.   Temporarily simulate that heat: accelerated particles are collided, so that their kinetic energy is available in the collision event.

10.   Primordial Big Bang: the hypothetical origin of the Universe, when space and time were created and a hot fireball of space, time and matter exploded.

11.   By annihilating electrons and positrons in the laboratory: the best way is to make accelerated particles collide head on, to get the maximum energy into the products of the collision.

External references

This activity is taken from Advancing Physics chapter 17, 50C