

Teaching conservation laws, symmetries and elementary particles with fast feedback

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Abstract

Lessons about elementary particles at the secondary school level can degenerate into listing a zoo of particles and reactions, resulting in disorganized and rather meaningless knowledge. A more powerful way is to focus on conservation laws, symmetries and reaction diagrams. The conservation laws and symmetries provide generalizing power that enables the students to predict whether or not certain reactions are possible and to derive new reactions from given ones by applying the symmetries. In this article we first present simplified Feynman diagrams and three symmetry operations. Then we discuss the fast feedback teaching method and present two lessons and a worksheet for teaching symmetries and reactions using this fast feedback. The method was developed and piloted during the last two school years in Dutch secondary schools.

Introduction

A number of countries have experimented with including elementary particles in secondary school physics programs (Hanley 2000). The Institute of Physics developed an interesting module in the early 1990s, which inspired curriculum makers in several other countries (IOP/Open University 1992). The Netherlands introduced the topic into the national pre-university syllabus in 1991 after a pilot project in the 1980s, but had to retract it when the syllabus turned out to be too overloaded in general, and Feynman diagrams and some other topics turned out to be too ambitious. At present Advancing Physics (2001) in the UK has a serious chapter on particle physics. Salters/Horners (2001) includes accelerators and detectors but avoids reactions of elementary particles. Hanley

(2000) provides an overview of recent projects and resources for teaching about particles. Popular books like those of Close (1983) and Ne'eman and Kirsh (1996) are very helpful in the preparation of secondary school lessons.

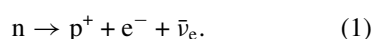
Several articles on teaching particle physics have appeared in *Physics Education*. Pascolini and Pietroni (2002) described an Italian way of presenting simplified Feynman diagrams in a qualitative way. Allday (1998) and Kalmus (1999) provided useful background articles for teachers. Dunne *et al* (1998) described the measurement of the mean lifetime of cosmic ray muons with simple means. The Dutch National Institute for Nuclear and High Energy Physics recently organized a network of muon detectors on the roofs of schools to track cosmic ray showers. CERN has stimulated

teaching projects through its summer school for teachers¹.

In the Netherlands in a Modern Physics project, which currently runs in 34 schools, we have another attempt to include elementary particles in the curriculum. This time we focus on conservation laws and symmetries. With just a few general principles, students can evaluate whether a given reaction is possible and then derive other possible reactions. Instead of studying a multitude of particles and reactions, students focus on the general principles. The physics aspects of the approach have been described recently (Hoekzema *et al* 2005). In this article we focus on presenting a *teaching method*, which has been used successfully in pilot schools for the past two years.

Reaction diagrams

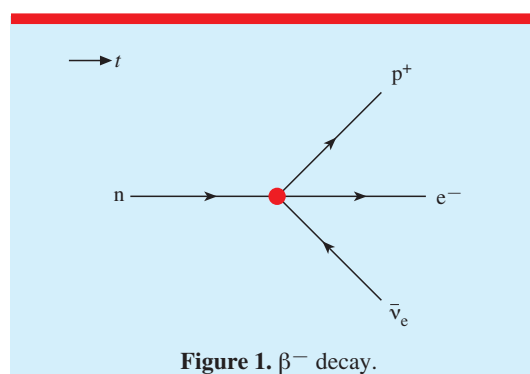
The different forms of beta decay can all be derived from the following equation by applying symmetries:



We will illustrate this using simplified Feynman diagrams. Figure 1 shows the most familiar form of beta decay. First we will explain the diagram.

Time is going from left to right in figure 1. The lines stand for particles; a point where the lines meet (called a vertex) represents an interaction. The diagram expresses conservation laws: conservation of baryon number in the case of the proton and neutron, and conservation of lepton number in the case of the electron and the antineutrino. Arrows to the right indicate

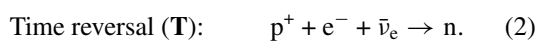
¹ teachers.web.cern.ch/teachers/



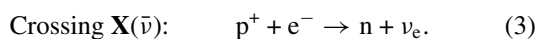
‘normal’ particles with positive baryon and lepton numbers such as the neutron and proton (baryons) and electron (lepton). Arrows pointing to the left indicate antiparticles such as the antineutrino (figure 1) and the positron (figure 3), which both have lepton number -1 . Photons are indicated by wavy lines without arrows, because photons are their own antiparticles. The simplified reaction diagrams are interpreted merely as graphical representations of reaction diagrams. They lack many of the connotations attached to real Feynman diagrams, because these turned out to be too difficult for secondary students. The diagrams are not interpreted as mathematical entities, nor do we go into any subtleties such as time ordering. As a result, the simplified diagrams are learned rather easily, particularly when introduced with the fast feedback method.

Beta decay and symmetries

Let’s return to the reaction in figure 1. We can apply three major symmetry operations to equation (1). Time reversal (**T**) states that the reverse reaction is possible in principle, although the probability of the reverse reaction may be small because of the required energy or the likelihood of finding the right particles at the same place and time. So the arrow in equation (1) can be reversed (as in equation (2) below). The second symmetry concerns charge conjugation (**C**) and states that all particles can be replaced by their antiparticle and that this results in a reaction that is possible. A third way of applying symmetry principles is ‘crossing’. With crossing (**X**) we can take any particle of a possible reaction and replace it by its antiparticle if we move it to the other side of the reaction equation. As an example we first apply time reversal to equation (1):



Then we apply the crossing operation (**X**) to the antineutrino, replacing it by its antiparticle and moving it to the right-hand side of the equation. We indicate this crossing operation on the antineutrino by $\mathbf{X}(\bar{\nu})$:



In nuclei with a relative shortage of neutrons, a proton can convert into a neutron through *electron capture*. This reaction takes place primarily in heavy nuclei. The inner electrons are then close

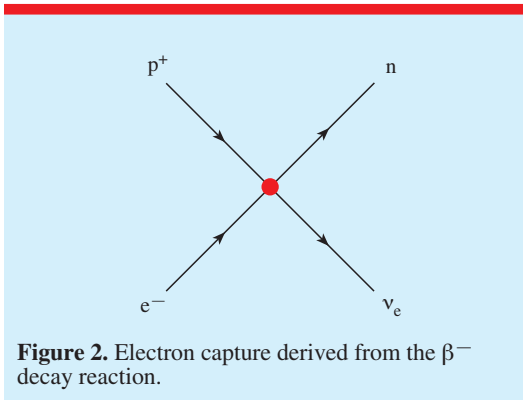


Figure 2. Electron capture derived from the β^- decay reaction.

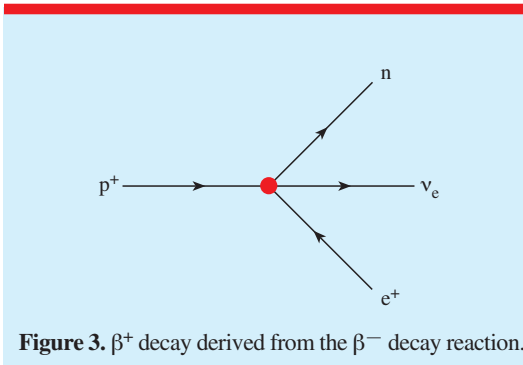


Figure 3. β^+ decay derived from the β^- decay reaction.

to the nucleus, which increases the chances of electron capture. This is exactly what is pictured in figure 2 and equation (3).

In equation (3) we can move the electron to the other side of the arrow—once again applying the crossing operation—and replace it with its antiparticle: the positron. The resulting process of β^+ emission is shown in figure 3 and equation (4):

$$\text{Crossing } X(e^-): \quad p^+ \rightarrow n + e^+ + \nu_e. \quad (4)$$

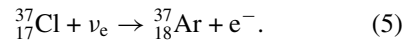
This reaction cannot take place in a free proton because the reaction requires energy. Within a nucleus, such energy might be available if there is a surplus of protons. In the nucleus, neutrons experience only attractive nuclear forces of other neutrons and protons². However, protons experience attractive nuclear forces as well as repulsive electrostatic forces of other protons. If there are too many protons the nucleus becomes unstable due to the electrostatic potential energy. Some of the electrostatic potential energy is used to create mass when a proton decays into a neutron

² At extremely short distances, nuclear forces are repulsive to prevent collapse of the nucleus.

and a positron plus a neutrino (figure 3). The last two will be ejected from the nucleus. The reaction is called β^+ decay. On the other hand the decay of a neutron into a proton plus an electron and an antineutrino is called β^- decay.

Summarizing: β^- decay occurs in nuclei with a surplus of neutrons. In the nucleus a neutron is converted into a proton. In nuclei with a surplus of protons, the reverse reaction can occur, in which a proton is converted into a neutron. This result can be achieved through two different reactions. The first of these reactions is called *electron capture*: a proton can capture an electron, resulting in a neutron and a neutrino (figure 2). The second is β^+ decay (figure 3).

By applying the crossing operation we can obtain yet another reaction as shown on the right in figure 4. A neutron and a neutrino can combine to produce a proton plus an electron. This reaction does indeed occur and can be used to detect neutrinos. Nobel laureate Ray Davis used the reaction of a neutrino with a chlorine nucleus, which then converts to argon, to detect and count neutrinos emitted by the Sun:



Note that crossing symmetry can be applied in the diagrams by mirroring an arrow: the antineutrino arrow in figure 4 (left) is reflected in a vertical axis through the vertex, resulting in the neutrino arrow on the right of figure 4.

By crossing the electron in the left part of figure 4 and then applying time reversal, we can get

$$p^+ + \bar{\nu}_e \rightarrow n + e^+. \quad (6)$$

Equation (6) shows a way to detect antineutrinos, and indeed the reaction is possible if the antineutrino is sufficiently energetic to produce the extra mass of neutron and positron.

Fast feedback method

Now we get to the pedagogy of how to teach about these symmetries and conservation laws. First we introduce the fast feedback method. Fast feedback is a ‘whole class’ teaching method in which the teacher gives a series of short tasks to be done by students individually but at a collective pace. The tasks can be answered in the form of a diagram, a sketch, a drawing or a few words. After giving a task the teacher goes around and

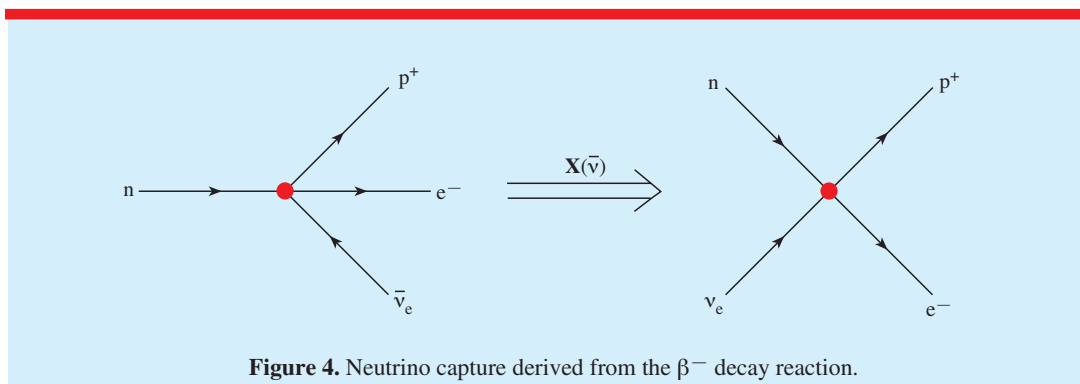


Figure 4. Neutrino capture derived from the β^- decay reaction.

Table 1. Elementary particles.

Fermions								
Quarks ^a				Leptons ^b				
Gen.	Particle/flavour	Mass (GeV/c ²)	Charge (e)	Gen.	Particle/flavour	Mass (GeV/c ²)	Charge (e)	
1	u	up quark	0.003	2/3	1	ν_e electron-neutrino	$< 1 \times 10^{-5}$	0
	d	down quark	0.006	-1/3		e^- electron	0.000 511	-1
2	c	charm quark	1.3	2/3	2	ν_μ muon-neutrino	< 0.0002	0
	s	strange quark	0.1	-1/3		μ^- muon	0.106	-1
3	t	top quark	175	2/3	3	ν_τ tau-neutrino	< 0.02	0
	b	bottom quark	4.3	-1/3		τ^- tau	1.7771	-1
Bosons								
<i>Strong interaction</i>				<i>Electro-weak interaction</i>				
	g	gluon	0	0	γ	photon	0	0
					W^-	W-minus boson	80.4	-1
					W^+	W-plus boson	80.4	+1
					Z^0	Z boson	91.2	0
						<i>Gravitation</i>		
						graviton (hypothetical)		

^a For every quark there is an antiquark with the same mass, opposite charge and baryon number -1.

^b For every lepton there is an antilepton with the same mass, opposite charge and lepton number -1.

^c Conservation of lepton number is considered separately for electron and electron-neutrino, muon and muon-neutrino, and tau particle and tau-neutrino.

looks at the students' work. Here and there (s)he asks students to clarify their answer. In one or two minutes the teacher can check a representative sample of 10–20 students. Then (s)he goes to the front and in plenary addresses one or two major problems with the task and then presents the next task. The teacher has to keep pace to keep the lesson moving. Not every single student error is discussed in plenary, just one or two of the most common errors before the class moves to the next task. If we count 2 or 3 minutes for each task and 2 minutes for plenary discussion, then in a 20 minute portion of a lesson the teacher can go through four or five tasks.

With this method the teacher gets immediate

feedback on whether students understand and what kind of misunderstandings there are. The students get immediate feedback, as the teacher can respond individually or in plenary to the common errors and misunderstandings (s)he observed. Fast feedback methods are a common element in so-called interactive engagement teaching methods (Hake 1998, Meltzer and Manivannan 2002). For example, the peer teaching method described by Mazur (1997) and Crouch and Mazur (2001) uses concept-focused multiple-choice questions. A quick vote on answers provides a good indication of prevalent student misconceptions. Subsequent small group discussion of answers triggers student engagement and provides more feedback for

Table 2. Some compound particles.

Particle	Composition	Baryon number
p^+ proton	u u d	1
p^- antiproton	$\bar{u} \bar{u} \bar{d}$	-1
n neutron	u d d	1
\bar{n} antineutron	$\bar{u} \bar{d} \bar{d}$	-1
π^- pi-minus meson	$\bar{u} d$	0
π^+ pi-plus meson	$u \bar{d}$	0
π^0 pi meson	u \bar{u} or $d \bar{d}$	0

students and teachers. Van den Berg (2003) outlined different formats for fast feedback in the classroom, and van den Berg *et al* (2000) contains a worked example for kinematics. The remainder of this article provides an example for elementary particles.

Two lessons

In our Modern Physics project we spent ten 50 minute lessons on nuclear reactions and elementary particles. Only lessons 6 and 7 are relevant here. Earlier lessons are on recalling chemical reaction equations, extending the idea to nuclear reactions, energy and mass, binding energy, computations with mass deficits, and accelerators. Lesson 5 introduces the particles of the standard model (tables 1 and 2). The exercises in lessons 6 and 7 are limited mainly to first-generation particles except for the muon.

Lesson 6

In a short class discussion the teacher and students recall the conservation laws they have encountered so far (linear momentum, energy–mass, charge and possibly angular momentum). Then the lesson proceeds in the following steps:

1. The *teacher* starts with the reaction $p^+ + e^- \rightarrow H$ and gives an example of C symmetry by replacing particles with antiparticles: $p^- + e^+ \rightarrow \bar{H}$. The resulting antihydrogen has been made at CERN, Geneva (Charlton 2005). So this reaction with antiparticles is indeed possible.
2. Then *students* answer exercises 1(a) and 1(b) from the worksheet (see below) and perhaps an additional exercise added by the teacher. The teacher walks around and identifies any problems students may have with the exercise.

3. The *teacher* discusses the answers to 1(a) and 1(b) and perhaps one or two problems in understanding that (s)he encountered when looking at the students’ answers. Then the teacher gives an example of time symmetry using the ionization of hydrogen: $H \rightarrow p^+ + e^-$. Reversing the arrow (time symmetry) also shows a possible reaction.
4. *Students* do exercise 1(c) and the teacher goes around and looks at answers.
5. The *teacher* discusses the answer to exercise 1(c) or skips that part altogether if everyone got it right. Then the teacher gives an example of the crossing operation. For example, $n + \nu_e \rightarrow p^+ + e^-$. It turns out that we can move particles to the right or left of the arrow if we replace them by their antiparticles. The reaction $n \rightarrow p^+ + e^- + \bar{\nu}_e$ is possible, but we are now dealing with an antineutrino. Whenever we apply the crossing operation to a valid and possible reaction, the particle has to be replaced by its antiparticle and we have another valid and possible reaction.
6. *Students* do exercises 1(d) and 1(e) and the teacher goes around to observe.
7. The *teacher* discusses 1(d) and 1(e).
8. In the same way the class proceeds with exercises 2(a)–2(f).

Lesson 7

Lesson 7 starts with an example of reaction diagrams (figure 5). On the left of the vertex are reactants and on the right are products. An arrow to the right stands for a particle and an arrow to the left stands for an antiparticle. For further details of these simplified Feynman diagrams we refer to our earlier article (Hoekzema *et al* 2005).

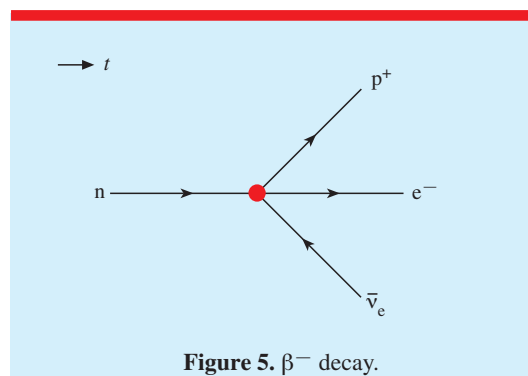
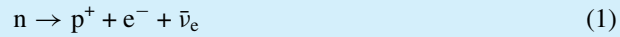


Figure 5. β^- decay.

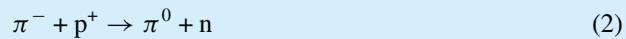
Worksheet on symmetries and reaction diagrams with answers

1. β decay



Exercise 1	Answers to exercise 1 ³
(a) Check for baryon, lepton and charge conservation.	(a) Baryon: $1 = 1$ Lepton: $0 = 1 - 1$ Charge: $0 = +1 - 1$
(b) Apply C symmetry to (1) and write the resulting equation.	(b) $\bar{n} \rightarrow p^- + e^+ + \nu_e$ Please note that n consists of $u d d$, while \bar{n} consists of $\bar{u} \bar{d} \bar{d}$ quarks, so neutron and antineutron are different ⁴ .
(c) Apply T symmetry to (1) and write the resulting equation.	(c) $p^+ + e^- + \bar{\nu}_e \rightarrow n$
(d) Apply X ($\bar{\nu}_e$) symmetry to (1).	(d) $n + \nu_e \rightarrow p^+ + e^-$
(e) Apply X (e^-) symmetry to (1).	(e) $n + e^+ \rightarrow p^+ + \bar{\nu}_e$

2. Reactions with pions



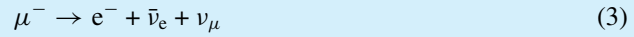
Exercise 2	Answers to exercise 2
(a) Check for baryon and charge conservation.	(a) Baryon: $0 + 1 = 0 + 1$ Charge: $-1 + 1 = 0 + 0$
(b) Apply C symmetry to (2) where π^+ is taken as the antiparticle of π^- and π^0 as the antiparticle of itself (see table 2).	(b) $\pi^+ + p^- \rightarrow \pi^0 + \bar{n}$
(c) Apply T symmetry to (2)	(c) $\pi^0 + n \rightarrow \pi^- + p^+$
(d) Apply X (n) to (2).	(d) $\pi^- + p^+ + \bar{n} \rightarrow \pi^0$
(e) Why is the last reaction rather unlikely?	(e) It is rather unlikely to find these three particles within 1 fm (10^{-15} m) of each other.
(f) The π^0 particle consists of an up quark and its antiparticle ($u \bar{u}$) or a down quark and its antiparticle ($d \bar{d}$). Will the particle last long? Explain.	(f) Annihilation can take place between u and \bar{u} or d and \bar{d} but not between quarks of different flavour such as u and \bar{d} and \bar{u} and d .

³ The student version should have a blank second column!

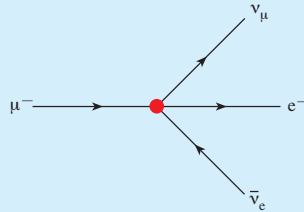
⁴ Strictly speaking, all antiparticles should be written with a bar (\bar{e}^+ , $\bar{\nu}_e$, \bar{n}); however, it is a custom to just write p^- and e^+ rather than \bar{p}^- and \bar{e}^+ .

3. Muon decay

The reaction for muon decay is



The reaction diagram⁵ is



Exercise 3

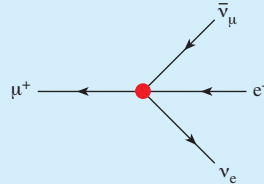
Answers to exercise 3

- (a) Check for lepton conservation
- (b) Apply C symmetry to (3)
- (c) Apply $\mathbf{X}(\nu_\mu)$ to (3)
- (d) Apply $\mathbf{X}(\bar{\nu}_e)$ to (3)

- (a) μ leptons: $+1 = +1$
e leptons: $0 = +1 - 1$
- (b) $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- (c) $\mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e$
- (d) $\mu^- + \nu_e \rightarrow e^- + \nu_\mu$

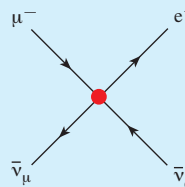
- (e) Draw the reaction diagram of 3(b)

- (e) Antimuon decay.



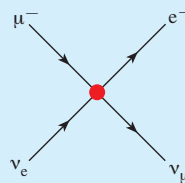
- (f) Draw the reaction diagram of 3(c)

- (f) Reaction of muon with muon-antineutrino.



- (g) Draw the reaction diagram of 3(d)

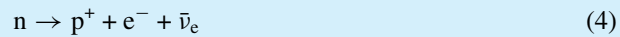
- (g) Reaction of muon with electron-neutrino.



⁵ At this point the teacher will introduce reaction diagrams and then the students continue with questions 3(a)–3(g) using the fast feedback method. Thus the teacher discusses the answer to 3(a) before students proceed to 3(b), etc.

4. Once again beta decay⁶

We return to β decay:



Exercise 4

Answers to exercise 4

- | | |
|---|---|
| (a) Use symmetries to derive an equation for beta decay, which results in the emission of a positron ⁷ . | (a) $X(e^-)$ would produce a positron on the left of the arrow. Then we apply T symmetry and reverse the arrow:
$p^+ + \bar{\nu}_e \rightarrow n + e^+$ |
| (b) Show that it is not possible to derive a reaction from equation (4) using symmetries in which, amongst others, a positron is produced from a neutron. | (b) Using crossing symmetry with the particles of equation (4) only, we would always end up with a positron and a neutron on the same side of the arrow. On the opposite side e^+ would have to be replaced by e^- . |
| (c) Use the symmetries and try to derive an equation in which an electron is absorbed into the nucleus. (In nature this can happen spontaneously in nuclei with high Z . It can also be contrived by shooting electrons at nuclei.) | (c) As <i>input</i> we need an electron. So we apply time symmetry on (4) and then move the antineutrino to the right using crossing: $p^+ + e^- \rightarrow n + \nu_e$. We can also get this by applying time symmetry to the answer to 1(d). |
| (d) Look at the equations once again. Which process could be used to detect electron-neutrinos and electron-antineutrinos ⁸ ? | (d) We can detect electron-neutrinos through collisions with neutrons $n + \nu_e \rightarrow p^+ + e^-$ and antineutrinos through collisions with protons: $p^+ + \bar{\nu}_e \rightarrow n + e^+$ |
| (e) The reaction in equation (4) can take place in a free neutron, but it is much more likely to occur in a neutron that is part of a nucleus such as $^{37}_{17}\text{Cl}$. Write this reaction for chlorine-37. | (e) $^{37}_{17}\text{Cl} \rightarrow ^{37}_{18}\text{Ar} + e^- + \bar{\nu}_e$ |
| (f) By crossing the reaction in chlorine-37 we can get a reaction that makes it possible to discover neutrinos when they collide with a chlorine nucleus. Write the reaction and add a reaction diagram ⁹ . | (f) $^{37}_{17}\text{Cl} + \nu_e \rightarrow ^{37}_{18}\text{Ar} + e^-$
or $n + \nu_e \rightarrow p^+ + e^-$ |

⁶ From this point on students work in small groups or alone at their own pace and no longer with fast feedback. However, the format of the worksheet still allows the teacher to supply quick individual feedback.

⁷ With questions 4(a) and 4(b) things get interesting. We can derive all forms of beta decay from just one equation (1). We can also immediately judge whether a certain variation is possible or not. So we can predict that absorbing an electron in a heavy nucleus is possible. However, such an electron cannot remain an electron, because its typical wavelength (10^{-10} m) would not fit the nucleus (10^{-15} m).

⁸ This question once again shows how the use of symmetries can lead to important predictions. It is indeed possible to detect neutrinos using these reactions.

⁹ The reaction with chlorine was used by Nobel laureate Davis (2002) to detect and count neutrinos emitted by the Sun.

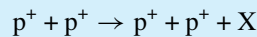
5. Collisions

Check whether the following reactions are possible or not and indicate why.

Exercise 5	Answers to exercise 5
(a) $\pi^+ + p^+ \rightarrow p^+ + p^+ + \bar{n}$	(a) Baryon conservation is okay: $0 + 1 = 1 + 1 - 1$. Also charge conservation is okay.
(b) $p^+ + p^+ \rightarrow p^+ + p^+ + n$	(b) No baryon conservation: $2 \neq 3$.

6. What kind of particles?

A reaction is as follows:



X is an unknown particle.

Exercise 6	Answers to exercise 6
(a) Is X a meson or a baryon? Why?	(a) X cannot be a baryon or antibaryon because the baryon number would not be conserved. It could be a neutral meson.
(b) Does X have charge or not? Why?	(b) X cannot have charge because there would be no charge conservation.
(c) Can X be a lepton?	(c) If X were a lepton there would not be conservation of lepton number.
(d) Answer (a), (b) and (c) in the case where two particles are formed (X and Y).	(d) A baryon and an antibaryon would be possible if X and Y were both be neutral or were to have opposite charge. Leptons would be possible, but then it would have to be a lepton and its antilepton.

9. Then exercises 3(a)–3(g) are done with fast feedback, just like problems 1(a)–1(e) and 2(a)–2(f) in the previous lesson. After every one or two exercises, the teacher interrupts, discusses the answers and the class moves on to the following exercise.

10. Exercises 4–6 are done by students individually or in small groups at their own pace and no longer in fast feedback format, because these exercises take more thinking time. Thanks to the format of the worksheet,

it is still possible for the teacher to very quickly assess the work of individual students and interact to find out the students' reasons for alternative answers and to engage in individual or small group discussions.

Comments (please read the worksheets first)

What students learn is the following. Given a reaction between certain particles, they can derive other possible reactions, and they do that by applying the conservation laws. Some might

object that students just learn some tricks. We think that learning to apply conservation laws and symmetries to reactions is valuable and that understanding of symmetries at a much deeper level is not attainable at secondary school and has to be postponed to university science programs.

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