# Chapter 1

# Matter in the early 20th century

In this first chapter we examine views of matter that existed in the early part of the 20th century. When results of experiments could not be explained by known theories, either more experiments were done or new theories were proposed. New theories led to different ideas about what the world around us was made of. Through a look at these experiments and theories, we will learn about some particles that you have probably heard of and some that you may not have heard much about. After completing this chapter you will:

- know what protons, neutrons, electrons, and neutrinos are.
- know the constituents of the atom and the nucleus.
- be able to name three types of radiation.
- know about conservation rules for energy, electric charge, and momentum.

## 1.1 Parts of the atom

### 1.1.1 Rutherford's experiments: the nucleus is uncovered

We begin with experiments by Ernest Rutherford and his colleagues in Great Britain around 1911. They used a type of radiation, alpha particles, to bombard atoms in an attempt to uncover their inner parts. They did not understand fully what alpha particles were, but they were able to use them. Figure 1.1 shows what their experiment was like. The main points of the experiment were as follows:

- polonium, which is a radioactive substance, was used as a source of alpha particles. Alpha particles were emitted from the polonium in all directions, but Rutherford was only concerned with the particles that hit the gold foil target.
- a movable screen painted with a material called a scintillator was used to detect the alpha particles that emerged from the target. Scintillator material gives off a flash of light when struck by an alpha particle. Rutherford was therefore able to study the position of the alphas after they passed through the target.

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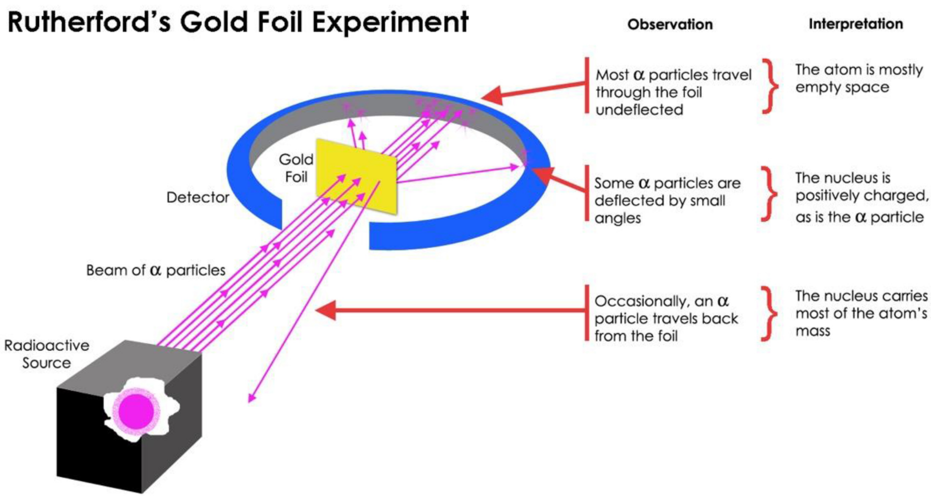



**Figure 1.1.** Rutherford's experiment.

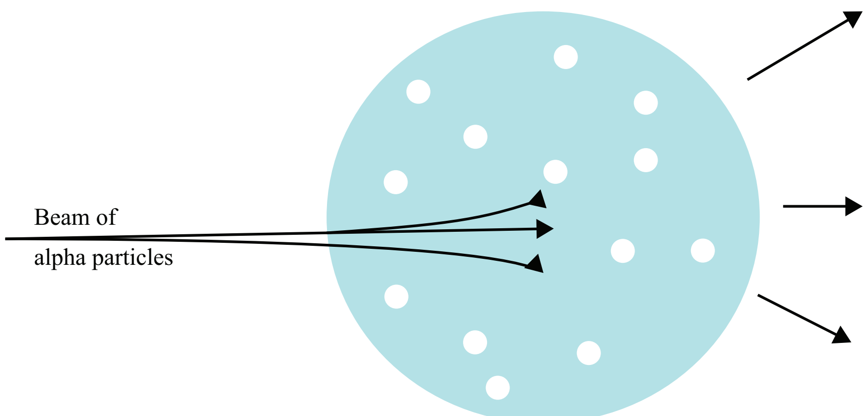



**Figure 1.2.** Plum pudding.

The results of these experiments were startling. At the time, a popular model of the atom was J J Thomson's 'plum pudding': a spherically shaped mass of positive charge in which the negatively charged electrons were embedded. (Electrons had been discovered just prior to the beginning of the 20th century by Thomson.) If this model were correct, the results of Rutherford's experiments should have been similar to what is shown in figure 1.2; the heavy alpha particles would soar through the atom, deflected slightly by their trip through the positive 'pudding'. To the scientists' surprise, however, some of the alpha particles came right back at them, as if they had bounced off something very massive, and that was inconsistent with the plum pudding model of the atom.

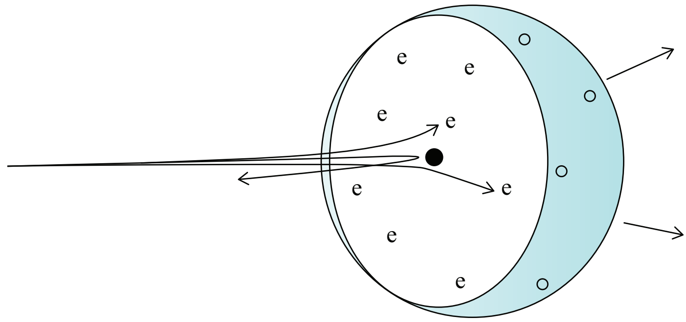



**Figure 1.3.** Discovery of the nucleus.

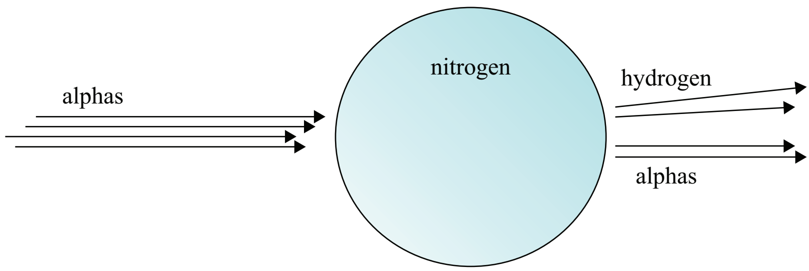



**Figure 1.4.** Alpha particles at nitrogen.

These results, however, were consistent with a new model, seen in figure 1.3. In this model, the atom contained:

- a solid nucleus in which all the atom's positive electric charge and almost all its mass were concentrated. The alpha particles bounced off this dense nucleus.
- light electrons existing somewhere in the empty region outside the nucleus. The electrons had a negative electric charge to balance the positive charge of the nucleus. The alpha particles brushed past the electrons deflected only slightly.

But this was not the last of the scientists' experiments. To learn more about the nucleus, Rutherford and James Chadwick continued to use alpha particles. In one series of experiments they shot the alpha particles at nitrogen nuclei and observed the results. As they expected, alpha particles came out, but so did hydrogen nuclei (see figure 1.4). Well, if hydrogen nuclei could be ejected from nitrogen nuclei, then perhaps nitrogen nuclei were composed of hydrogen nuclei. In fact, perhaps all nuclei were made of hydrogen nuclei.

A proton is the name given to a hydrogen nucleus. Protons have one unit of electric charge, equal but opposite to the electron charge. Protons also have mass, and for simplicity we quote all masses in terms of the proton mass (1 unit). In these units, the mass of an electron is about 1/1800.

These experiments showed that nuclei had some sort of internal structure. They too were composed of parts, or protons. The more positive charge a nucleus was found to have, the more protons it must have contained.

### 1.1.2 Models of the nucleus: protons and neutrons

The nucleus contains protons. But this is not the complete picture. The simplest model of the nucleus, composed solely of protons and electrons, was suggested in 1914 (see figure 1.5). Let's see how this model works for the nitrogen nucleus. Below is a table with properties of the nitrogen nucleus, the proton, and the electron.

| Object | Charge | Mass |
|---|---|---|
| proton | +1 | 1 |
| electron | −1 | 0 |
| nitrogen nucleus | +7 | 14 |

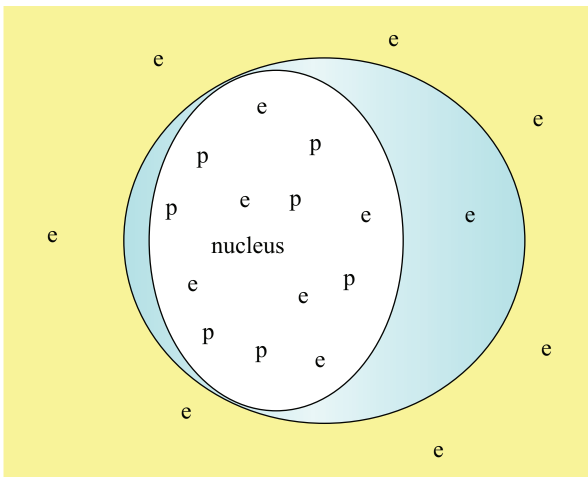



**Figure 1.5.** Early model of the nitrogen nucleus.

The only way to combine protons and electrons into a nitrogen nucleus is shown in figure 1.6. Remember, these particles are *in* the nucleus, there will still be seven electrons *outside* the nucleus.

Or, in terms of the particles involved, one can see how the charge and mass of the constituents add up to the charge and mass of the nucleus as a whole.

| | 14 p + | 7 $e^-$ | = | nitrogen nucleus |
|---|---|---|---|---|
| charge | 14 | −7 | = | 7 |
| mass | 14 | 0 | = | 14 |

There is a problem with this model, however, in that the spin is not correct. Spin is a property that a particle can have, just as it can have charge and mass. The classical analogy that is most often given for spin is that of a top spinning on its axis. You may think of spin this way, but electrons and protons and all other particles with spin do not actually spin like a top. Spin is an internal property of a particle that can be calculated or measured, just like mass can. Electrons and

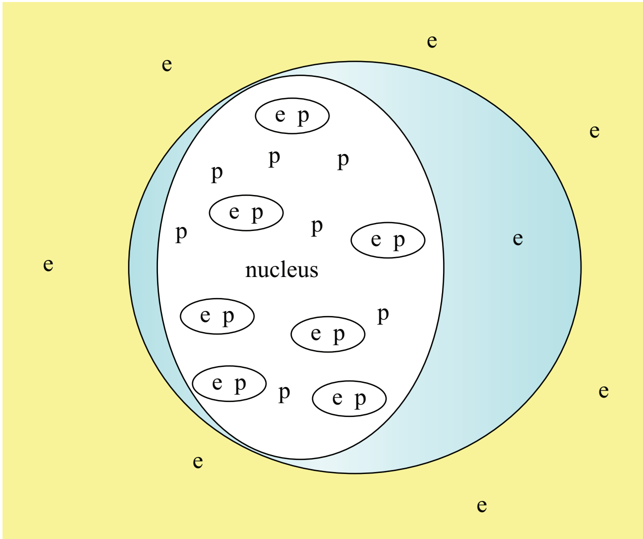



**Figure 1.6.** Early nuclear model.

protons each have a spin of 1/2 unit. The spin of the electron or proton is said to be up or down, and these are the only possibilities. Now, our model has 21 particles in the nucleus, each with a spin of 1/2. The nitrogen nucleus has a spin measured at 1 unit. It is not possible for an odd number of particles with 1/2 unit of spin each (21 in our case) to have a combined spin equal to an integer (1 in our case). This point is illustrated in figure 1.7 for some simpler cases with three or four particles, each with a spin of 1/2.

By 1930, many physicists realized the inadequacy of the simple model of protons and electrons as the constituents of the nucleus. If we require the nitrogen nucleus to have the correct spin as well as charge and mass, then there must be an even number of objects in the nucleus. So, if we combine 7 of the 14 positively charged protons with the 7 negatively charged electrons in the nucleus, we get 7 neutral objects with

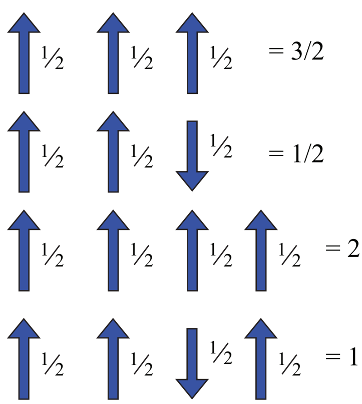



**Figure 1.7.** Examples of spin combinations. (Spin: https://www.youtube.com/watch?v=cd2Ua9dKEl8)

masses essentially equal to the proton mass. Figure 1.7 shows how this combination might be viewed. As early as 1920, there were suspicions of a neutral object (with the same mass as the proton) in the nucleus. By 1932, the neutron had been discovered. Seven protons and seven neutrons in the nitrogen nucleus give the correct charge, mass, and spin. Go ahead and verify it.

The neutron was discovered by Chadwick in another experiment involving alpha particles. A sketch of the basic setup is shown in figure 1.8. The main points of this experiment were:

- alpha particles were aimed at a beryllium target.
- Chadwick observed something coming out of the beryllium that did not have electric charge (we use the term neutral particles or neutral radiation).
- this radiation hit a paraffin target.
- protons were knocked out of the paraffin target.

Chadwick concluded that the neutral radiation was indeed the neutron, as it had to have a mass close to the proton to knock one out of the paraffin.

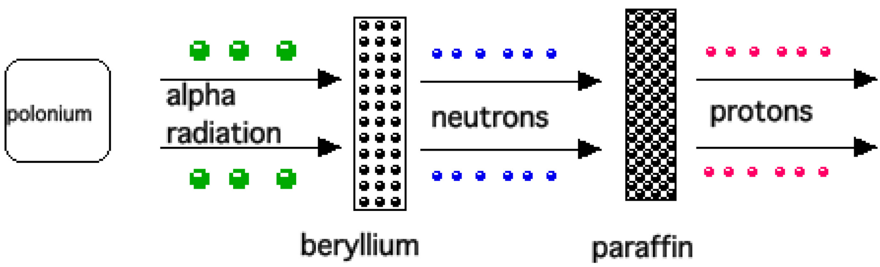



**Figure 1.8.** Discovery of the neutron.

## 1.2 Radiation

Unstable nuclei spontaneously decay by emitting particles. This process is called radioactivity. The three types of radiation are called:

- alpha ($\alpha$).
- beta ($\beta$).
- gamma ($\gamma$).

We have already seen that alpha particles were useful in Rutherford's experiments on the atom. Alpha ($\alpha$) radiation, or alpha particles are just helium nuclei (two protons and two neutrons). An example of a process that produces alpha particles is a radium nucleus decaying into a radon nucleus and an alpha particle, as shown in figure 1.9. You can see that the total number of protons and the total number of neutrons remain constant.

$$\text{radium nucleus} \Rightarrow \text{radon nucleus} + \text{alpha}$$

Gamma ($\gamma$) radiation is high-energy electromagnetic radiation. When a nucleus gets into an excited state, it can emit the extra energy it has by gamma radiation. Just to put the energy in perspective, gamma rays prevalent in high-energy physics processes

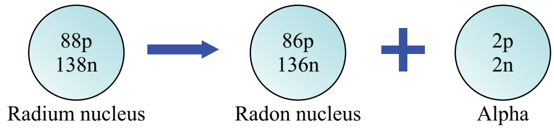



**Figure 1.9.** Example of alpha radiation.

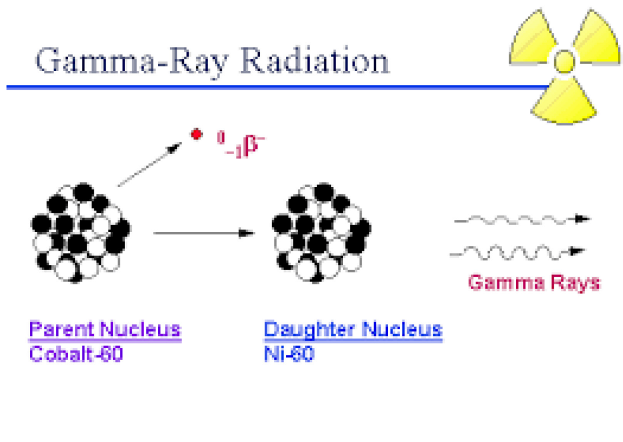



**Figure 1.10.** Gamma radiation as secondary process.

have an energy about 10 billion times that of microwaves. Many different types of nuclei can become excited and emit gamma rays. The example shown in (figure 1.10) shows first beta radiation (next section) and then the Ni-60 is in an excited state so it emits gamma radiation.

$$\text{excited nucleus} \Rightarrow \text{unexcited (same) nucleus} + \gamma$$

Beta ($\beta$) radiation involves the emission of an electron. But this electron is not one of the electrons from outside the nucleus. It is an electron that is created within the nucleus. An example, as shown in figure 1.11.

$$\text{calcium} \Rightarrow \text{potassium} + \text{electron}$$

Unlike the process that produces alpha radiation, in this process the total number of protons and the total number of neutrons are not separately conserved. We have gained a proton and lost a neutron. The underlying process here is a neutron decaying into a proton and an electron. Studying this process of beta decay led physicists to propose a new particle called the neutrino (as seen in figure 1.11). The neutrino was postulated when neutron beta decay did not follow some important conservation principles of physics. The neutrino will be discussed in greater detail after we discuss these conservation principles.

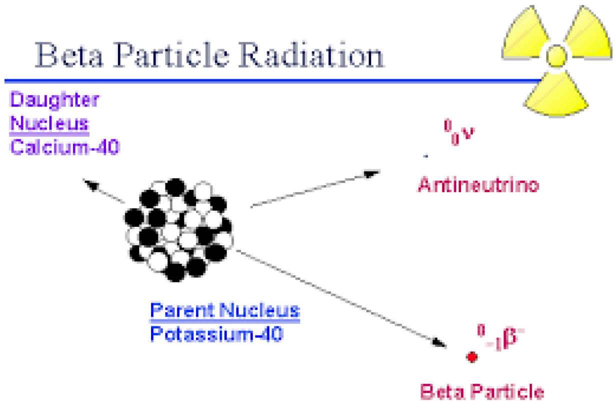



**Figure 1.11.** Example of beta radiation.

## 1.3 Some conservation laws

Conservation principles are important in physics, and they can help us to explain why some things happen and others don't. Three conservation rules that must be obeyed in all physical processes are:

- conservation of electric charge
- conservation of momentum
- conservation of total energy.

We will not derive these rules, but we will use them to determine whether certain particle reactions can or cannot occur.

### 1.3.1 Charge conservation

The total electric charge of a system of particles must remain the same. That is, if you add up all the charges of the particles on one side of a reaction, they must exactly equal the sum of all the charges of the particles on the other side of the reaction. For example, both the following reactions obey the principle of charge conservation. Note that these are not the only possibilities, but just two examples of reactions.

| | | | | | |
|---|---|---|---|---|---|
| + | − | ⇒ | 0 | 0 | |
| + | − | ⇒ | + | − | 0 |

In both examples, two charged objects, one with a positive charge and the other with a negative charge, are the initial particles (those to the left of the arrow). In the first case, the final particles (those to the right of the arrow) both have no electric charge. In the second case, there are three particles: one positive, one negative, and one neutral. In either case, the total charge of the final particles is zero.

### 1.3.2 Energy conservation

The total energy of the particles before a decay or reaction (two particles in the initial state) must be equal to the total energy of the particles afterward. Now, here we speak of the *total energy*, because the energy that concerns us comes in two forms:

- kinetic energy, or energy of motion, which depends on the velocity of the particle
- mass energy, which arises from Einstein's famous equation

$$E = mc^2$$

In this equation, the energy ($E$) is equal to the product of the mass of the particle and the speed of light (which is a constant) squared. The greater the mass of the particle, the more mass energy it has. For decays, our criterion for satisfying energy conservation will be that the mass (or mass energy) of the decaying particle be greater than or equal to the sum of the masses of the end products. How does this lead to energy conservation? Energy conservation for particle A initially at rest gives us

mass of A = mass of B + kinetic energy of B + mass of C + kinetic energy of C

and since all energies are positive

(mass of A) > (mass of B) + (mass of C)

For reactions, the two particles in the initial state can have a total mass less than the total mass of the final particles because they can bring kinetic energy into the reaction to ensure that energy is conserved.

### 1.3.3 Momentum conservation

The total momentum of the particles must remain the same in any physical process when no external forces are involved. For velocities that are very low compared to the speed of light, the momentum of a particle is the product of its mass and its velocity. In a particle reaction, if the initial total momentum (the sum of the momenta of the individual particles involved) is zero then the final total momentum must be zero as well. For particle decays, such as one particle becoming two or more particles, this conservation of momentum manifests itself in an interesting visual way. In particular, if one particle decays into exactly two particles then these particles must emerge from the reaction in exactly opposite directions for momentum to be conserved.

This is illustrated in figure 1.12. In this example

$$A \Rightarrow B + C$$

$M$, the mass of particle B, is larger than $m$, the mass of particle C. Therefore, the velocity of particle C must be larger than the velocity of particle B (as indicated by the length of the arrows). Equivalently, the momentum of particle B ($Mv$) is the same as the momentum of particle C ($mV$).

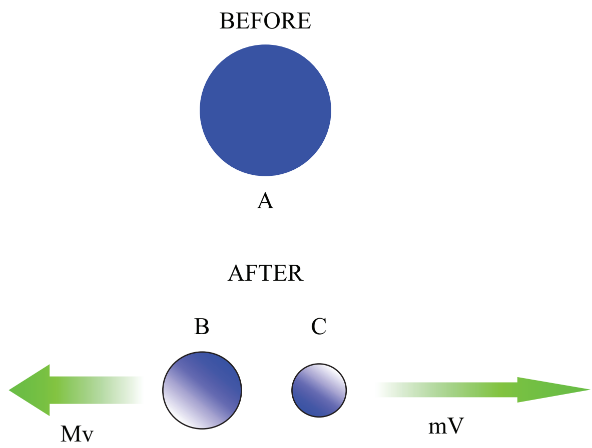



**Figure 1.12.** Conservation of momentum.

## 1.4 Neutrinos

A reaction that violates one of these conservation principles cannot occur. The process of nuclear beta decay was studied carefully in the 1920s. One of the things that scientists found was that energy in beta decay of the neutron was not conserved. Physicists at this point had a tough choice: They could abandon the principle of energy conservation, or they could accept a new hypothesis put forth by Wolfgang Pauli. Pauli proposed that a new particle, which could not be detected, ran off with the missing energy. This particle was to have no electric charge, little (or no) mass, and the same spin as protons and electrons. It was given the name neutrino, which means 'little neutral one' in Italian. Existence of this particle was well accepted by physicists by the 1950s.

By the late 1950s, it was also seen that momentum was not conserved in beta decay of the neutron unless the neutrino was considered a part of the process. If the neutron decayed into only two particles, then the diagram on the left in figure 1.13 shows what one must see to guarantee conservation of momentum. The proton and the neutron must emerge from the decay back-to-back.

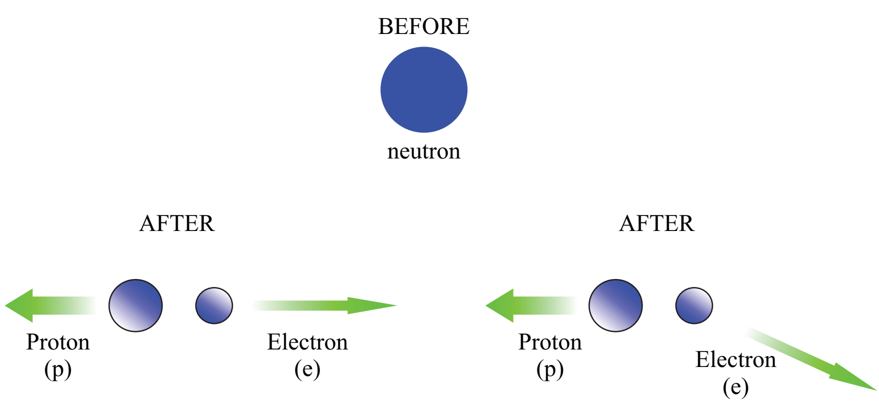



**Figure 1.13.** Neutron decay possibilities.

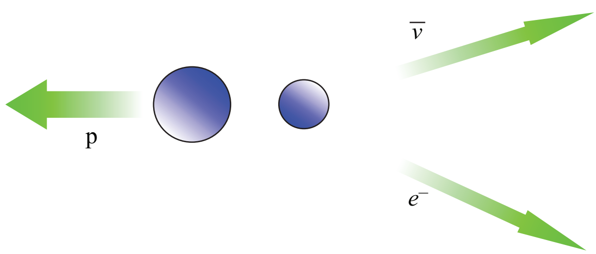
But that is not what physicists observed in cloud chamber pictures. Instead, the emerging particles looked something like those shown in the diagram on the right in figure 1.13.

The idea of the neutrino ‘fixed’ neutron beta decay so that it obeyed all the conservation rules. However, experimental verification was needed before everyone would believe in the neutrino. In 1956, about 25 years after it was initially proposed, the neutrino was discovered outside a nuclear reactor. At the Savannah River (Ga.) reactor, the number of neutrinos emerging per second was extremely high, and physicists waited with their detector until they eventually detected some.

So the theory of beta decay must be modified to include the neutrino. The symbol for the neutrino is the Greek letter $\nu$, and it has no electric charge and little (or no) mass. Current experiments are placing limits on the mass of the neutrino, but for our purposes it will be taken as zero. This may be the first particle that you have not heard of. To this point we have dealt with the traditional everyday atom, stable or not, composed of protons, neutrons, and electrons. Now we encounter the neutrino, whose existence was postulated when neutron beta decay did not follow important conservation principles. A diagram of the process is shown in figure 1.14, with the four subatomic particles all linked together in beta decay. In this process it is actually an antineutrino (but more about that later).

*‘Radioactive decay is responsible for my existence today. Some like to say the weak force brought me into this world today, but I prefer to think my mother gave her life for me. Mom was a neutron. After a relatively short life of fifteen minutes, she decayed into her three children. I’m a proton and my two little sisters are an electron and a neutrino. Mom was a model particle. She didn’t cause much trouble and stayed out of other particles’ business because she was so neutral.’*

*Taegan D Goddard*




$$n \Rightarrow p + e^- + \bar{\nu}$$

**Figure 1.14.** Neutron decay.

## Summary

In this chapter:

We saw how the experiments done in the early part of the century led to:

- the model of the atom: a dense nucleus containing most of the mass and all of the positive charge, with electrons somewhere outside the nucleus
- the model of the nucleus: protons and neutrons, with protons having positive electric charge and neutrons having none
- the discovery of the neutron.

We learned about three types of radiation ($\alpha$, $\beta$, $\gamma$) and that the study of one of the types, beta radiation, led to the theory of the neutrino.

We introduced three conservation laws for:

- charge
- momentum
- energy.

## Self-test 1

For multiple choice, check all that apply.

1. Rutherford used which kind of radiation to study atomic and nuclear structure?
   a. alpha
   b. beta
   c. gamma
2. Match the items in the left column with those in the right.

| | |
|---|---|
| alpha | a neutron changes into a proton |
| beta | high-energy electromagnetic radiation |
| gamma | a helium nucleus |

3. Neutrinos were proposed by Pauli:
   a. because they were seen at a nuclear reactor.
   b. because of missing energy in beta decay.
   c. to guarantee charge conservation in beta decay.
4. Name the three conserved quantities you have learned about so far.
5. Fill in the chart

| object | symbol | mass | charge | spin |
|---|---|---|---|---|
| proton | | | | |
| neutron | | | | |
| electron | | | | |
| neutrino | | | | |

6. Test each reaction for charge conservation and conclude whether it passes or fails.

$$e^- + p \Rightarrow n + n$$

$$e^- + p \Rightarrow \nu + n$$

$$e^- + n \Rightarrow p + n$$

7. Draw a picture of a helium atom as seen by a physicist in 1932.

## Answers to self-test 1

1. Rutherford used which kind of radiation to study atomic and nuclear structure?
   a. alpha ×
   b. beta
   c. gamma
2. Match the items in the left column with those in the right.

| | |
|---|---|
| alpha | a neutron changes into a proton |
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| gamma | a helium nucleus |

3. Neutrinos were proposed by Pauli:
   a. because they were seen at a nuclear reactor.
   b. because of missing energy in beta decay. ×
   c. to guarantee charge conservation in beta decay.
4. Name the three conserved quantities you have learned about so far.
   momentum
   energy
   charge
5. Chart

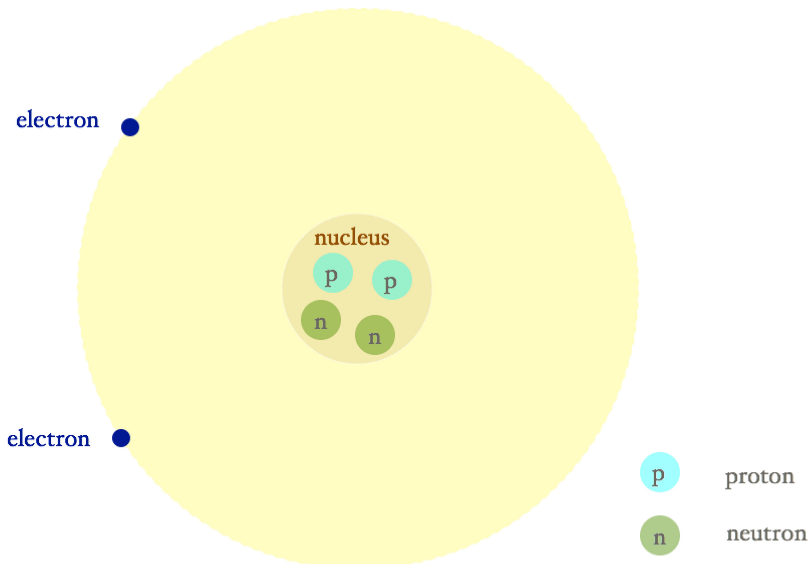
| object | symbol | mass | charge | spin |
|---|---|---|---|---|
| proton | p | 1 | +1 | 1/2 |
| neutron | n | 1 | 0 | 1/2 |
| electron | $e^-$ | 1/1800 | −1 | 1/2 |
| neutrino | $\nu$ | 0 | 0 | 1/2 |

6. Test each reaction for *charge conservation.*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $e^-$ | + | p | ⇒ | n | + | n | |
| − | | + | | | 0 | 0 | conserved |
| $e^-$ | + | p | ⇒ | $\nu$ | + | n | |
| − | | + | | | 0 | 0 | conserved |
| $e^-$ | + | n | ⇒ | p | + | n | |
| − | | 0 | | | + | 0 | not conserved |

7. A helium atom as seen by a physicist in 1932. Helium has 2 protons, 2 neutrons, and 2 electrons. This and all other drawings in this book are not

to scale. The nucleus takes up an extremely small fraction of the total size of an atom. The atom has a diameter about 10 000 to 100 000 times as big as the diameter of the nucleus.




*'Oh, this endless spinning. The monotony is overwhelming. I could have been a proton; I could have been a neutrino, but no. I'm an electron; a negatively charged, crazily spinning particle, and I don't even get to choose my path. I'm stuck on this highway and it's one big circle (sort of). I start in the same place, and I end up in the same place, and then I start all over again. Basically, I am leashed onto this nucleus, and I can't get away until some better prospect comes along or until I'm spit out. I just keep going around and around. I've got this serious attraction to my nucleus. There's something so positive about it, so electrically alluring…'*

*Danielle Otis*