sck cen Academy

Lesson activity

Basic principles of radiological protection
Protection from external radiation

Credits: The Society for Radiological Protection (https://www.srp-uk.org)

Checklist for the teacher

Target audience
Third-grade science/STEM pupils

Format of activity
interactive class activity as part of a lesson or summary

Duration
15 minutes

Learning objectives
After completing this learning activity, the pupil will be able to:
- Visually illustrate the basic principles of how radiation from radioactive sources (alpha, beta and possibly gamma) interacts with materials
- Think critically about the materials used that were presented to them

Required equipment and space
- Large space where pupils can stand in a line or in a semi-circle (e.g. sports hall)
- Large inflatable gym ball
- Bag of smaller plastic balls

Activity

Ask the pupils to stand about 1 metre apart, in a line or in a semicircle. The idea is that the pupils represent the nucleus of atoms that make up a material: they form the 'living model' of a helium atom. Give each pupil two balls. These balls represent the electrons that rotate around the nucleus to form electrically neutral atoms. To represent the continuous movement of the electrons, encourage the pupils to juggle as best they can. A little competition may develop between pupils who want to show off their juggling skills. Most of the pupils will be able to handle a maximum of 2 balls at a time. The challenge for the pupils is to keep up with their electrons when they are bombarded with radiation – simulated by the gym ball and more plastic balls.
There are several opportunities for review and links to other parts of the science curriculum, as well as opportunities for the pupils to critically examine this model. Some ideas are given in the appendix to this document.

Alpha particles

The teacher or an appropriate volunteer can simulate the effect of alpha particles by (gently) hitting the jugglers at the front of the group with the gym ball. Because of the large size of the ball, it will be very likely to hit a target and thereby "disconnect" the electrons from the juggler. This will cause the pupils (atoms) to lose any hope of keeping up with their balls (electrons). The gym ball is highly effective in 'ionizing' the pupils due to its large size. At atomic and sub-atomic scales, the diameter of the alpha particles becomes less important because the distance is large enough relative to the Coulomb force. Alpha particles interact most strongly with atomic electrons due to their large electrical charge and relatively slow speed. This activity validates how alpha particles cause the greatest density of ionisations by reacting strongly with many atomic electrons.

Beta particles

To simulate beta particles, the further balls are now used as projectiles. With some caution, a volunteer can throw these at the juggling pupils with the goal of loosening the balls in the juggling game. Make sure the balls are light (e.g. sponge balls or plastic balls) and that pupils remove glasses, etc. Make sure the balls are thrown gently. Because of the much smaller size of the projectiles, the chance of interaction with one of the atomic electrons will be far smaller, so the projectiles will reach much farther. The equal dimensions between the projectile electrons and the target electrons reminds the pupils that beta particles are actually the same as electrons. Again, the physical size will be less important, similar to the alpha particles, but due to the smaller size and higher velocity, the beta particles will interact less strongly with matter compared to the alpha particles.

Gamma rays

The pupils should be familiar with gamma rays as high-energy electromagnetic radiation with short wavelengths – a type of light. Gamma rays are the most pervasive of the three major types of radiation, and have the lowest density in ionisations.

One might argue that the above simple model demonstrating interactions of charged particles does not adequately capture the full complexity of gamma interactions. The individual photon properties of gamma rays cannot be represented, and this provides an opportunity for pupils to reflect on the limitations of this model. The light passes through the jugglers without interacting with the balls. The scattering effect of the flashlights may cause the jugglers to drop the balls (thus simulating the effect of ionisation). The light passes without interacting with the balls.

The science

The full explanation of how ionising radiation interacts with matter is highly complex. For an understandable overview of the theory with few mathematical approximations, see Liley [1]. The commonality among all types of ionising radiation arising from radioactive decay is that it originates from the nucleus of an atom and primarily interacts with atomic electrons, where ionisations and excitations are ultimately formed. These two responses are therefore central to all aspects of radiation detection and measurement. Moreover, the ionising nature of a type of radiation determines how harmful it is to the body: radiation-induced ionisation in biologically important materials can initiate a complex series of chemical reactions that ultimately lead to biological disruption and disease. Similarly, the ionising nature of radiation is important when used in medical applications, such as radiotherapy where cancer cells are destroyed.

Charged particles (alpha and beta) excite atomic electrons via the electrostatic force (Coulomb force). The amount of interaction with each individual atomic electron, and thus the ability of radiation to ionise, depends on two major factors:

- The electrical charge of the particle – the greater the charge, the greater the attraction or repulsion force acting on atomic electrons for a given distance
- The speed at which the particle is flying. The slower the speed, the greater the time a particle will take to pass by an atom – thus the greater the *impulse* (average force x time) is felt by the atomic electrons. In other words, it will therefore be less likely for a fast particle to be close for a sufficiently long time to cause excitation or ionisation.

The ionisation density (number of ionisations produced per length unit) resulting from the passage of charged particles also depends on the properties of the material. A dens material with a high Z value such as lead will have a higher density of 'target' electrons, and will have a high *stopping power* – as well as, of course, a high ionisation density.
Alpha particles, with an unshielded charge of $+2^e$, will cause the highest ionisation density and therefore have the lowest permeation among the major types of ionising radiation. For the typical energies at which alpha particles are emitted (a few MeV), their velocity will be low enough that there will be sufficient time to react with atomic electrons. The alpha particle is far more passive than an electron; thus, many collisions must occur before the projectile is brought to a stop. Each collision will exchange only a small amount of kinetic energy. In some materials, an alpha particle mat interact with millions of individual electrons before coming to rest and being electrically neutralised – but this is at very short distances.

The physics of how **beta particles** react is identical to alpha particles. However, the beta particle is singularly charged, and is usually emitted at far greater speed than alpha particles because of its smaller mass. As a result, the interaction of beta particles with matter will be much weaker: the probability that a beta particle will ionise an individual atom on its trajectory is much lower. When the beta particle does interact with an atomic electron, a significant fraction of the kinetic energy (and possibly all of it) will be exchanged due to an equality in mass. A smaller number of collisions that are less likely bring the beta particle to rest.

Gamma rays are high-energy electromagnetic radiation, photons, arising from nuclear transitions, with wavelengths similar to the dimensions of the atomic nucleus. **Interactions of gamma rays with matter are more complex than the process of the electrostatic (Coulomb) force in charged particles.** For gamma rays, there are three processes by which the initial energy can be transferred, namely *photoelectric absorption*, *Compton scattering* and, for sufficiently energetic photons, *electron-positron pair production*. The occurrence of each reaction depends upon the energy of the gamma rays and the material the radiation strikes. Just as with several other interaction processes, ionisation by gamma rays constitutes a fitting example of the wave/particle duality; it is reasonable to think that gamma rays propagate as waves, but when an interaction occurs, it is a localised process and, in so doing, the particle nature of the radiation is revealed. Gamma rays are the most pervasive of the main types of ionising radiation because they interact with individual atoms with very low probability. They therefore have the smallest ionisation density.

Pupils are expected to have an idea of the various penetrating powers of ionising radiation. They should be familiar with the idea that a few cm of air or a sheet of paper are sufficient to completely block alpha radiation, while beta particles are able to penetrate aluminium of several mm thick. On the other hand, for gamma rays, one would need several cm of lead (or another equivalent material of the same density) to block them effectively.