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

30 minutes

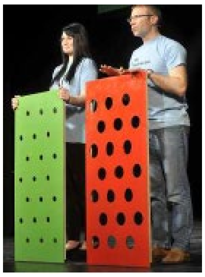
Learning objectives

After completing this learning activity, the pupil will be able to:

- Identify time, distance, shielding as the main principles for protection against external radiation
- Describe the effects of a change in exposure time, distance from the source and shielding from the source in relation to the dose incurred

Required equipment and space

- Large space (e.g. sports hall)
- Toy weapon that can fire multiple rounds in a row (ideally 15-20 without reloading, e.g. Nerf Dart Tag)
- Darts with Velcro tip
- Velcro vest
- Safety glasses (x2)
- Cardboard board with 21 large holes (80 mm diameter)
- Cardboard board with 42 small holes (40 mm diameter) – optional
- Cardboard board with 21 small holes (40 mm diameter)
- Stopwatch
- (Paper) adhesive tape



Teacher action	Pupil action
Remind the pupils that X-ray devices and some radioactive sources emit ionising radiation that can penetrate far into materials and tissues, causing damage. Explain the learning objectives of this activity. Explain that the dart gun represents a source of ionising radiation and that the dart is the radiation or particles emitted. The idea is to simulate how we can reduce the amount of radiation that will hit a person. Choose 1 pupil who will be the shooter, and 1 who will be the target.	(for each of the experiments) Both pupils will put on goggles (personal protective equipment – PPE is very important when working with radiation!) and the target should put on a Velcro vest. The shooter will shoot all the darts in the gun at the target to get as many darts on the Velcro vest as possible. Once all the darts have been fired, the other pupils can count the number of darts hit and note the result.
Distance experiment Explain that they are going to investigate what effect the distance between the source and the target will have. Measure and mark out a distance of 5 metres between the shooter and the target. Tell them that only the darts that end up on the Velcro vest count. Reorganise the setup to allow for reloading and re-shooting at a distance of 10 metres from the target. Ask the pupils to think about what happened to the number of 'rays' that hit the target when the distance was increased and how this observation could be used if one were really working with radioactive material. For a sufficient number of randomly shot darts, a correlation of inverse square can be observed. In this experiment, of course, the shooter is intelligent and will deliberately aim at the target. A degree of randomness can be introduced if the shooter is blindfolded.	
Time experiment If desired, a new shooter and a new target can be chosen. Explain that they will now examine the effect of exposure time. Tell the shooter they have 20 seconds to hit the target. Designate another pupil to operate the stopwatch and give a signal when the time is up. Reorganise the setup so that it can be reloaded and explain that the shooter will only get 10 seconds this time, and repeat the experiment. Ask the pupils what happened to the number of darts that hit the target when the exposure time was reduced and how this finding could be used when working with real radioactive materials.	

Shielding experiment If necessary, choose a new shooter and target. Explain that they are now going to investigate the effect of different types of shielding between the shooter and the target. Give the target the shield with the largest holes. Reorganise the setup so that it can be reloaded. Swap the shield for the one with medium holes (if available) and repeat the experiment. Finally, reorganise for reloading and swap the shield for the one with the smallest holes, and repeat the experiment. Ask the pupils what happened to the number of darts when different shielding was used. Ask what the different types of shielding represent.	
These demonstrations can be followed by an example/video of a real radioactive source shielded by different materials (e.g. a gamma source shielded with paper, aluminium and lead).	

The science

The three basic principles in radiological protection can be summarised as follows:

- **time** – the time in the vicinity of a radiation source should be minimised
- **distance** – the distance between the individual and the radiation source should be kept as great as possible
- **shielding** – an appropriate barrier should be placed between the individual and the radiation source

Minimising time in the presence of a radiation source is an obvious way to reduce exposure. However, a simple explanation of the physics about distance and shielding is shown below.

Distance to the source: the inverse squared law

Radioactive materials typically emit radiation in all directions. If the ionising radiation emitted is of the gamma radiation type, it can travel through air with little attenuation. Therefore, gamma radiation from high-activity sources can be measured from hundreds of metres away, and may pose an exposure risk to individuals close to the source. Note that the gamma sources used for detection exercises do not contain high activity and are therefore low-risk: they are barely detectable at more than a few metres distance.

The intensity of the radiation can be expected to decrease with increasing distance from the source. In many circumstances, the *geometry of a sphere* can be assumed, which makes it easy to determine the relationship between the intensity of the radiation (and thus dose rate) and the distance from the source. Geometry of a sphere means that a source can be considered a point in space, with no shape or volume. This assumption works well when the distance from the source is much greater than the dimensions of the source itself. Given that radiation is emitted in all directions, the intensity of the radiation at a certain distance will follow the *inverse square law*. This means that the intensity drops by inverse proportion to the square of the distance, or in other words if you keep twice as much distance from the source, the intensity will drop by a factor of $2^2 = 4$. If you triple the distance, the intensity will drop by a factor of 9, and so on.

At any distance r from the point source, the radiation will be scattered over an area of a sphere of $4\pi r^2$. If the rate of photon emission from the point source P is photons s^{-1}, and the intensity φ (the rate of photons passing through a surface perpendicular to the direction of photons) at a distance r is $\varphi = \frac{P}{4\pi r^2}$ where φ is expressed in photons m^{-2}. Alternatively, considering that for a given radiation source the rate of photon emission from a point source is proportional to the power emitted, P can be expressed in watts and φ in Wm^{-2}.

For the practical test with the dart gun, it should be observed that fewer darts hit the target when it is further away and are actually shot randomly rather than aimed. The inverse-square law should be followed approximately, such that it may be worthwhile to try this with a more proficient group. A degree of randomness in all directions can be simulated with the dart gun by giving the shooter a blindfold for hitting the target.

Shielding

For a (very) simplified version of how ionising radiation interacts with matter, and as an interactive session in the classroom, see, for example, P. Sapple (2015) and references [1]. Gamma rays are high-energy electromagnetic radiation arising from changes to the nucleus, with wavelengths comparable to the dimensions of the nucleus. Gamma ray interactions with matter are more complex than the simple Coulomb forces for charged particles. For gamma rays, there are three main processes by which the initial energy can be transferred, namely the *photoelectric effect*, *Compton scattering* and, for sufficiently energetic photons, *electron-positron pair production*. The relative importance of each process depends on the energy of the gamma rays and the material being irradiated.

These processes ultimately remove the photons from the initial gamma flux through a given material. Gamma rays are the most pervasive of the three types of radiation because their interaction with individual atoms has a low probability. The probability that a gamma photon will interact with an individual atom via a previously mentioned process is expressed by the *interaction cross-section*. The cross-section 's' is a surface dimension. One can imagine that each atom presents a disc-shaped region to the gamma flux – if the photon's trajectory crosses the disk, an interaction will occur. Of course, such a geometric way of thinking is not quite realistic given that these processes work quantum-mechanically with some degree of probability, rather than as classical collisions. But the model of the disc is a useful one. The cross section depends on the type of material and the energy of the incident photons. In general, atoms with a higher atomic mass (high Z) with large numbers of electrons will have a larger cross-section.

The simplest (macroscopic) situation that can be described mathematically is that of a uniform mono-energetic radiation beam incident upon a target (in this context, shielding). The intensity of the beam I after the radiation passes through a material with thickness x is given by the formula:

$$I = I_0 e^{-\mu x} \qquad (2)$$

Where I_0 represents the intensity of the radiation beam incident upon the shielding, and μ the *linear attenuation coefficient*. The linear attenuation coefficient is a specific property for a material and is ultimately related to s (i.e. the atomic properties of the material), and the mass density (higher density means more atoms with which to interact). Generally, a high-Z and high-density material such as lead will have a high μ value. As mentioned, the relative contributions of each of the interaction processes are energy-dependent, meaning that the total attenuation coefficient is defined by the photon energy.

The three forms of shielding described in the next section propose two different types of attenuation material, such as concrete and lead. The diameter of the holes represent s (smaller holes mean less penetration depth). The green (1) and yellow (2) shielding are of the same basic material because they have the same dimensions for the holes. The green version represents a denser shape of the material because it has fewer holes for the darts to pass through and more 'wood' to stop the darts. For example, concrete can be made in different densities by compacting the material. Different densities of concrete will have the same cross-section (same material), but different linear attenuation coefficients due to the different densities. The red shielding consists of different (less attenuating) material because it has larger holes to allow more darts (photons) to pass through.

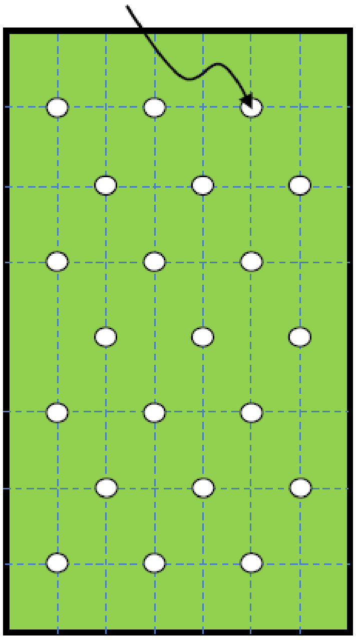
Different materials have different mass attenuation coefficients and this factor also changes with the energy of the radiation. The effect is simply that some materials will reduce radiation more than others and therefore represent better shielding. For example, 30 mm of lead will reduce gamma radiation from Cobalt-60 (a common radioactive source) by up to 50%, while 30 mm of steel will reduce the radiation by only 10%.
For the practical test with the dart guns, the material with the largest holes will have a given thickness of poor gamma shielding, such as aluminium. The material with the smallest holes represents a thicker version of the same material, or the same thickness of good gamma shielding, such as lead.

APPENDIX 1: Design of the shielding

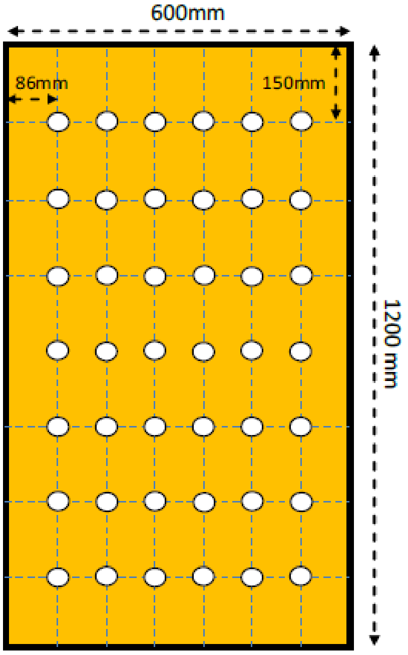
Small holes
Painted plywood
(40 mm diameter)

Large holes

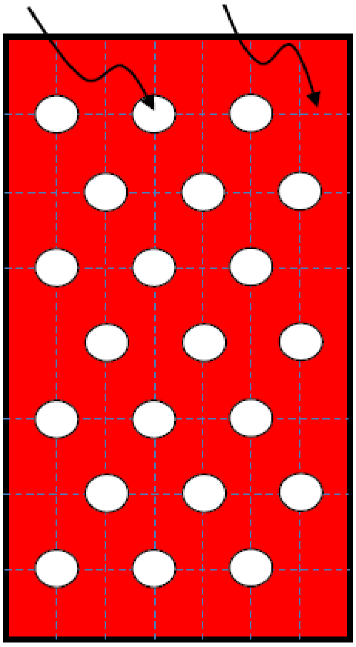
(80 mm diameter)



shielding A1 (factor 1)



shielding A2 (factor ½)



shielding A3 (factor ¼)

A comparison of A1 vs. A2 shielding demonstrates the 'physical density' (A2 has twice as many holes as A1 and all the holes are the same size, so A2 represents half as much shielding).
A comparison of A1 vs. A3 demonstrates the 'interaction cross-section' (A1 and A3 have the same number of holes, but A3's holes are twice as large in diameter, so they represent 4 times less shielding).
Experience shows that plywood proves to be an easy material to work with (in terms of drilling the holes).