Classroom Activity:

Basic Principles of Radiation Protection – for external sources

Teacher's Checklist

- **Target audience:** Secondary school students taking physics courses – hazards of radiation modules
- **Activity format:** Interactive whole-class activity to form part of a lesson or revision session
- **Nominal duration:** 30 minutes
- **Purpose:**
  - To visually illustrate the key principles used to reduce exposure to sources of ionising radiation external to the body (time, distance and shielding)
  - To illustrate the effect of changing time, distance and shielding on the radiation dose received
  - To provide a potential revision activity
  - To provide potential links between radiation and other parts of the science syllabus
  - To encourage students to think critically about the materials presented to them
  - To excite, enthuse and inspire students about the physics of radiation

- **Learning Objectives**

  By the end of this activity, students will be able to:
  - identify time, distance and shielding as the three key principles used to reduce exposure to sources of ionising radiation external to the body; and
  - explain the effect of changing time, distance and shielding on the radiation dose received

- **Equipment & Space Required**
  - A large enough free floor space to run the activity – a sports hall or similar space is most suitable
  - Repeat-firing foam-dart gun (ideally able to fire 15-20 darts without reloading) – e.g. Nerf Dart Tag Swarmfire or Quick 16
  - Foam darts with Velcro-tips e.g. Nerf Dart Tag
  - Velcro-vest
  - Safety goggles x 2
  - A hardboard or chipboard 'shield' with 21 x large (80mm diameter) holes* } Appendix 1
  - A hardboard or chipboard 'shield' with 42 x small (40mm diameter) holes (optional)* } Appendix 1
  - A hardboard or chipboard 'shield' with 21 x small (40mm diameter) holes* } Appendix 1
  - Stopwatch
  - Tape measure

Overview of Physics

The three key principles of radiation protection may be summarised as:

- Time – individuals to spend as short a time as is reasonably possible in the vicinity of the source of radiation
- Distance – individuals to stay as far away as reasonably possible from the source
- Shielding – an appropriate material barrier to be placed between the source and the individual

The minimising of time spent near sources of ionising radiation is an obvious way to limit one's exposure. However, a simple treatment of the physics relating to distance and shielding are developed here.

Distance to Source: the inverse square law

Radioactive materials generally emit randomly in all directions. If the ionising radiation emitted is gamma radiation, it travels through air with little attenuation, therefore for high activity sources the gamma radiation can be detected at distances of hundreds of meters and can therefore present an external exposure hazard for people located near to the source. Note that standard school gamma-emitting sources are not high activity, and so present far less of a hazard; they are barely detectable at much more than a few metres.

Intuitively, one might expect that the intensity of radiation will fall with distance from the source. Under many circumstances, a condition of *"spherical geometry"* can be assumed, which makes it easy to quantify the relationship between radiation intensity (and thus dose rate) and distance from source. Spherical geometry means that source can be treated as a point in space, with no shape or volume. This approximation works well when the distance to the source is much bigger than the source itself. As the radiation is emitted equally in all directions, the intensity of radiation at a particular distance will follow an *inverse-square law*. This means that the intensity falls in inverse proportion with the square of the distance i.e. if you move twice as far from the source, the intensity will drop by a factor of $2^2 = 4$. By tripling your distance, the intensity falls 9-fold, and so on.

At any distance r from the point source, the radiation will be spread over a spherical area of $4\pi r^2$. If the rate of photon emission from the point source is P photons s^{-1}, then the intensity ϕ (the rate of photons through an area perpendicular to the direction of the photons) at distance r is $\phi = \frac{P}{4\pi r^2}$ where ϕ is in photons m^{-2}. Alternatively, since for a particular radiation source the rate of photon emission from the point source is proportional to the power emitted, P can be in watts and ϕ in Wm^{-2}.

> For the dart-gun practical, it should be observed that fewer darts hit the target when it is further away and in fact, fired randomly spatially rather than aimed, the inverse-square should be approximately followed, which may be worth trying if with a higher ability group. A degree of randomness in directions of emission can be simulated by the dart gun, by having the shooter wear blackout goggles, while trying to hit the target.

Shielding

For a (very) simplified version of the treatment of how ionising radiations interact in matter, and an interactive classroom demonstration, see for example P. Sapple (2015) and references within [1]. Gamma rays are high energy electromagnetic radiation originating from nuclear transitions, with wavelengths comparable to nuclear dimensions. Gamma-ray interactions in matter are more complex than the simple Coulomb force process for charged particles. For gamma rays, there are three principle processes by which the initial energy can be transferred; namely *photoelectric absorption*, Compton scatter, and for sufficiently energetic photons, electron-positron pair production. The relative importance of each process depends upon the energy of gamma rays, and on the material being irradiated.

These processes ultimately remove photons from the incident gamma-ray flux through a given material. Gamma rays are the most penetrating of the three major radiations – as interaction with individual atoms is of very low probability. The probability of a gamma photon interacting with an individual atom via the aforementioned process is quantified by the *interaction cross section,* s. Cross-section has dimensions of [*length*]^2 i.e. it can interpreted as an area. One can imagine that each atom presents a given, disk-like area to the gamma-ray flux – if the trajectory of the photon intersects the disk, an interaction will happen. Of course, such a geometric way of thinking isn't totally realistic – as these processes are quantum-mechanical, probabilistic events, rather than classical collisions – but the disk picture is a useful one for modelling. The cross-section depends upon the type of material and the energy of the incident photons. Generally, high atomic mass (high-Z) atoms, with large numbers of electrons will have higher s.

The simplest (macroscopic) situation which can be described mathematically is that of a uniform, mono-energetic beam of radiation, incident on a target (i.e. in this context, a shield). The beam intensity *I* after the radiation has passed through a material of thickness *x* is given by the formula:

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

Where I_0 is beam intensity that is incident upon the shield, and μ is the *linear attenuation coefficient*. Linear attenuation coefficient is a material specific property, ultimately linked to s (i.e. the material's atomic properties), and the mass density (higher density means more target atoms along a given path). Generally, a high-*Z* and high-density material, like lead, will have a high m value. As mentioned, the relative contribution of each of the major attenuation processes is energy-dependent, meaning that the total attenuation coefficient is defined for given photon energy.

The three shields described in the next section represent two different types of attenuating material e.g. concrete and lead. The diameter of the holes represents s (smaller holes means less penetration). The green (1) and yellow (2) shields are the same basic material, because they have the same size holes. But the green more represents a more dense form of the material, because it has fewer holes to let darts through and more 'wood' to stop the darts. For example, concrete can be made to different density grades, by compaction of the material. Differing grades of concrete will have the same cross-section (same materials), but differing linear attenuation coefficients, owing to the differing densities. The red shield is a different (and less attenuating) material, because it has bigger holes to let more darts (photons) through.

Different materials have different mass attenuation factors and the factor also varies with radiation energy. However, the effect is simply that some materials will reduce the radiation more than others and therefore provide better shielding, for example 30 mm of lead will reduce the gamma radiation from Cobalt-60 (a common radioactive material found in nuclear power stations) by 50%, but 30 mm of steel will only reduce the radiation by 10%.

For the dart-gun practical, the shielding with the largest holes therefore represents a given thickness of a poor-gamma shield such as aluminium and the shielding with the smallest holes either represents a thicker amount of the same material or the same thickness of a good shielding material such as lead.

Activity

Teacher Actions	Learner Actions
Remind students that X-ray generators and some radioactive materials emit penetrating ionising radiation that will cause harm to the body. Explain the learning objectives of this activity. Explain that the dart-gun is going to represent the source of ionising radiation and the darts are the radiation. The idea is for the students to simulate how to reduce the amount of radiation hitting a person. Pick one student to be the shooter and one to be the target. **Distance experiment** Explain that they are going to investigate the effect of distance between the 'source' and the 'target'. Measure a point 5 m from the shooter for the target to stand. Explain only darts hitting the Velcro vest will count. Organise for the gun to be reloaded and measure a new distance of 10 meters from the shooter to target. Ask the students to consider what happened to the amount of 'radiation' hitting the target when the distance was increased, and how this finding might be used in real applications when working with radioactive materials. For a large enough number of darts fired randomly, an inverse-square law relationship should be observed. If course, in this activity the shooter is intelligent, and is likely to aim for the target. A degree of randomness could be introduced by having the shooter wear blackout goggles over their face protection.	Both students should put on safety glasses (Personal Protective Equipment PPE is very important when dealing with radiation!) and the 'target' should put on the Velcro vest. The shooter fires all the darts in the gun at the target, trying to get as many as possible to hit the Velcro vest. Once all the darts have fired, the rest of the students count the number of successful hits and record the result. 

Teacher Actions

Time experiment

If desired, pick new students to be the shooter and target.

Explain that they are now going to investigate the effect of the amount of time the target is exposed to the source.
Explain to the shooter that they will initially have 20 seconds to try and hit the target

Get another student to operate the stopwatch and shout stop when the time is up.

Organise for the gun to be reloaded and explain this time they will only have 10 seconds.
Repeat as before.

Ask the students to consider what happened to the amount of 'radiation' hitting the target when the exposure time was reduced, and how this finding might be used in real applications when working with radioactive materials.

Shielding experiment

If desired, pick new students to be the shooter and target.

Explain that they are now going to investigate the effect of different shielding between the shooter and target.
Provide the target with the shield with the biggest holes.

Organise for the gun to be reloaded. Switch the shield for one with medium holes (if available)
Repeat as before.

Finally, organise for the gun to be reloaded and switch the shield for one with the smallest holes.
Repeat as before.

Ask the students to consider what happened to the amount of 'radiation' hitting the target with the different shielding.
Ask what type of material the different shields might represent.

These demonstrations could be followed up with:

- example of a real radioactive source being shielded by different materials (e.g. a gamma emitter being shielded by paper, aluminium and then lead)

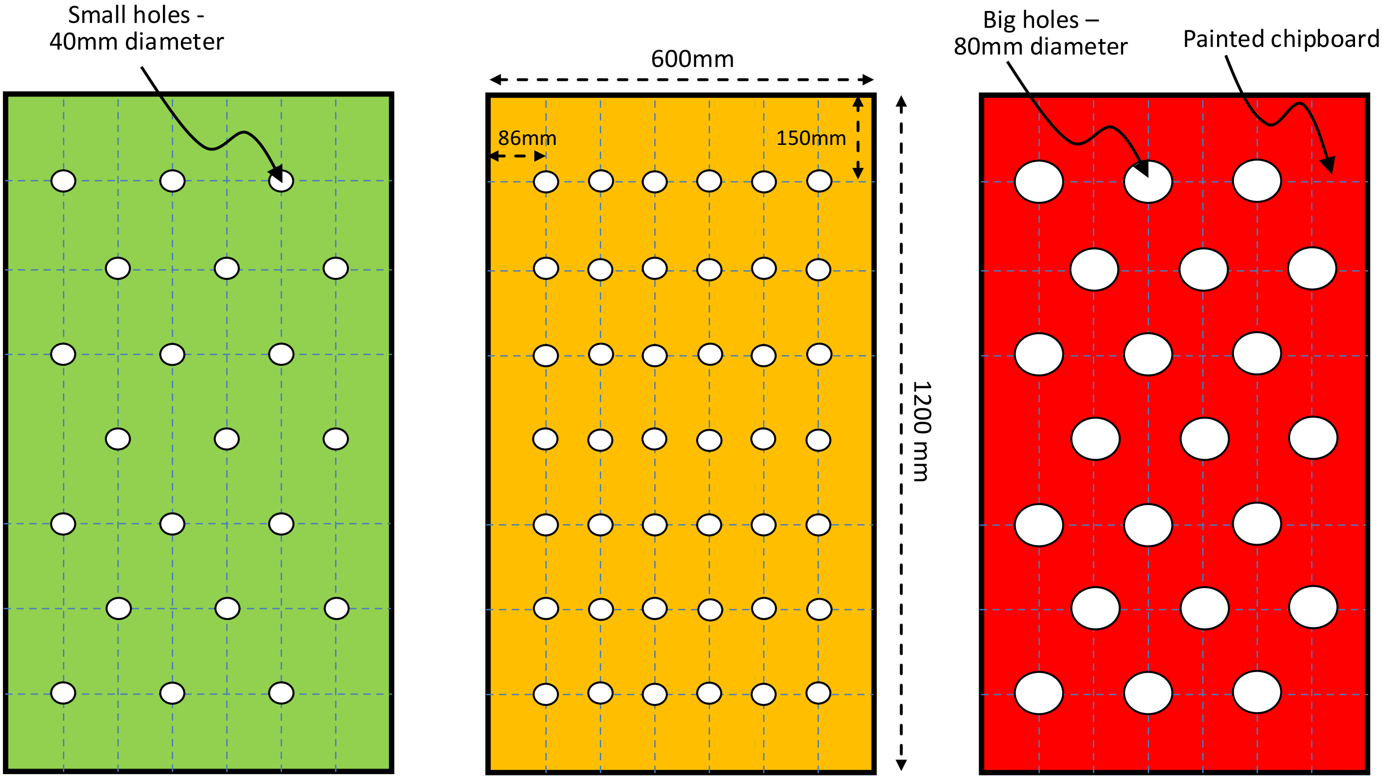
Learner Actions

Both students should put on safety glasses (Personal Protective Equipment PPE is very important when dealing with radiation!) and the 'target' should put on the Velcro vest.

The shooter fires all the darts in the gun at the target, trying to get as many as possible to hit the Velcro vest.

Once all the darts have fired, the rest of the students count the number of

APPENDIX 1: Shield Design



Shield No. 1 (factor 1)   Shield No. 2 (factor ½)   Shield No. 3 (factor ¼)

Comparison of No. 1 and No. 2 demonstrates 'physical density' (No. 2 has twice as many holes as No. 1 and all holes same size – thus No. 2 has half the shielding).

Comparison of No. 1 and No. 3 demonstrates 'interaction cross section' (No. 3 and No. 1 have same number of holes – but No. 3 holes are twice diameter and so 4 times less shielding).

It is worth noting that in the experience of those who've tested this activity, chipboard has proven to be an easy material to work with, in terms of drilling the holes.