*Physics > Big idea PMA: Matter > Topic PMA5: Nuclear physics*

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| **Key concept (age 14-16)** |
| **PMA5.2: Radioactive decay** |

**What’s the big idea?**

A big idea in physics is matter. Matter is a more formal word for ‘stuff’. Anything that can be stored in a container, or weighed, is matter. Scientific ideas can help to explain why a given material behaves as it does, and may help scientists to develop new materials with specific properties.

**How does this key concept develop understanding of the big idea?**

This key concept helps to develop the big idea by exploring the different reasons for alpha, beta and gamma radiation in order to help develop a mental model that can be used to begin to understand the random nature of radioactive decay.

The conceptual progression starts by checking understanding of the forces acting between nucleons in a nucleus. It then supports the development of an understanding of how these forces interact, in order to enable understanding of alpha decay and the emission of gamma radiation from an excited nucleus. A second learning progression introduces the understanding that neutrons are unstable away from the close proximity of protons, in order to understand the reasons for beta decay.



**Using the progression toolkit to support student learning**

Use diagnostic questions to identify quickly where your students are in their conceptual progression. Then decide how to best focus and sequence your teaching. Use further diagnostic questions and response activities to move student understanding forwards.

**Progression toolkit: Alpha decay**

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| **Learning focus** | Some large nuclei, which are unstable because they contain too many protons, decay spontaneously by alpha radiation because of repulsive forces between protons. | | | | |
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| **As students’ conceptual understanding progresses they can:** | **C o n c e p t u a l p r o g r e s s I o n** | | | | |
| Describe the effect of the electrostatic force within an atomic nucleus.  **P** | Interpret nuclear equations to describe the alpha decay of radioactive nuclei. | Describe what happens to an atom and its nucleus during an alpha decay. | Explain why large nuclei with too many protons emit alpha particles rather than protons.  **B** | Explain why a nucleus usually emits gamma radiation after an alpha decay. |
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| **Diagnostic questions** | Unstable nucleus | Alpha decay | Alpha decay story | Why alpha? | After alpha |
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| **Response**  **activities** |  |  | Explaining alpha decay | | Alpha and gamma |

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| Key: | | | |
| **P** | Prior understanding from earlier stages of learning | **B** | Bridge to later stages of learning |

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| **Unstable nucleus** | **Alpha decay** | **Alpha decay story** | **Why alpha?** | **After alpha** |
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| Two-tier multiple choice | Confidence grid | Explanation story | Multiple choice | Simple multiple choice |
| **Explaining alpha decay** | **Alpha and gamma** |  |  |  |
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| Linking ideas | Talking heads |  |  |  |

**Progression toolkit: Beta decay**

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| **Learning focus** | Some nuclei, which are unstable because they have too many neutrons, decay spontaneously by beta radiation  because neutrons are unstable away from the close proximity of protons. | | | | |
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| **As students’ conceptual understanding progresses they can:** | **C o n c e p t u a l p r o g r e s s I o n** | | | | |
| Restate, in own words, the reasons why a nucleus cannot be made of just neutrons. | Interpret nuclear equations to describe the beta decay of radioactive nuclei. | Describe what happens to an atom and its nucleus during a beta decay. | Explain why a nucleus can often emit gamma radiation after a beta decay. | Explain why the chances of beta decay increase with the proportion of neutrons to protons in a nucleus.  **B** |
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| **Diagnostic questions** | Differently unstable | Beta decay | Beta origin | After beta | Neutron rich |
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| **Response**  **activities** |  |  | Beta decay story | | The chances of beta |

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| Key: | | |
| **B** | Bridge to later stages of learning |

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| **Differently unstable** | **Beta decay** | **Beta origin** | **After beta** | **Neutron rich** |
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| Two tier multiple choice | Confidence grid | Simple multiple choice | Simple multiple choice | Simple multiple choice |
| **Beta decay story** | **The chances of beta** |  |  |  |
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| Explanation story | Talking heads |  |  |  |

**What’s the science story?**

A stable nucleus does not change over time. Smaller atoms that are stable have approximately the same number of protons as neutrons; larger stable atoms have more neutrons than protons.

(In a nucleus, protons repel each other with an electrostatic force and attract each other, and neutrons, with the *strong nuclear force*. Neutrons attract both neutrons and protons with the *strong nuclear force*. Neutrons help hold protons together in a nucleus; and by moving protons further apart, reduce the electrostatic forces pushing protons apart. On their own, neutrons quickly decay into protons and electrons.)

An unstable nucleus may spontaneously change into a more stable nucleus by emitting radiation in the form of a particle or a gamma photon. This is a random event that is not affected by a chemical reaction. A substance that contains atoms with unstable nuclei is radioactive. Some isotopes of an element may be stable and others may be radioactive.

Activity is the rate at which a source of unstable nuclei decays. It is measured as the number of decays each second, in Becquerel (Bq).

Alpha-decay

* Alpha-particles (α) are often emitted by unstable nuclei that are very large.
* An alpha-particle comprises of two protons and two neutrons. This is the same as the nucleus of a helium atom, however an alpha particle is emitted from an unstable nucleus at a very high speed (in the order of twenty million metres per second).
* The nuclear equation for alpha decay can be represented as:

Beta-decay

* Beta-particles (β) are often emitted by unstable nuclei that have too many neutrons. During beta-decay a neutron changes into a proton and a beta-particle.
* A beta-particle is a single electron. It differs from electrons in an atom in that it is emitted from an unstable nucleus at an extremely high speed (in the order of two hundred million metres per second).
* The nuclear equation for beta decay can be represented as:

Gamma emission

* A gamma photon (ν) is a very high frequency electromagnetic radiation.
* Following an alpha- or beta-decay, protons and neutrons in the remaining (daughter) nucleus may not be in their most stable arrangement. In order for them to move into a more stable arrangement, a gamma photon is emitted to transfer energy away from the nucleus, with no change to the type of particles in the nucleus.
* The nuclear equation for gamma emission can be represented as:

**Earlier development of understanding (BEST 11-14)**

When applying their understanding to novel situations, students of all ages often revert to earlier misunderstandings. Before moving forward, it is worthwhile using diagnostic questions from earlier topics to check that students do not have any persistent misunderstandings that can form barriers to learning. Time spent consolidating the scientific understanding of earlier key concepts before moving forward can accelerate progression later.

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| **Key concept CPS6.1: Atomic model**  **Learning focus:** The structure of an atom may be represented by an atomic model.  This key concept:   * Introduces subatomic structure of a basic atomic model. * Develops an understanding of the properties of key parts, and the scale, of the atom. * Compares two models of atom used in chemistry. |

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| **Key concept CPS7.1: Metallic bonding**  **Learning focus:** A model of metallic structure, made up of positive metal ions surrounded by ‘free’ outer electrons, can explain some properties of metals.  This key concept:   * Consolidates understanding of the electron shell model of an atom. * Develops an understanding that an electron shell diagram is a model and not a copy of reality. * Develops this understanding to explain metallic structure and bonding. |

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| **Key concept PEM4.1: Moving charge**  **Learning focus:** Around every particle or object with an electric charge there is a region of space called an electric field, with which every other particle or object with an electric charge will interact and cause both to experience a force.  This key concept:   * Consolidates understanding that electrostatic forces act at a distance around an electric charge. * Develops an understanding of an electric field and the effect it has on charged particles. * Develops this understanding to explain how a battery causes current to flow around a complete circuit. |

**What does the research say?**

Before learning about radioactive decay, it is important for students to have a secure understanding of atomic and nuclear structure, and to have some understanding of isotopes and about what makes some nuclei stable and others unstable and radioactive (Brock, Manning and Walsh, 2021). This is because students’ reasoning difficulties about radioactive decay often stem from their inaccurate mental models about the atom (Prather, 2005). These ideas are explored in the BEST key concept: *PMA5.1 Atomic nuclei*.

Ideas about why some nuclei are stable and others unstable, are useful for explaining, in simple terms, the processes of radioactive decay and why radioactive decay is random. At ages 14-16, students are rarely taught about these ideas or that the causes of alpha, beta and gamma radiation are each different. By thinking about the mechanisms behind each of these types of radioactive decay, this key concept is designed to support the development of useful mental models that can help challenge students’ misunderstandings about radioactive decay and clarify gaps in understanding that could otherwise lead to some confusion or uncertainty.

Key to understanding the reasons for alpha decay, is an understanding of the repulsive electrostatic forces between protons in a nucleus. However, amongst students age 13-18, the level of awareness is low that an electrostatic force attracts electrons to a nucleus and causes electrons around a nucleus, or protons within a nucleus, to repel each other (Harrison and Treagust, 1996; Tabor, 2013). In his study, Taber (2013) found that it was more common for students aged 15-18 (N=105) to think instead, that gravity or magnetism attracts electrons towards a nucleus. These findings suggest it is likely that many students think about atomic structure in isolation from their thinking about electrostatic forces and need support to defragment their understanding of each concept.

During alpha decay, the nucleus of the radioactive atom loses two protons and two neutrons and therefore becomes an atom of a different element. Similarly, in beta decay, a neutron in the nucleus decays into a proton and a high-speed electron, which is emitted from the nucleus, leaving an atom of a different element. In both cases, the valence electrons around the nucleus will be affected indirectly because after radioactive decay the proton number of the atom is changed. However, the actual process of radioactive decay involves just the nucleus; and all alpha and beta particles originate from a nucleus and account for a very small fraction of its mass.

This does not appear to be understood by the majority of students. In a study in the USA, Prather (2005) found that just 26% of high school students (n=19) and 33% of first year undergraduate students, who were non-science majors studying physics (n=258), thought that radioactive decay involved just the nucleus of an atom. In the case of beta-decay, he found that it was common for them to think that electron emitted was one of the valence electrons.

Prather (2005) also found that, even after tuition, 59% of the undergraduates believed that the mass or volume of a radioactive substance reduced by half after one half-life, when half the substance had decayed. This outcome is suggestive that the language used to describe what is happening: ‘half of it has decayed’ and ‘half-life’ is taken literally by students; which in turn suggests that many students do not have a clear mental model of radioactive decay that they can draw on.

When discussing radioactive decay, it is important to make a clear distinction between a radioactive particle and radiation. These two terms are commonly mixed up and this can lead to the forming of misunderstanding (Plotz, 2017). A radioactive atom is unstable and may undergo radioactive decay, and emit radiation. Alpha and beta particles are types of radiation. They are not radioactive because they are both stable particles and do not undergo radioactive decay.

**Guidance notes**

*Nuclear equations*

An atom can be represented as , where: X is the atomic symbol; Z is the atomic number, equal to the number of protons (and equal to the number of electrons); and A is the mass number, equal to the total number of protons *and* neutrons in a nucleus of the atom. The mass number is also called the nucleon number.

N.B. ***The mass number of an atom is not the same as atomic mass.***

The atomic mass of an element is the average mass of all the different isotopes of the element when their relative abundances are accounted for. The atomic mass of each element is given on a periodic table, and mass numbers are not.

In a nuclear equation, sub-atomic particles can be represented in a very similar way as , where: X is the atomic symbol of a nucleus *or* the symbol of a particle; Z is the charge number, equal to the charge relative to that of a proton (-1 for an electron); and A is the mass number that is equal to the total number of protons *and* neutrons.

*Random decay*

The idea that radioactive decay is a random process and cannot be altered by chemical reactions is touched upon in this key concept, and is explored more thoroughly in the BEST key concept PMA5.4: Radio-active half-life.

*Alpha decay*

Alpha decay is most likely in large nuclei that are have a greater proportion of protons to neutrons than is found in similar sized nuclei that are stable. The larger number of protons increase the repulsive force between them and makes it more likely that the nucleus will be forced apart.

The seemingly logical outcome to this is for the nucleus to push out protons one by one until it is stable, but instead alpha particles, comprising of two protons and two neutrons, are forced out. The reasons for this are that: the repulsive force on the two protons in an alpha particle is twice as big as the repulsive force on a single proton because they have twice the charge; the strong nuclear force holds a combination of two protons and two neutrons together very tightly; and the force on an alpha particle that is needed to emit it is reached before the force on a single proton, that is needed to emit it, is reached.

*Beta decay*

Beta decay (strictly beta-minus decay) is most likely in nuclei that contain a greater proportion of neutrons to protons than is found in similar sized nuclei that are stable. On its own, a neutron has about a fifty-fifty chance of decaying into a proton and an electron inside the next ten minutes, but in close proximity to protons they are much more stable.

Within a stable atomic nucleus, neutrons are in close proximity to protons and are stable. However, the greater the proportion of neutrons to protons, the further neutrons are, on average, to protons and the less stable they become.

*Gamma decay*

Alpha and beta particles are emitted from a nucleus at very high speeds: in the order of 10s of millions of metres per second for alpha; and up to close to the speed of light for beta. Radioactive decay often leaves a nucleus in an agitated state due to the recoil from the emitted particle and typically the nucleus emits a gamma photon in order to transfer away its excess energy.

**References**

Brock, R., Manning, A. and Walsh, K. (2021). Atomic physics. In de Winter, J. & Hardman, M. (eds.) *Teaching Secondary Physics.* 3rd ed. London: Hodder Education.

Harrison, A. G. and Treagust, D. F. (1996). Secondary students' mental models of atoms and moelcules: Implications for teaching chemistry. *Science Education,* 80(5)**,** 509-534.

Plotz, T. (2017). Students' conceptions of radiation and what to do about them. *Physics Education,* 52(1)**,** 014004.

Prather, E. (2005). Students' beliefs about the role of atoms in radioactive decay and half-life. *Journal of Geoscience Education,* 53(4)**,** 345-354.

Tabor, K. S. (2013). Upper secondary students' understanding of the basic physical interactions in analogous atomic and solar system models. *Research in Science Education,* 43**,** 1377-1406.