A2 Level Physics

Chapter 2 – Particles and radiation

2.2.2 The Nuclear Atom

Worked Examples

The Nuclear Atom

Exam Style Question 1

(a) Describe how the strong nuclear force between two nucleons varies with the separation of the nucleons quoting suitable values for separation.

(b) An unstable nucleus can decay by the emission of an alpha particle.

(i) State the nature of an alpha particle.

(ii) Complete the equation below to represent the emission of an α particle by a ${}^{238}_{92}U$ nucleus.

(c) ${}^{238}_{92}U$ decays in stages by emitting α particles and β^- particles, eventually forming ${}^{206}_{82}Pb$, a stable isotope of lead.

(i) State what is meant by isotopes.

(ii) If there are eight alpha decays involved in the sequence of decays from ${}^{238}_{92}U$ to ${}^{206}_{82}Pb$ deduce how many β^- decays are involved.

The Nuclear Atom

Exam Style Question 1

(a)Describe how the strong nuclear force between two nucleons varies with the separation of the nucleons quoting suitable values for separation.

- **It has a very short range**

It does not extend much beyond adjacent nucleons and so has no effect outside the nucleus (i.e. $F_S \approx 0$ at separations $(r) > about\ 5.0 \times 10^{-15} m$).

- **It is independent of charge**

So it acts between all nucleons (i.e. proton-proton, proton-neutron and neutron-neutron).

- **It is attractive**

Until the separation (r) becomes $< about\ 2.0 \times 10^{-15} m$.
And then it becomes increasingly repulsive. Otherwise the nucleons would collapse in on themselves.

(b) (i) State the nature of an alpha particle.
A helium nucleus.

(b) (ii) Complete the equation below to represent the emission of an α particle by a ${}^{238}_{92}U$ nucleus.

$$ {}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha $$

(c) (i) State what is meant by isotopes.
Same atomic number (or proton number) different number of neutrons.

(c) (ii) If there are eight alpha decays involved in the sequence of decays from ${}^{238}_{92}U$ to ${}^{206}_{82}Pb$ deduce how many β^- decays are involved.

$$ {}^{238}_{92}U \rightarrow {}^{206}_{82}Pb + 8\ {}^{4}_{2}\alpha $$

The nucleon number on the RHS is 238 and this is the same as the nucleon number on the LHS. However, the LHS proton number is just 92, while the proton number on the RHS is 98. Therefore, if each beta particle removes one proton, we need six beta decays.
The answer is therefore 6 beta decays.

The Nuclear Atom

Exam Style Question 2

(a) Explain how the experiments on the scattering of alpha-particles by a metal foil provided evidence for the nuclear model of the atom.

(b) Fig. 5.1 shows an alpha-particle $\left({}^{4}_{2}He\right)$ of kinetic energy $8.0\ MeV$ moving directly towards a nucleus of aluminium-27 $\left({}^{27}_{13}Al\right)$, initially at rest.

Fig. 5.1

(i) The alpha-particle comes to rest instantaneously a short distance away from the aluminium nucleus. It then reverses its direction of travel. Describe and explain the motion of the aluminium nucleus at the instant the alpha-particle is at rest.

(ii) Calculate the initial speed of the alpha-particle.
$mass\ of\ alpha - particle\ =\ 6.6\ \times\ 10^{-27}\ kg$

(iii) The electric force experienced by the alpha-particle when it is close to the aluminium nucleus is $270\ N$. Calculate the separation r between the alpha-particle and the aluminium nucleus when the alpha-particle experiences this force.

(iv) Consider the situation where the alpha-particle travels much closer to the aluminium nucleus than in $(b)(iii)$.

Discuss how the strong nuclear force may affect the resultant force on the alpha-particle

The Nuclear Atom

Exam Style Question 2

(a)Explain how the experiments on the scattering of alpha-particles by a metal foil provided evidence for the nuclear model of the atom.

Observations:
1) Most of the alpha particles went straight through the foil.
2) Some of the alpha particles were scattered through large angles.

Conclusions:
Observation 1 shows that most of the atom is empty space and
Observation 2 showed the existence of small dense positive nucleus.

(b) (i) Describe and explain the motion of the aluminium nucleus at the instant the alpha-particle is at rest.

The aluminium nucleus moves to the right away from the alpha particle. There is a repulsive force on the aluminium nucleus to the right and according to the conservation of momentum the aluminium nucleus must move to the right.

(b) (ii) Calculate the initial speed of the alpha-particle.

$$KE = 8.0\ MeV = 8.0 \times 10^{6} \times 1.6 \times 10^{-19} = 1.28 \times 10^{-12}\ J$$

$$1.28 \times 10^{-12}\ J = \frac{1}{2} \times 6.6 \times 10^{-27}\ kg \times v^{2}$$

$$v = \sqrt{\frac{1.28 \times 10^{-12}\ J}{\frac{1}{2} \times 6.6 \times 10^{-27}\ kg}} = 1.97 \times 10^{7}\ m\ s^{-1}\ (3\ s.f.)$$

The Nuclear Atom

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(ii) Calculate the initial speed of the alpha-particle.
$mass\ of\ alpha-particle = 6.6 \times 10^{-27}\ kg$

(iii) The electric force experienced by the alpha-particle when it is close to the aluminium nucleus is 270 N. Calculate the separation r between the alpha-particle and the aluminium nucleus when the alpha-particle experiences this force.

(iv) Consider the situation where the alpha-particle travels much closer to the aluminium nucleus than in $(b)(iii)$.

Discuss how the strong nuclear force may affect the resultant force on the alpha-particle

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The Nuclear Atom

Exam Style Question 2

(b) (iii) Calculate the separation r between the alpha-particle and the aluminium nucleus when the alpha-particle experiences this force.

Use $F = \frac{Qq}{4\pi\varepsilon_0 r^2}$ and rearrange for r:

$$r = \sqrt{\frac{Qq}{F\ 4\pi\varepsilon_0}}$$

$$Q = Charge\ on\ Al = 13e = 13 \times 1.6 \times 10^{-19}\ C$$

$$Q = 2.08 \times 10^{-18}\ C$$

$$q = charge\ on\ alpha-particle = 2e = 2 \times 1.6 \times 10^{-19}\ C$$

$$q = 3.2 \times 10^{-19}\ C$$

$$\therefore r = \sqrt{\frac{(2.08 \times 10^{-18}\ C)(3.2 \times 10^{-19}\ C)}{(270\ N)(4\pi)(8.85 \times 10^{-12}\ F\ m^{-1})}}$$

$$r = 4.7 \times 10^{-15}\ m\ (2\ s.f.)$$

(iv) Discuss how the strong nuclear force may affect the resultant force on the alpha-particle.

The strong force is attractive and pulls the alpha particle towards the Al particle.

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Exam Style Question 3

An alpha particle is fired at high speed directly towards a stationary nucleus of a gold atom. At its distance of closest approach to the gold nucleus, the alpha particle stops and the gold nucleus has a small velocity, see Fig. 4.1. The alpha particle and the gold nucleus both have positive charges.

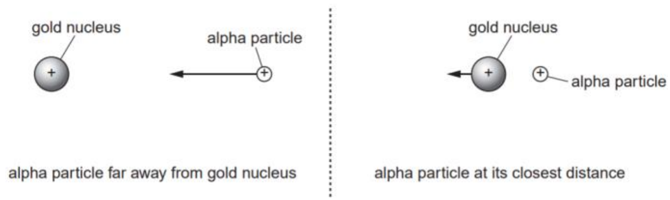

Fig. 4.1

(a) Explain why, at this distance of closest approach, the gold nucleus has a velocity and the alpha particle does not.

(b) Fig. 4.2, shows the alpha particle at its closest distance to the gold nucleus. Draw one electric field line from point A and one from point B. For each field line, show the direction of the field.

Fig. 4.2

The Nuclear Atom

Exam Style Question 3

(c) Show that the electrical force experienced by the alpha particle at its closest distance of $6.0 \times 10^{-14}\ m$ to the gold nucleus is about $10\ N$.

The gold nucleus has $79\ protons$ and the alpha particle has $2\ protons$.

(d) On Fig. 4.3, sketch a graph to show the variation of the electrical force F on the alpha particle with distance r from the centre of the gold nucleus. The value of F at the distance of closest approach has been marked on the graph.

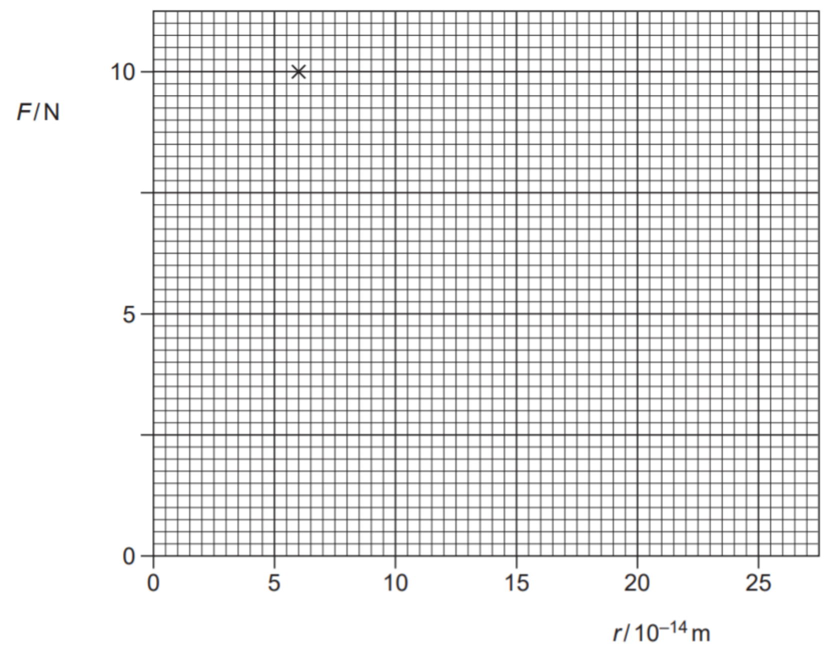

Fig. 4.3

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The Nuclear Atom

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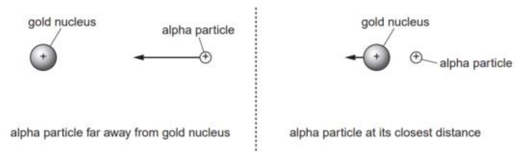

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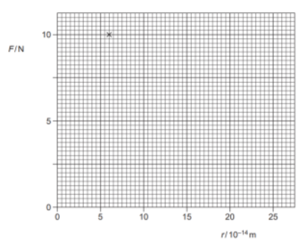

Fig. 4.3

The Nuclear Atom

Exam Style Question 3

(a) Explain why, at this distance of closest approach, the gold nucleus has a velocity and the alpha particle does not.

There is a repulsive electrical force between the gold nucleus and the alpha particle.

Momentum is conserved because there are no external forces therefore initial momentum of alpha particle = final momentum of gold nucleus.

KE of alpha particle transformed into electrical PE.

(b) Draw one electric field line from point A and one from point B. For each field line, show the direction of the field.

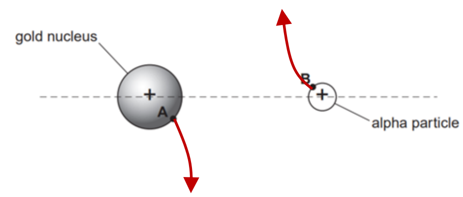

Fig. 4.2

(c) Show that the electrical force experienced by the alpha particle at its closest distance of $6.0 \times 10^{-14}\ m$ to the gold nucleus is about $10\ N$.

Use $F = \frac{Qq}{4\pi\varepsilon_0 r^2}$

$Q = gold\ nucleus\ charge = 79e$ and $q = charge\ of\ alpha\ particle = 2e$

$$F = \frac{(79 \times 1.60 \times 10^{-19}\ C)(2 \times 1.60 \times 10^{-19}\ C)}{4\pi(8.85 \times 10^{-12}\ F\ m^{-1})(6.0 \times 10^{-14}\ m)^2}$$
$$F = 10.1\ N\ (1\ d.p.)$$

The Nuclear Atom

Exam Style Question 3

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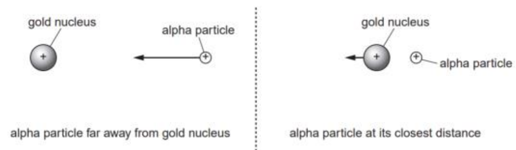

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The gold nucleus has 79 $protons$ and the alpha particle has 2 $protons$.

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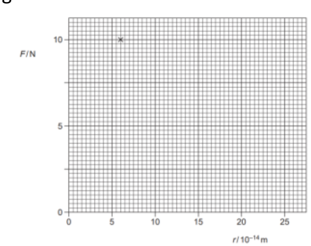

Fig. 4.3

The Nuclear Atom

Exam Style Question 3

(d) On Fig. 4.3, sketch a graph to show the variation of the electrical force F on the alpha particle with distance r from the centre of the gold nucleus. The value of F at the distance of closest approach has been marked on the graph.

We know that $F \propto \frac{1}{r^2}$ and therefore follows the inverse square law. So:

$$F = \frac{k}{r^2}$$

Rearrange for k and pick values for F and r to calculate k. There is the value of F at the distance of closet approach already marked on the graph for you so use those values for F and r to calculate k.

$$k = F\,r^2 = (10.1\ N)(6.0 \times 10^{-14})^2$$

$$k = 3.636 \times 10^{-26}$$

$$F = \frac{3.636 \times 10^{-26}}{r^2}$$

Now pick different values for r from the graph and start to plot them.

$$F = \frac{3.636 \times 10^{-26}}{(10 \times 10^{-14}\ m)^2} = 3.636\ N$$

$$F = \frac{3.636 \times 10^{-26}}{(15 \times 10^{-14}\ m)^2} = 1.616\ N$$

$$F = \frac{3.636 \times 10^{-26}}{(20 \times 10^{-14}\ m)^2} = 0.909\ N$$

$$F = \frac{3.636 \times 10^{-26}}{(25 \times 10^{-14}\ m)^2} = 0.58176\ N$$

Graph on the next page.

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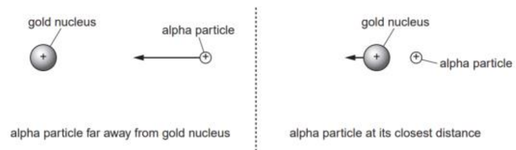

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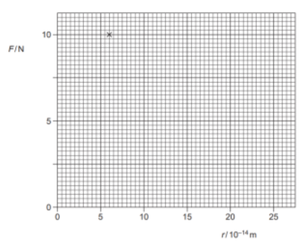

Fig. 4.3

The Nuclear Atom

Exam Style Question 3

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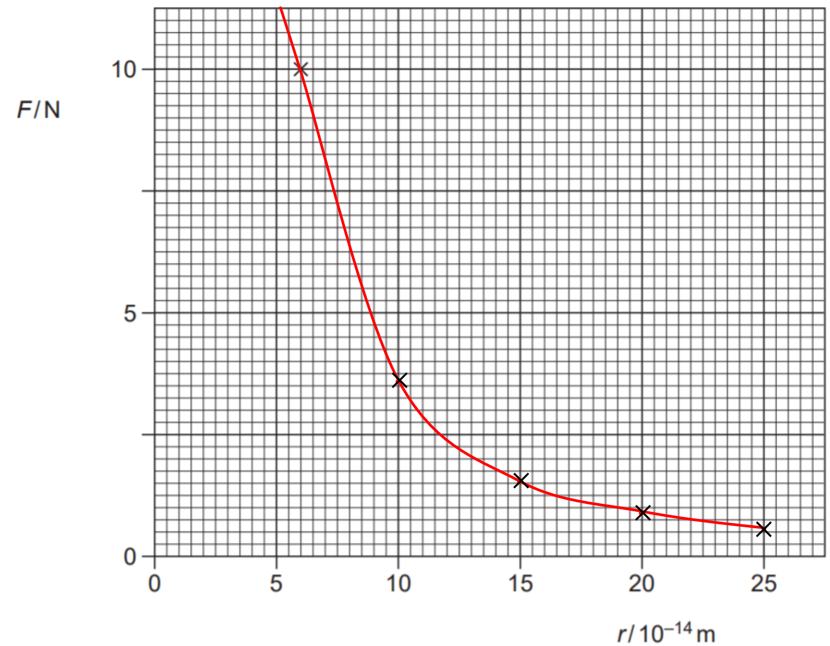

Fig. 4.3

The Nuclear Atom

Exam Style Question 4

(a) In experiments carried out to determine the nature of atoms, alpha particles were fired at thin metal foils. Describe how the alpha-particle scattering experiments provide evidence for the existence, charge and size of the nucleus.

(b) Describe the nature and range of the three forces acting on the protons and neutrons in the nucleus.

(c) The radius of a ${}^{235}_{92}U$ nucleus is $8.8 \times 10^{-15}\ m$. The average mass of a nucleon is $1.7 \times 10^{-27}\ kg$.

(i) Estimate the average density of this nucleus.

(ii) State one assumption made in your calculation.

The Nuclear Atom

Exam Style Question 4

(a) Describe how the alpha-particle scattering experiments provide evidence for the existence, charge and size of the nucleus.

- Most of the alpha particles went straight through some deviated through small angles. Hence most of the atom is empty space.
- Some alpha particles were repelled through large angles. This showed the existence of a tiny positive nucleus.

(b) Describe the nature and range of the three forces acting on the protons and neutrons in the nucleus.

1) Gravitational force

This force is attractive and is long ranged and obeys the inverse square law with distance $\left(\frac{1}{r^2}\right)$.

2) Strong nuclear force

This force is attractive at larger distances or repulsive at short distances.

3) Electrostatic force

This force is repulsive between protons and zero between neutrons and protons and neutrons.

Long ranged and obeys the inverse square law with distance $\left(\frac{1}{r^2}\right)$.

(c) (i) Estimate the average density of this nucleus.

Use $density = \frac{mass}{volume}$

$$mass = 235 \times 1.7 \times 10^{-27}\ kg = 3.995 \times 10^{-25}\ kg$$

$$volume_{sphere} = \frac{4}{3}\pi r^3$$

$$Volume_{sphere} = \frac{4}{3}\pi\left(8.8 \times 10^{-15}\right)^3 = 2.8545 \ldots \times 10^{-42}\ m^3$$

$$density = \frac{3.995 \times 10^{-25}\ kg}{2.8545 \ldots \times 10^{-42}\ m^3} = 1.4 \times 10^{17}\ kg\ m^{-3}\ (1\ d.p.)$$

The Nuclear Atom

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Exam Style Question 4

(c) (ii) State one assumption made in your calculation.
The nucleons are packed together with little or no empty space.

Please see '2.2.1 The Nuclear Atom notes' pack for revision notes.

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