Teacher notes
Topic E

Why do nuclei emit alpha particles?

We know that alpha decay is a common decay for heavy nuclei. But why does this happen for heavy unstable nuclei and why are alpha particles and not *other* combinations of protons and neutrons emitted as well?

These are questions asked by alert students, so what do we say?

Alpha decay does happen for heavy nuclei with the notable exception of beryllium that decays into 2 alpha particles: ${}^{8}_{4}\text{Be} \to {}^{4}_{2}\text{He} + {}^{4}_{2}\text{He}$. How can we understand that alpha decay occurs predominantly for heavy nuclei? Consider the alpha decay: ${}^{A}_{Z}\text{X} \to {}^{4}_{2}\text{He} + {}^{A-4}_{Z-2}\text{Y}$. The energy released is given in terms of binding energies by (in obvious notation, $B(Z,A)$ is the binding energy of a nuclide with proton number *Z* and nucleon number *A*)

$$Q = B(2,4) + B(Z-2, A-4) - B(Z,A)$$

The decay is possible if $Q > 0$, i.e. $B(2,4) > B(Z,A) - B(Z-2, A-4)$.

Now,

$$\frac{dB}{dA} \approx \frac{\Delta B(Z,A)}{\Delta A} = \frac{B(Z,A) - B(Z,A-4)}{4} \approx \frac{B(Z,A) - B(Z-2,A-4)}{4}$$

And so

$$B(2,4) > 4\frac{dB}{dA}$$

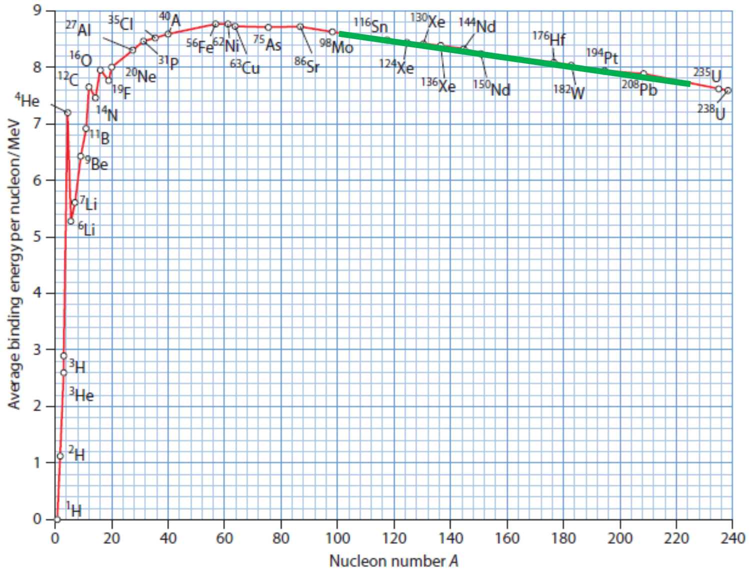
The binding energy curve plots *b* = *B*/*A* so

$\dfrac{d(B/A)}{dA} = \dfrac{\frac{dB}{dA}A - B}{A^2} = \dfrac{1}{A}\dfrac{dB}{dA} - \dfrac{B}{A^2}$ by the quotient rule and so $\dfrac{dB}{dA} = A\dfrac{db}{dA} + b$. (Lower case *b* is binding energy per nucleon.)

So, we need to satisfy:

$B(2,4)>4\left(A\frac{db}{dA}+b\right)$ The binding energy of helium is about 28 MeV and so we need $28>4\left(A\frac{db}{dA}+b\right)$ or

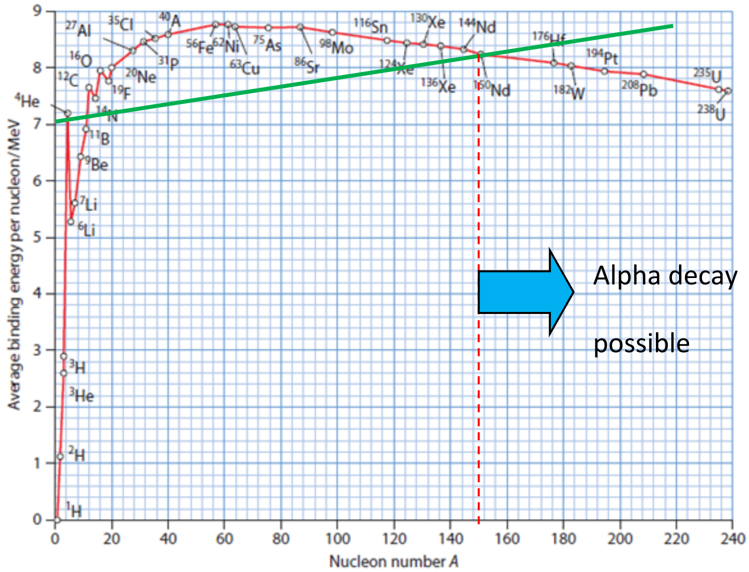
$7>A\frac{db}{dA}+b$.



Above A = 100, $\frac{db}{dA}\approx -8\times 10^{-3}$ MeV ($\frac{db}{dA}$ is the gradient of green line above and equals

$\frac{db}{dA}=\frac{7.6-8.6}{125}\approx -8\times 10^{-3}$ MeV).

So, $7>-8\times 10^{-3}A+b$. The critical case is $b=7+8\times 10^{-3}A$. This is a straight line on the binding energy graph:



It intersects the binding energy graph at about A = 150.

This explains why nuclei that decay by alpha decay are heavy nuclei (A > 150).

We now come to the second question: why are alpha particles emitted and not other combinations of protons and neutrons? The answer is that nuclei *do emit* other combinations! One example is ${}^{222}_{88}\mathrm{Ra} \rightarrow {}^{14}_{6}\mathrm{C} + {}^{208}_{82}\mathrm{Pb}$. In this decay, a combination of 6 protons and 8 neutrons is emitted, a nucleus of a carbon isotope. However, this only happens very rarely compared to alpha emission: for the example above, ${}^{222}_{88}\mathrm{Ra}$ is more than 10^{10} times more likely to decay by alpha decay than by carbon decay. (Another example is ${}^{238}_{94}\mathrm{Pu} \rightarrow {}^{32}_{14}\mathrm{Si} + {}^{206}_{80}\mathrm{Hg}$; this is 10^{16} times less likely to occur than alpha decay.)

The reason for this is a combination of the high binding energy of helium (28 MeV) which keeps the 4 nucleons firmly together and the low mass of the alpha particle. The mass enters in an interesting way. The alpha particle is not free to escape from the nucleus because its kinetic energy is less than the combined potential energy due to electric and strong nuclear forces. The particle manages to escape by exploiting a quantum mechanical phenomenon known as tunnelling. The particle goes through the barrier not over it! Now, the probability of tunnelling is **very strongly** dependent on mass; the lower the mass the higher the probability of transmission through the barrier.

This explains why alpha particle emission is common, but emissions of heavier combinations of protons and neutrons are not.