Nuclear reactions that transform atomic nuclei alter their identity and spontaneously emit radiation via processes of radioactive decay.

Types of Nuclear Decay

In 1889, Ernest Rutherford recognized and named two modes of radioactive decay, showing the occurrence of both processes in a decaying sample of natural uranium and its daughters. Rutherford named these types of radiation based on their penetrating power: heavier alpha and lighter beta radiation. Gamma rays, a third type of radiation, were discovered by P. Villard in 1900 but weren't recognized as electromagnetic radiation until 1914. Since gamma radiation is only the discharge of a high-energy photon from an over-excited nucleus, it does not change the identity of the atom from which it originates and therefore will not be discussed in depth here.

Because nuclear reactions involve the breaking of very powerful intra nuclear bonds, massive amounts of energy can be released. At such high energy levels, the matter can be converted directly to energy according to Einstein's famous Mass-Energy relationship $E = mc^2$. The sum of mass and energy are conserved in nuclear decay. The free energy of any spontaneous reaction must be negative according to thermodynamics ($\Delta G < 0$), and $\Delta G$ is essentially equal to the energy change $\Delta E$ of nuclear reactions because $\Delta E$ is so massive. Therefore, a nuclear reaction will occur spontaneously when:

$$\Delta E = \Delta mc^2 < 0$$

$$\Delta E < 0 \text{ or } \Delta m < 0$$

When the mass of the products of a nuclear reaction weigh less than the reactants, the difference in mass has been converted to energy.

There are three types of nuclear reactions that are classified as beta decay processes. Beta decay processes have been observed in 97% of all known unstable nuclides and are thus the most common mechanism for radioactive decay by far. The first type (here referred to as beta decay) is also called Negatron Emission because a negatively charged beta particle is emitted, whereas the second type (positron emission) emits a positively charged beta particle. In electron capture, an orbital electron is captured by the nucleus and absorbed in the reaction. All these modes of decay represent changes of one in the atomic number $Z$ of the parent nucleus but no change in the mass number $A$. Alpha decay is different because both the atomic and mass number of the parent nucleus decrease. In this article, the term beta decay will refer to the first process described in which a true beta particle is the product of the nuclear reaction.

Beta Decay / Negatron Emission

Nuclides can be radioactive and undergo nuclear decay for many reasons. Beta decay can occur in nuclei that are rich in neutrons - that is - the nuclide contains more neutrons than stable isotopes of the same element. These "proton deficient" nuclides can sometimes be identified simply by noticing that their mass number $A$ (the sum of neutrons and protons in the nucleus) is significantly more than twice that of the atomic number $Z$ (number of protons in nucleus). In order to regain some stability, such a nucleus can decay by converting one of its extra neutrons into a proton, emitting an electron and an antineutrino($\nu$). The high energy electron emitted in this reaction is called a beta particle and is represented by $\text{(}_{-1}^{0}\text{e}^{-})$ in nuclear equations. Lighter atoms ($Z < 60$) are the most likely to undergo beta decay. The decay
of a neutron to a proton, a beta particle, and an antineutrino \( \text{\^{}}\bar{\nu} \) is

\[
\text{\^{}}_{0}^{1}n^0 \rightarrow \text{\^{}}_{0}^{1}p^+ + _{-1}^{0}e^- + \text{\^{}}\bar{\nu}
\]

Some examples of **beta decay** are

\[
\text{\^{}}_{2}^{6}He \rightarrow \text{\^{}}_{3}^{6}Li + _{-1}^{0}e^- + \text{\^{}}\bar{\nu}
\]

\[
\text{\^{}}_{11}^{24}Na \rightarrow \text{\^{}}_{12}^{24}Mg + _{-1}^{0}e^- + \text{\^{}}\bar{\nu}
\]

In order for beta decay to occur spontaneously according to \( \Delta m < 0 \), the mass of the parent **nucleus** (not atom) must have a mass greater than the sum of the masses of the daughter nucleus and the beta particle:

\[
m[\text{\^{}}A\text{\^{}}Z] > m[\text{\^{}}A(Z+1)] + m[0.1e^-]
\]

\((\text{Parent nucleus}) > (\text{Daughter nucleus}) + (\text{electron})\)

The mass of the antineutrino is almost zero and can therefore be neglected. The equation above can be reached easily from any beta decay reaction, however, it is not useful because mass spectrometers measure the mass of **atoms** rather than just their nuclei. To make the equation useful, we must make these nuclei into neutral atoms by adding the mass of \( Z + 1 \) electrons to each side of the equation. The parent nucleus then becomes the neutral atom \( [\text{\^{}}A\text{\^{}}Z] \) plus the mass of one electron, while the daughter nucleus and the beta particle on the right side of the equation become the neutral atom \( [\text{\^{}}A(Z+1)] \) plus the mass of the beta particle. The extra electron on the left cancels the mass of the beta particle on the right, leaving the inequality

\[
m[\text{\^{}}A\text{\^{}}Z] > m[\text{\^{}}A(Z+1)]
\]

\((\text{Parent atom}) > (\text{Daughter atom})\)

The change in mass then equals

\[
\Delta m = m[\text{\^{}}A(Z+1)] - m[\text{\^{}}A\text{\^{}}Z]
\]

The energy released in this reaction is carried away as kinetic energy by the beta particle and antineutrino, with an insignificant of energy causing recoil in the daughter nucleus. The beta particle can carry anywhere from all to none of this energy, therefore the maximum kinetic energy of a beta particle in any instance of beta decay is \(-\Delta E\).

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**Positron Emission**

Nuclides that are imbalanced in their ratio of protons to neutrons undergo decay to correct the imbalance. Nuclei that are rich in protons relative to their number of neutrons can decay by conversion of a proton to a neutron, emitting a **positron** \( ^0_1e^+ \) and a neutrino \( \nu \). Positrons are the antiparticles of electrons, therefore a positron has the same mass as an electron but with the opposite (positive) charge. In positron emission, the atomic number \( Z \) decreases by 1 while the mass number \( A \) remains the same.

Some examples of **positron emission** are
Positron emission is only one of the two types of decay that tends to happen in "neutron deficient" nuclides, therefore it is very important to establish the correct mass change criterion. Positron emission occurs spontaneously when

$$m[AZ] > m[A(Z-1)] + m[0^+ + 1^-]$$

\[(\text{Parent nucleus}) > (\text{Daughter nucleus}) + (\text{positron})\]

In order to rewrite this inequality in terms of the masses of neutral atoms, we add the mass of \(Z\) electrons to both sides of the equation, giving the mass of a neutral \([AZ]\) atom on the left and the mass of a neutral \([A(Z-1)]\) atom, plus an extra electron, (since only \(Z-1\) electrons are needed to make the neutral atom), and a positron on the right. Because positrons and electrons have equal mass, the inequality can be written as

$$m[AZ] > m[A(Z-1)] + 2m[0^-]$$

\[(\text{Parent atom}) > (\text{Daughter atom}) + (2 \text{ electrons})\]

The change in mass for positron emission decay is

$$\Delta m = m[A(Z)] - m[AZ] - 2m[0^-]$$

As with beta decay, the kinetic energy \(-\Delta E\) is split between the emitted particles - in this case the positron and neutrino.

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**Electron Capture**

As mentioned before, there are two ways in which neutron-deficient / proton-rich nuclei can decay. When the mass change \(\Delta m < 0\) yet is insufficient to cause spontaneous positron emission, a neutron can form by an alternate process known as electron capture. An outside electron is pulled inside the nucleus and combined with a proton to make a neutron, emitting only a neutrino.

\[\ce{^1_1p + ^0_{-1}e^- → ^1_0n + \nu }\]

Some examples of electron capture are

\[\ce{^\{231\}_{92}U + ^0_{-1}e^- → ^\{231\}_{91}Pa + \nu }\]
\[\ce{^\{81\}_{36}Kr + ^0_{-1}e^- → ^\{81\}_{35}Br + \nu }\]

Electron capture happens most often in the heavier neutron-deficient elements where the mass change is smallest and positron emission isn’t always possible. For \(\Delta m < 0\), the following inequality applies:

$$m[AZ] + m[0^-] > m[A(Z-1)]$$

\[(\text{Parent nucleus}) + (\text{electron}) > (\text{Daughter nucleus})\]

Adding \(Z\) electrons to each side of the inequality changes it to its useful form in which the captured electron on the left
cancels out the extra electron on the right

\[ m[^{\text{A}}Z] > m[^{\text{A}}(Z-1)] \]

(Parent atom) > (Daughter atom)

The change in mass then equals

\[ \Delta m = m[^{\text{A}}(Z-1)] - m[^{\text{A}}Z] \]

When the loss of mass in a nuclear reaction is greater than zero, but less than \(2m[^{0}\text{-1e}^{-}]\), the process cannot occur by positron emission and is spontaneous for electron capture.

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**Alpha Decay**

The other three processes of nuclear decay involve the formation of a neutron or a proton inside the nucleus to correct an existing imbalance. In alpha decay, unstable, heavy nuclei (typically \(Z > 83\)) reduce their mass number \((A)\) by 4 and their atomic number \((Z)\) by 2 with the emission of a helium nuclei (\((\ce{^4_2He^{2+}}))\), known as an **alpha particle**.

Some examples of **alpha decay** are

\[ \ce{^{222}_{88}Ra} \rightarrow \ce{^{218}_{86}Rn + ^4_2He^{2+}} \]

\[ \ce{^{233}_{92}U} \rightarrow \ce{^{229}_{90}Th + ^4_2He^{2+}} \]

As with beta decay and electron capture, \(\Delta m\) must only be less than zero for spontaneous alpha decay to occur. Since the number of total protons on each side of the reaction does not change, equal numbers of electrons are added to each side to make neutral atoms. Therefore, the mass of the parent atom must simply be greater than the sum of the masses of its daughter atom and the helium atom.

\[ m[^{\text{A}}Z] > m[^{\text{A-4}}(Z-2)] + m[^{4}_2He^{2+}] \]

The change in mass then equals

\[ \Delta m = m[^{\text{A}}Z] - m[^{\text{A-4}}(Z-2)] - m[^{4}_2He^{2+}] \]

The energy released in an alpha decay reaction is mostly carried away by the lighter helium, with a small amount of energy manifesting itself in the recoil of the much heavier daughter nucleus. Alpha decay is a form of spontaneous fission, a reaction in which a massive nucleus can lower its mass and atomic number by splitting. Other heavy unstable elements undergo fission reactions in which they split into nuclei of about equal size.

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**Summary**

Proton-deficient or neutron-deficient nuclei undergo nuclear decay reactions that serve to correct unbalanced neutron/proton ratios. Proton-deficient nuclei undergo **beta decay** - emitting a beta particle (electron) and an antineutrino to convert a neutron to a proton - thus raising the elements atomic number \(Z\) by one. Neutron-deficient nuclei can undergo
**positron emission** or **electron capture** (depending on the mass change), either of which synthesizes a neutron - emitting a positron and a neutrino or absorbing an electron and emitting a neutrino respectively - thus lowering Z by one. Nuclei with $Z > 83$ which are unstable and too massive will correct by **alpha decay**, emitting an alpha particle (helium nucleus) and decreasing both mass and atomic number. Very proton-deficient or neutron-deficient nuclei can also simply eject an excess particle directly from the nucleus. These types of decay are called **proton** and **neutron emission**. These processes are summarized in the table below.

<table>
<thead>
<tr>
<th>Decay Type</th>
<th>Emitted Particle</th>
<th>$\Delta Z$</th>
<th>$\Delta A$</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>$^4_2\text{He}^{2+}$</td>
<td>-2</td>
<td>-4</td>
<td>$Z &gt; 83$</td>
</tr>
<tr>
<td>Beta</td>
<td>Energetic $e^-$, $\gamma$</td>
<td>+1</td>
<td>0</td>
<td>$A/Z &gt; (A/Z)_{\text{stable}}$</td>
</tr>
<tr>
<td>PE</td>
<td>Energetic $e^+$, $\gamma$</td>
<td>-1</td>
<td>0</td>
<td>$A/Z &lt; (A/Z)_{\text{stable}}$, light nuclei</td>
</tr>
<tr>
<td>EC</td>
<td>$\nu$</td>
<td>-1</td>
<td>0</td>
<td>$A/Z &lt; (A/Z)_{\text{stable}}$, heavy nuclei</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Photon</td>
<td>0</td>
<td>0</td>
<td>Any excited nucleus</td>
</tr>
</tbody>
</table>

### Problems

1. Write the balanced equation for the beta decay of $^{14}\text{C}$.
2. Write the balanced equation for the positron emission decay of $^{22}\text{Na}$.
3. Write the balanced equation for electron capture in $^{207}\text{Bi}$.
4. Write the balanced equation for the alpha decay of $^{238}\text{U}$.
5. Calculate the maximum kinetic energy of the emitted beta particle in the decay $^{24}_{11}\text{Na} \rightarrow ^{24}_{12}\text{Mg} + ^0_{-1}e^- + \nu$  
   Use **Table A4** of particle masses to do this calculation.
6. Calculate the maximum kinetic energy of the positron emitted in the decay $^8_3\text{B} \rightarrow ^8_4\text{Be} + ^0_1e^+ + \nu$  
   Use **Table A4** of particle masses to do this calculation.
7. Will $^{231}_{92}\text{U}$ likely decay to $^{231}_{91}\text{Pa}$ by positron emission or by electron capture? Use the mass criterion equations.

### Solutions

1. $^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + ^0_{-1}e^- + \nu$
2. $^{22}_{11}\text{Na} \rightarrow ^{22}_{10}\text{Ne} + ^0_{+1}e^+ + \nu$
3. $^{207}_{83}\text{Bi} + ^0_{-1}e^- \rightarrow ^{207}_{82}\text{Pb} + \nu$
4. $^{238}_{92}\text{U} \rightarrow ^{234}_{90}\text{Th} + ^4_2\text{He}$
5. Given the masses of relevant atoms and the mass change criteria for beta decay, we calculate:
\[ \Delta m = m_{^{24}_{12}\text{Mg}} - m_{^{24}_{11}\text{Na}}} \]
\[ \Delta m = 23.9850419 \text{ u} - 23.990963 \text{ u} = -0.0059211 \text{ u} \]
\[ \Delta E = (-0.0059211 \text{ u})(931.494 \text{ MeV / u}) = -5.515 \text{ MeV} \]
The maximum kinetic energy of the beta particle is 5.515 MeV.

6. The change in mass is:
\[ \Delta m = m_{^{8}_{4}\text{Be}} + 2m_{^0_{-1}\text{e}^-} - m_{^{8}_{5}\text{B}}} \]
\[ \Delta m = 8.005305 \text{ u} + 2(0.000548579911 \text{ u}) - 8.012406 \text{ u} = -0.01820384 \text{ u} \]
\[ \Delta E = (-0.01820384 \text{ u})(931.494 \text{ MeV / u}) = -16.9568 \text{ MeV} \]
The maximum kinetic energy of the positron is 16.9568 MeV.

7. The difference in mass between the daughter and parent atom is:
\[ \Delta m = m_{^{231}_{91}\text{Pa}} - m_{^{231}_{92}\text{U}}} \]
\[ \Delta m = 231.035879 \text{ u} - 231.03689 \text{ u} = -0.00041 \text{ u} \]
\[ 2m_{^0_{-1}\text{e}^-} = 0.0010971598 \text{ u} \]
Since 0.00041 \text{ u} is less than 2m_{^0_{-1}\text{e}^-}, the process cannot occur by positron emission. The mass criterion \( \Delta m < 0 \) for electron capture is met, therefore \( ^{231}_{92}\text{U} \) decays by electron capture.

References

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