Beta decay and neutrinos

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Beta decay is due to the **weak nuclear interaction,** with the following properties:

1. Affects both nucleons and electrons.
2. Affects both charged and uncharged quanta.
3. Has very short range $\leq 10^{-3}$ fm.
4. Typically transforms quanta from one type to another.
5. Typically involves neutrinos or antineutrinos.

The daughter nucleus has the same number of nucleons, the mass number changes by one:

$$
\begin{aligned}
{}^{A}_{Z}\mathsf{X} &\rightarrow {}^{A}_{Z+1}\mathsf{Y} + e^{-} \\
{}^{A}_{Z}\mathsf{X} &\rightarrow {}^{A}_{Z-1}\mathsf{Y} + e^{+}
\end{aligned}
$$

Nucleon number and total charge are conserved by this description, but we'll see that $E, \vec{p}$ are *not*, so something else is happening.

$$
\begin{aligned}
{}^{14}_{6}\mathsf{C} &\rightarrow {}^{14}_{7}\mathsf{N} + e^{-} \\
{}^{12}_{7}\mathsf{N} &\rightarrow {}^{12}_{6}\mathsf{C} + e^{+}
\end{aligned}
$$

In β decay a neutron changes to a proton, or vice-versa. The electron or positron is *created* out of the rest energy of the decaying nucleus.

Energetics of β decay.

Imagine that only an electron is emitted in the decay. We'll take the case of a decaying isolated neutron, $n \rightarrow p + e^-$. Then the energy release would be

$$Q = (m_n - m_p - m_e)c^2$$

all these are definite values, Q is fixed, so we would expect the electron to emerge with only *one* value of E, using conservation of energy and momentum.

Experimentally, this is **not** what happens.

Neutrinos

What is found is that there is a *continuous distribution* of energies up to the “two-particle” decay energy K_{max}, see fig. 13.19

Spin and momentum would also not be conserved, unless there is another particle involved.

Pauli proposed this and Fermi named it—the neutrino, ν. It has

- zero charge,
- a very small rest mass, $0 < m_\nu < 2.8$ eV/c^2,
- spin $\frac{1}{2}$,
- a *very* weak interaction with matter.

β decay in full

$$
\begin{aligned}
{}^{A}_{Z}\mathrm{X} &\rightarrow {}^{A}_{Z+1}\mathrm{Y} + e^{-} + \bar{\nu} \text{ (electron decay)} \\
{}^{A}_{Z}\mathrm{X} &\rightarrow {}^{A}_{Z-1}\mathrm{Y} + e^{+} + \nu \text{ (positron decay)}
\end{aligned}
$$

The **antineutrino** $\bar{\nu}$ is produced e^{-} beta decay.

Electron capture competes with e^{+} decay. The nucleus captures an orbital electron and emits a ν, converting a $p \rightarrow n$:

$$
{}^{A}_{Z}\mathrm{X} + e^{-} \rightarrow {}^{A}_{Z-1}\mathrm{X} + \nu
$$

This is usually an inner K-shell electron, so it is also called **K capture**.

Energy release

The Q-values are

$Q = (M_X - M_Y)c^2$ e^- and electron capture,

(electron mass is in atomic M_Y) and

$Q = (M_X - M_Y - 2m_e)c^2$ for e^+ decay.

Nuclear stability

Alpha and beta decay are the main mediators of the stability of an isotope. Typically:

1. neutron-poor isotopes undergo electron capture or e^+ β decay,
2. neutron-rich isotopes undergo e^- β decay,
3. massive nuclei $(Z > 82)$ undergo α decay.

See the graphic at

`http://www.meta-synthesis.com/webbook/33_segre/segre2.html#2`