Nuclear Reactions – Fission and Fusion

Radioactivity vs Nuclear Reactions

In many ways nuclear reactions and radioactivity are different

- Radioactivity is a spontaneous process, which means that it will proceed without the need for any outside intervention. A $^{137}\text{Cs}$ nucleus will at some time eject an electron (β particle) and leave behind a $^{137}\text{Ba}$ nucleus. By contrast, nuclear reactions are made to happen. Without any other intervention a $^{235}\text{U}$ nucleus will emit an α particle, although it might take a very long time to do so. However, in a nuclear reaction it can be made to immediately split into two smaller nuclei by the impact of a neutron.

- In the radioactive decay of an unstable isotope the product (daughter) is well defined. $^{137}\text{Cs}$ always produces $^{137}\text{Ba}$. In nuclear reactions the product(s) are often unpredictable. Many possibilities exist.

There are also many ways in which they are similar

- The total charge involved in the reaction is conserved, that is the total atomic number before the reaction must match the total atomic number after the reaction.

- The total number of nucleons involved in the reaction is conserved, that is the total atomic mass before the reaction must match the total atomic mass after the reaction.

- Any nuclear reaction will only proceed if the total mass decreases. Any reaction which would increase the mass will not occur.

- The energy produced in a nuclear reaction corresponds to the mass lost by Einstein’s relationship $E = mc^2$.

Nuclear Fission

Nuclear fission is the reaction by which a heavy nucleus (that is one with a high value of Z) is hit with a small particle, as a result of which it splits into two (occasionally more) smaller nuclei. The incoming particle must be able penetrate right into the center of the atom, down to the nucleus, which limits the choice of particle to be used.

- A particle with a negative charge (such as an electron) will be repelled by the electrons of the target atom, and never get anywhere close to the nucleus.

- A particle with a positive charge (such as a proton) will be able to pass through the electrons of the target atom, but will be repelled by the protons in the nucleus.

- A neutral particle with no charge (such as a neutron) will not be repelled by either the electrons or the protons, and will make it all the way to the nucleus. Neutrons are the choice for inducing the fission reaction that we use to make a nuclear power plant.

As an example of fission reaction, let us look at the fission of $^{235}\text{U}$ by a $^{1}\text{n}$. The total atomic number is 92, which must also be the total atomic number of the products, and the
total atomic mass is 236, which must be the total atomic mass of the products. However within these constraints there are a variety of possibilities. As a rule of thumb the products usually consist of two relatively large fragments, the nuclei of two new atoms, and a number of small fragments. One of the possible reactions is
\[ ^1_0\text{n} + ^{235}_{92}\text{U} \rightarrow ^{140}_{54}\text{Xe} + ^{94}_{38}\text{Sr} + 2 ^1_0\text{n} + \gamma \]

Note that the two nuclei produced by the fission reaction don’t have to be Xe and Sr. In principle any two nuclei can be produced, providing the total atomic number and the total atomic mass remain unchanged.

Fission reactions, mass, and energy

A fission reaction such as the one above must produce energy (after all if it didn’t we couldn’t use it generate electricity). And to produce energy it must lose mass. To calculate how much energy is produced we can perform the same calculation as we did for the radioactive process, with the one exception that we now have to include a neutron in the initial mass.

For the reaction above the masses (in amu) are

<table>
<thead>
<tr>
<th>Before the reaction</th>
<th>After the reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1_0\text{n}$</td>
<td>1.008665</td>
</tr>
<tr>
<td>$^{235}_{92}\text{U}$</td>
<td>235.0439</td>
</tr>
<tr>
<td>Total mass</td>
<td>236.0526</td>
</tr>
<tr>
<td>$^{140}_{54}\text{Xe}$</td>
<td>139.9216</td>
</tr>
<tr>
<td>$^{94}_{38}\text{Sr}$</td>
<td>93.9154</td>
</tr>
<tr>
<td>$2 ^1_0\text{n}$</td>
<td>0.1983</td>
</tr>
<tr>
<td>Total mass</td>
<td>235.8543</td>
</tr>
</tbody>
</table>

There has been a mass loss of 0.1983 amu, which corresponds to an energy release of 0.1983 amu * 931.4 MeV/amu = 185 MeV. This energy is principally shared between the two neutrons and the γ ray.

Note that although this energy is larger than the energy which would be released in the α decay of $^{235}\text{U}$, it is not that much larger. The principal reason that fission is useful for building a nuclear power plant is not the energy produced in the reaction, but that we can induce so many reactions per second.

Fission and $^{238}\text{U}$

When struck by a neutron a $^{235}\text{U}$ nucleus readily will split into two parts. The same is not true of a $^{238}\text{U}$ nucleus. To see why, lets look at the fission process again, in a bit more detail. The first event is the absorption of the neutron by the $^{235}\text{U}$ nucleus, which is then followed by the actual fission. The above reaction could have been written as
\[ ^1_0\text{n} + ^{235}_{92}\text{U} \rightarrow ^{236}_{92}\text{U} \rightarrow ^{140}_{54}\text{Xe} + ^{94}_{38}\text{Sr} + 2 ^1_0\text{n} + \gamma \]

If a neutron strikes a $^{238}\text{U}$ nucleus it will also absorb the neutron, but the chances of fission are very much smaller. For the most part the resulting $^{239}\text{U}$ nucleus holds together,
although it is radioactive, being a $\beta$ emitter with a half life of 23.5 minutes. The daughter nucleus is also radioactive and also a $\beta$ emitter, with a half life of 2.4 days. We then have a three step process resulting in the formation of plutonium

\[
\begin{align*}
^{1}\text{n} + ^{238}\text{U} & \rightarrow ^{239}\text{U} \\
^{239}\text{U} & \rightarrow ^{239}\text{Np} + ^{0}\text{e} \\
^{239}\text{Np} & \rightarrow ^{239}\text{Pu} + ^{0}\text{e}
\end{align*}
\]

The failure of $^{238}\text{U}$ to split when bombarded with a neutron is a problem for nuclear power plants, it leads to a loss of neutrons. It does have its upside though, being the means by which we manufacture plutonium, another isotope which will split. Plutonium is just as good (perhaps better) a fuel as $^{235}\text{U}$.

**Problems with fission**

As a means of generating the energy for an electrical power plant fission has advantages and disadvantages. On the plus side its immediate environmental impact is small. Unlike plants which use fossil fuels, nuclear power plants produce zero CO$_2$ emissions. The supply of uranium is not unlimited, but it is also not threatened either, unlike the supply of oil.

That is not to say that fission is a “clean” source of energy by any means. It does produce waste, and that waste is difficult to handle, and to store. When the fuel rod is extracted from the reactor vessel it is loaded with fission products, such as $^{140}\text{Xe}$, $^{94}\text{Sr}$, and all the other possible isotopes that can be created. As a result it is very radioactive, and has to be stored in safe secure facilities. The level of activity drops quite rapidly as the short lived isotopes decay away\(^1\), leaving the less active but longer lived isotopes which must be stored for very long times.

**Fusion**

Fusion is the opposite of fission, it is the joining together of two light nuclei to form a heavier one (plus a small fragment). For example if two $^2\text{H}$ nuclei (two deuterons) can be made to come together they can form He and a neutron

\[^2\text{H} + ^2\text{H} \rightarrow ^3\text{He} + \text{n}\]

There is also energy produced (because the mass decreases) of about 3.3 MeV, most of which appears as the kinetic energy of the neutron. As with fission, there are other possible products of a fusion reaction, although the possibilities are considerably fewer. For example, there is one other possible outcome of the fusion of two deuterons in addition to the formation of $^3\text{He}$ (as above), it could also result in the formation of a tritium ($^3\text{H}$) nucleus

\[^2\text{H} + ^2\text{H} \rightarrow ^3\text{H} + \text{p}\]

with a release of 4 MeV of energy.

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\(^1\) remember that the activity is an isotope is determined by its decay constant, $k = \ln 2/T_s$
Advantages and Disadvantages of Fusion

Certainly one of the advantages of fusion is the abundance of fuel. Uranium (for fission plants) is a finite resource, we must eventually exhaust it. The supply of deuterium (the $^2\text{H}$ atom) is essentially inexhaustible. Deuterium is a naturally occurring isotope of hydrogen, and although there are only about one deuterium atom for every 6,800 ordinary hydrogen atoms in sea water, there is a lot of sea water. That is still a lot of deuterium atoms.

A second advantage, specifically in comparison to fission, is the lack of highly radioactive fission waste products. In the above reactions of two deuterium nuclei the waste products are $^3\text{He}$ which is stable, and $^3\text{H}$ which is radioactive, but with a half life of only 12 years (as compared with 24,000 years for $^{239}\text{Pu}$.) That make storage less of a long term problem.

The big problem is the difficulty in getting the reaction started. In order to combine two deuterons we have to first get them together close enough that they “touch”. That means that their separation must be of the order the size of an atomic nucleus, about $10^{-15}$ m. However as the two deuterons approach each other there is a strong electrostatic repulsion due to them both being positively charged, and the closer they get the stronger the force of repulsion. The only method available to solve this problem is to have the deuterons moving very fast, so that they “touch” before the repulsion is able to force them apart, and that is not easy. It requires that we produce a plasma with a temperature in excess of 10,000,000 K at high enough pressure and for long enough duration for the fusion process to get started. At the moment this is too severe of a technological problem for us to construct a commercial fusion power plant, although prototypes are being worked on.

Fusion and the Sun

Although we have difficulty creating the right conditions for nuclear fusion here on Earth, the tremendous gravity generated by stars is more than capable creating the right conditions in their interiors, although only close to their centers. (For a star the size of the Sun the right conditions occur only in about the middle $1/3$rd of the star.) In these regions the pressures and temperatures are both very high, and nuclear fusion of hydrogen into helium provides the energy which drives the star, including the light that it eventually emits.

In its simplest form, the process which drives the star is the fusion of four hydrogen nuclei to form one helium nucleus

$$^1\text{H} + ^1\text{H} + ^1\text{H} + ^1\text{H} \rightarrow ^4\text{He} + e^+ + e^-$$

with the release of 24.7 MeV of energy. The details are more complicated, with two possible reactions schemes known as the p-p chain and the CNO cycle. Details can be found at [http://www.jca.umbc.edu/~george/html/courses/glossary/pp_chains.html](http://www.jca.umbc.edu/~george/html/courses/glossary/pp_chains.html) and [http://www.jca.umbc.edu/~george/html/courses/glossary/cno_cycle.html](http://www.jca.umbc.edu/~george/html/courses/glossary/cno_cycle.html).