Modern Physics

Unit 16: Nuclear Reactions
Lecture 16.1: Fission

Ron Reifenberger
Professor of Physics
Purdue University
Definition

A nuclear reaction is any process in which two nuclei, or a nucleus of an atom and a subatomic particle (such as a proton or a neutron) from outside the atom, collide to produce products different from the initial particles.
Distinguish between Atomic and Nuclear Mass

Nuclear reactions require nuclear masses

\[ ^{14}_7N + ^{4}_2He \rightarrow ^{1}_1p + ^{17}_8O \]

Chemical reactions require atomic masses

\[ 2H + O \rightarrow H_2O \]

What’s the difference between a nuclear mass and an atomic mass?

**ELECTRONS**

Example: What is the nuclear mass of \(^{3}_2He\) if the atomic mass is 3.016 030 u?

\[
M\left( ^{3}_2He \right) = m\left( ^{3}_2He \right) + 2e^- \\
m\left( ^{3}_2He \right) = M\left( ^{3}_2He \right) - 2e^- \\
= 3.016 030 \text{ u} - 2(0.000 549 \text{ u}) = 3.014 932 \text{ u}
\]
Binding energy per nucleon vs. nucleon number

- Fusion
- Fission

Fe is most stable nucleus

Uranium
Fission and Fusion of the Nucleus

**Fission:** A heavy nucleus breaks up into two smaller, more stable nuclei, releasing energy.

**Fusion:** Light nuclei fuse into a heavier one, releasing energy.
The Important Element Uranium

- Uranium - discovered in 1789
- heaviest naturally occurring element
- Mined primarily in Canada, Australia and Kazakhstan
### Uranium Isotopes

26 isotopes: U-217→U-242

Only three naturally occurring isotopes

<table>
<thead>
<tr>
<th>Protons</th>
<th>Neutrons</th>
<th>Nucleons</th>
<th>Symbol</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>142</td>
<td>234</td>
<td>U-234</td>
<td>(0.0055%)</td>
</tr>
<tr>
<td>92</td>
<td>143</td>
<td>235</td>
<td>U-235</td>
<td>(0.72%)</td>
</tr>
<tr>
<td>92</td>
<td>146</td>
<td>238</td>
<td>U-238</td>
<td>(99.27%)</td>
</tr>
</tbody>
</table>

Naturally occurring Uranium enriched to ~4% U-235 is known as reactor-grade Uranium

Naturally occurring Uranium enriched to ~85% U-235 is known as weapons-grade Uranium

Enrichment process itself requires a large amount of energy.
1932-34: Fermi’s Experiment - attempt to produce an element heavier than Uranium using neutrons to penetrate the nucleus.

1935: Light isotope U-235 discovered at University of Chicago

<table>
<thead>
<tr>
<th>protons</th>
<th>neutrons</th>
<th>nucleons</th>
<th>symbol</th>
<th>abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>146</td>
<td>238</td>
<td>U-238</td>
<td>(99.27%)</td>
</tr>
<tr>
<td>92</td>
<td>143</td>
<td>235</td>
<td>U-235</td>
<td>(0.72%)</td>
</tr>
</tbody>
</table>
1938: Hahn, Strassmann
1939: Meitner, Frisch
Performing very similar experiments as Fermi, discover new elements produced in U after neutron bombardment. New elements are lighter than U. Hahn receives 1944 Noble Prize in chemistry.


Before

\[ {_{92}^{235}U} \]

\[ \text{low energy neutron} \]

During

\[ {_{92}^{236}U} \]

After

\[ {_{36}^{91}Kr} \]

3 neutrons released + ENERGY
The Idea of a Chain Reaction

Chain Reaction

Many end products are possible:

\[
\begin{align*}
1^0 n + 235^{\text{U}} &\rightarrow 236^{\text{U}} \rightarrow 141^{\text{Ba}} + 3^0 n + 170 \text{ MeV} \\
1^0 n + 235^{\text{U}} &\rightarrow 236^{\text{U}} \rightarrow 144^{\text{Ba}} + 2^0 n + 200 \text{ MeV} \\
1^0 n + 238^{\text{U}} &\rightarrow 236^{\text{U}} \rightarrow 139^{\text{Te}} + 2^0 n + 197 \text{ MeV} \\
1^0 n + 235^{\text{U}} &\rightarrow 236^{\text{U}} \rightarrow 137^{\text{Xe}} + 2^0 n + 191 \text{ MeV}
\end{align*}
\]

etc......

\[\approx 200 \text{ MeV}\]

released from

ONE atom

unstable

How many reactions/s to produce 1 W?

\[
N \left( \frac{200 \text{ MeV / fission reaction}}{s} \right) = \frac{1 \text{ J/s}}{1.6 \times 10^{-19} \text{ J}} \times 6.25 \times 10^{18} \text{ eV/s} \\
N \approx \frac{6.25 \times 10^{18} \text{ eV/s}}{200 \times 10^6 \text{ eV}} \approx 3 \times 10^{10} \text{ fission reactions/s}
\]

Exponential multiplication of low energy neutrons
Distribution of $^{235}$U Fission Fragments

YIELD (%) vs. Fragment Mass Number (A)

A ~ 95
A ~ 140
Why was the discovery of fission so surprising?

Until 1938, radioactive decay could “chip away” at the nucleus, removing a few nucleons at a time

+ 10’s MeV of energy

With the discovery of fission, you could now “split” the nucleus into two roughly equal parts

+ 100’s MeV of energy
First controlled nuclear chain reaction
University of Chicago
December 2, 1942

Graphite (carbon) was selected as a moderator to slow the neutrons emitted from the Uranium fuel


Schematic Diagram of Nuclear pile or Nuclear reactor

Graphite blocks (~385 tons of graphite!)

Neutron adsorbing Control rods

Geometry must be optimized

Natural uranium fuel
(99.3% U-238 and 0.7% U-235)
The completed pile contained 771,000 pounds of graphite, 80,590 pounds of uranium oxide and 12,400 pounds of uranium metal when it went critical.

The pile cost about $2.7 million to produce and build. It took the form of a flattened ellipsoid which measured 25 feet wide and 20 feet high. It produced about 200 W of power.

A.H. Compton was director of the Chicago lab that supported Fermi’s team.
Details in patent application:
Nuclear chain reactions
(~75 years later)

\[ ^{238}\text{U} + \text{n} \rightarrow ^{239}\text{U} \quad \text{(not interesting)} \]

\[ ^{235}\text{U} + \text{n} \rightarrow ^{236}\text{U}^* \rightarrow \text{Kr} + \text{Ba} + 3\text{n} \]

Critical mass ~50 kg (110 lbs)
Spherical diameter ~ 0.17 m

Uncontrolled

Controlled

Image from http://myweb.rollins.edu/jsiry/Fission.html

Select “Chain Reaction” at
Nuclear Reactors in the USA

- Number of commercially operating nuclear power plants in USA: 62
- Oldest operating nuclear reactors in USA: Oyster Creek (NJ) and Nine Mile Point 1 (NY) (both entered commercial service on December 1, 1969)
- The last nuclear reactor to enter service in USA was Watts Bar 1 (TN) in 1996.
- Estimate that commercial operation of Watts Bar 2 could begin in December 2015.

www.eia.gov/tools/faqs/
Up Next – Nuclear Fusion