For centuries chemists, magicians and swindlers dreamed of converting lead into gold - this was the great quest of "alchemy". Nuclear reactions are the modern form of alchemy - and it is even possible to convert lead into gold via nuclear reactions. It is said that in 1972 Russian scientists found the shielding of their reactor in Lake Baikal in Siberia had turned to gold. How?
**Units of Radioactivity**

1. **Activity**

\[ R = \lambda N = -dN/dt \]

Bequerel (Bq) = decays/second  
1 Curie (Ci) = 3.7 \times 10^{10} \text{ Bq}

2. **Exposure**

in Gray (Gy) = 1J/Kg = 100 rad.

3. **Dose Equivalent**

Dose = RBE \times \text{Exposure}

in Sievert (Sv) [J/Kg].

(RBE=relative biological exposure)

<table>
<thead>
<tr>
<th>RBE</th>
<th>Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X-rays and Beta (electrons), muons</td>
</tr>
<tr>
<td>5</td>
<td>Slow neutrons (1-50MeV)</td>
</tr>
<tr>
<td>20</td>
<td>Alpha (denser trail of ionized atoms)</td>
</tr>
<tr>
<td></td>
<td>Nuclear Fission products, heavy nuclei</td>
</tr>
</tbody>
</table>
e.g. In April 2011, a typical worker inside the Fukushima reactor building would absorb 20J of radiation with an RBE of 2 Sv/Gy in one hour. Assuming that the maximum safe equivalent dose is 0.05 Sv (0.05 J/Kg = 5 rem), and that the worker has a mass of 80kg, what is the longest time the worker can safely stay inside the reactor building?

Exposure = 20J/80kg = 0.25 Gy in one hour

Dosage = 2x0.25 = 0.5Sv in one hour

Dosage/time = 0.5Sv/hour = D

Max dosage is 0.05Sv. Longest time the worker can stay in the reactor building will then be Dt = 0.05, i.e. t = 1/10 Hour = 6 minutes
Nuclear Reactions

By colliding high energy particles into nuclei, one can produce a nuclear reaction. E.g.

\[ ^4_2 \text{He} + ^{14}_7 \text{N} \rightarrow ^{17}_8 \text{O} + ^1_1 \text{H} \]

- \( A_1 + A_2 = A_3 + A_4 \) \( (4 + 14 = 17 + 1) \)
- \( Z_1 + Z_2 = Z_3 + Z_4 \) \( (2 + 7 = 8 + 1) \)
- \( Q = \left( m_1 + m_2 - m_3 - m_4 \right) c^2 \)

\( Q > 0 \) K.E. increases \( Q < 0 \) K.E. decreases. Exothermal

\( NEW \ \text{ELEMENT!} \)
e.g. $^7\text{Li}$ bombarded by a proton to give two $\alpha$ particles

What is the disintegration energy?

$^1\text{H} + ^3\text{Li} \rightarrow ^4\text{He} + ^4\text{He}$

1: $^1\text{H}$ \hspace{1cm} 1.007825u
2: $^3\text{Li}$ \hspace{1cm} 7.016004u

---

3: $^4\text{He}$ \hspace{1cm} 4.002603u
4: $^4\text{He}$ \hspace{1cm} 4.002603u

---

$1.007825u + 7.016004u = 8.023829u$

---

$M_1 + M_2 - M_3 - M_4 = 0.018623u$

$Q = (0.018623u) \times (931.5 \text{ MeV/u}) = 17.35 \text{ MeV}$
\[
\begin{align*}
4 \text{He} + 9 \text{Be} & \rightarrow 12 \text{C} + n \\
\text{Chadwick, 1932.} \\
\text{Discovery of neutron.}
\end{align*}
\]

\[
\begin{align*}
4 \text{He} & \quad 4.002603 \\
9 \text{Be} & \quad 9.012182 \\
\_ & \quad 13.014785 \\
\hline
\_ & \quad 13.008665 \\
\_ & \quad 13.008665 \\
\end{align*}
\]

\[
Q = (0.00612) \times 931.5 \text{MeV/u} = 5.7 \text{MeV}
\]

Reverse reaction

\[
n + 12 \text{C} \rightarrow 4 \text{He} + 9 \text{Be}
\]

has \( Q = -5.7 \text{MeV} \)

\[
K_{\text{cm}} = \frac{M}{M+m} \]

\[ K > \frac{13}{12} \times 5.7 = 6.175 \text{ MeV} \]
Fission

Predicted by Lise Meitner. Expt Otho Hahn + Fritz Strassman 1938

Example of neutron absorption

\[
\frac{235}{92} U + \text{'n} \rightarrow \frac{236}{92} U^* \rightarrow 144_{\text{Ba}} + 89_{\text{Kr}} + 3_0 \text{'n} \\
\rightarrow 140_{\text{Xe}} + 94_{\text{Sr}} + 2_0 \text{'n}
\]

\[
\Delta B/\text{nucleon} \sim 8.5 - 7.6 = 0.9 \text{MeV}
\]

\[Q \approx 235 \times 0.9 = 200 \text{MeV/nucleon}.
\]
On average ~ 2.5 neutrons/decay ⇒ 40% = \frac{1}{2.5} \times 100 \text{ reqd for chain reaction}

Chain Reaction

\begin{itemize}
  \item Have excess of neutrons
\end{itemize}
Nuclear Reactors

(Chernobyl, 1986)

Core = Moderator
(Water)

Pressure Vessel

Control Rods

Steam Turbines

Steam Generator

Coolant

Generator

Efficiency ~ 1/3rd. (Governed by efficiency \( < \left( \frac{A - Teou}{Teou} \right) \))

Decay fragments undergo Beta Decay.

\[
\begin{align*}
^{140}_{54} \text{Xe} & \xrightarrow{\beta^-} ^{140}_{56} \text{Cs} \\
& \xrightarrow{\beta^-} ^{140}_{56} \text{Ba} \\
& \xrightarrow{} ^{140}_{57} \text{La} \\
& \xrightarrow{\gamma} ^{140}_{58} \text{Ce}
\end{align*}
\]

Continues even when fission has ceased. \( \sim 15\% \) power.

Without cooling water \( \rightarrow \) Melt Down. (Nearly occurred 3 mile island, 1979).
e.g. Calculate mass of $^{235}\text{U}$ needed for 3000 MW of power

$200\text{MeV} / ^{235}\text{U \ atom.}$

$200\text{MeV} \times (1.6 \times 10^{-13} \text{J/MeV}) = 3.2 \times 10^{-11} \text{J}$

Each second, 3000 MJ = $3 \times 10^9 \text{J}$

$$\frac{3 \times 10^4}{3.2 \times 10^{-11}} = 9.4 \times 10^{14} \text{ decays/second.}$$

$$9.4 \times 10^{14} \times 235 \times (1.66 \times 10^{-22} \text{ kg/n}) = 3.9 \times 10^{-9} \text{ kg} \times 9.4 \times 10^{14} = 3.7 \times 10^{-5} \text{ kg} = 37 \text{ mg.}$$

Per day

$\# \text{ kg} = 3.7 \times 10^{-5} \times 86,400 \text{ s} = 3.2 \text{ kg}$
The frightening power of a hydrogen bomb, the sunshine that comes from the sun—both are examples of a source of power—fusion power—that mankind has yet to successfully tame for peaceful uses.

Nuclear fission takes advantage of the energy gained by splitting large heavy nuclei into smaller, more stable components. By contrast, fusion takes advantage of the additional stability obtained by combining lighter nuclei. Iron and nickel have the largest binding energies...
per nucleon and are therefore the most stable.

It follows that the fusion of nuclei lighter than iron or indeed generally releases energy.

It takes considerable energy to bring nuclei together for fusion, basically because of the huge Coulomb forces that repel like charged nuclei. Nevertheless, the energy released once the nuclei fuse is far greater.
**FUSION OF TWO PROTONS**

\[ E \]

\[ U = \frac{e^2}{4\pi\varepsilon_0 r} = \frac{(1.6 \times 10^{-19} \text{c})^2 \times (9 \times 10^9 \text{Jm/c}^2)}{2 \times 10^{-15} \text{m}} \]

\[ = 1.2 \times 10^{-13} \text{J} \]

\[ = 0.7 \text{ MeV} \]

\[ Q = (2m_p - m_O - m_e)c^2 \]

\[ = \left[ 2\left(\frac{1}{2}M\right) - \frac{1}{2}M - 2m_e \right]c^2 \]

\[ = \left[ 2(1.007825) - 2.01402 - 2(0.000548) \right] \times 931.5 \text{ MeV/u} \]

\[ = 0.421 \text{ MeV} \]

*This is the first and key step in solar fusion.*
Proton-Proton Chain

\[ Q_1 = 0.42 \text{MeV} \]
\[ Q_2 = 5.49 \text{MeV} \]
\[ Q_3 = 12.86 \text{MeV} \]

\[ ^1\text{H} + ^1\text{H} \rightarrow ^2\text{H} + e^+ + \nu_e \]
\[ ^2\text{H} + ^1\text{H} \rightarrow ^3\text{He} + \gamma \]
\[ e^+ + e^- \rightarrow 2\gamma \]

\[ 2(Q_1 + Q_1' + Q_2) + Q_3 = 26.7 \text{MeV} \]

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + ^1\text{H} + ^1\text{H} \]

Dominates stars the size of the sun or smaller.
\[ 4 \text{p}^+ \rightarrow (^4\text{He} + 2 \text{e}^+) + 4 \nu \]

\[
\begin{align*}
4 \ \text{m}_p & = 4.029108u = (\text{^1M}_-\text{me}) \times 4 \\
\text{Mass } ^4\text{He} & = 4.002602u = ^4\text{M} \\
\text{Mass diff} & = 0.026478u \equiv 24.66\text{MeV}
\end{align*}
\]

\[ \text{e}^+ + \text{e}^- \rightarrow 2\gamma \]

\[ Q = 2(0.511) = 1.022\text{MeV} \]

\[ \text{Total energy } / 4\text{p} = 24.66 + 2.044 = 26.72\text{ MeV} \]

\# protons / g of sun \( \approx 4.5 \times 10^{23} \)

\[ \text{Energy } / g \approx \frac{26.72}{4} \times 4.5 \times 10^{23} = 3 \times 10^{24} \text{ MeV} \]

\[ = 5 \times 10^{16} J \]

\[ \approx 130 \text{ kWhr/g} \]

**SUN:** Enough protons to last 75 billion years.
Controlled Fusion

H-fusion. How hot must a gas be for fusion?

\[ \frac{3}{2} k_B T = E \]

\[ T = \frac{2E}{3k_B} \approx \frac{2 \left(0.6 \times 10^{-13} J\right)}{3 \left(1.4 \times 10^{-23} J/K\right)}, \quad 3 \times 10^9 K \]

The core of the sun has \( T \approx 1.5 \times 10^7 K \), and only the electrons at the edge of the Maxwell-Boltzmann distribution achieve fusion. The energy release rate in the core of the sun is about

\[ 0.1 \, \text{mW/cm}^3 \]

No use for terrestrial devices — we have to do better!

In a practical fusion reactor, require temperatures \( \sim 10^8 K \) for "breakeven"
A Deuteron & a Tritium nucleus fuse to form an alpha particle and a neutron. How much energy is liberated?

\[ _1^2H + _1^3H \rightarrow _2^4He + _0^n \]

\[ ^1_2H \quad 2.014102u \quad ^4_2He \quad 4.002603 \]
\[ ^1_3H \quad 3.016049u \quad ^1_0n \quad 1.008665 \]

\[ M_{\text{initial}} = 5.03015 \quad M_{\text{final}} = 5.01127 \]

\[ (M_i - M_f) \times 931.5 = 17.59 \text{ MeV} \]

The detection of \( \alpha \)-particles in a Tokamak is an important indicator that fusion is taking place.
MAGNETIC CONFINEMENT: THE TOKAMAK

Plasma ~ 100MK
Contains fuel:
- Deuterium $^2\text{H}$
- Tritium $^3\text{H}$

Tokamak

*person.

See www.jet.efda.org

\[
\begin{align*}
Q/\text{MeV} \\
D + D &\rightarrow T + H & 4 \\
T + D &\rightarrow {^4}\text{He} + n & 17.6 \\
D + D &\rightarrow {^3}\text{He} + n & 3.3 \\
{^3}\text{He} + D &\rightarrow {^4}\text{He} & 18.3
\end{align*}
\]

JET (Culham, UK) 70% of power required to heat plasma.
ITER (Cadarache, France 2015) 500MW Fusion Power [IGNITION]
Other less successful ideas

- **INERTIAL CONFINEMENT.** (Lasers compress & heat fuel pellets)

- **MUON CATALYZED FUSION**

  \[ ^1\text{H} \cdots e \cdots ^1\text{H} \]

  Tiny molecule

  $\rightarrow$ **COLD FUSION**