Nuclear Physics

measure mass in energy equivalent of rest mass

e. g. for electron \( m = 9.1 \times 10^{-31} \) kg

\[
mc^2 = 9.1 \times 10^{-31} \text{ kg} \left[ 3 \times 10^8 \text{ m/s} \right]^2 = 8.19 \times 10^{-14} \text{ J}
\]

or

\[
mc^2 = 8.19 \times 10^{-14} \text{ J} \left[ 1.602 \times 10^{-19} \text{ J/eV} = 0.511 \text{ MeV} \right]
\]

\( m \leftrightarrow 0.511 \text{ MeV} \)

matter \( \leftrightarrow \) energy
<table>
<thead>
<tr>
<th>object/particle</th>
<th>charge</th>
<th>$mc^2$</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron/beta-minus</td>
<td>-e</td>
<td>0.511 MeV</td>
<td></td>
</tr>
<tr>
<td>$e^- / \beta^-$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>positron/beta-plus</td>
<td>+e</td>
<td>0.511 MeV</td>
<td>anti-particle of electron</td>
</tr>
<tr>
<td>$e^+ / \beta^+$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>proton</td>
<td>+e</td>
<td>938.272 MeV</td>
<td></td>
</tr>
<tr>
<td>$p^+$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>neutron</td>
<td>0</td>
<td>938.566 MeV</td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$-particle</td>
<td>+2e</td>
<td>3728.402 MeV</td>
<td></td>
</tr>
<tr>
<td>= He nucleus $\alpha$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>0</td>
<td>&gt; 1 eV</td>
<td>involved in weak force</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0</td>
<td>0</td>
<td>photon $E=hf$</td>
</tr>
</tbody>
</table>
13-1b

matter $\Leftrightarrow$ energy

pair creation

$\gamma \rightarrow \text{e}^+ \text{e}^-$

$hf \sim 2 \, m_0 c^2$

pair annihilation

$E_I = E_F$

$2m_0 c^2 = 2 \, hf$

C. Bamber et al Phys. Rev D 60 092004
Radioactivity

Rutherford

- α-rays
- β-rays
- γ-rays

α-rays (charge)
β-rays (-charge)

Recall $\frac{mv^2}{r} = qVr$

For β particles $\frac{m}{q}$ = electrons

For α-particles $\sum m = 4 \times 1$ He nucleus

Radioactive sample (radium)
Nuclear notation

atomic mass units \( 1 \text{ u} = 931.5 \text{ MeV/c}^2 \)

\[
\begin{align*}
A & \quad \text{atomic mass number} = \# n+p \\
Z & \quad \text{chemical element (determined by \# p)} \\
& \quad \text{atomic number} = \# p
\end{align*}
\]

A nucleons \( A-Z = \# \text{ neutrons} = N \)

examples

\[
\begin{align*}
_{12}^6 \text{C} & \quad 16 \\
_8 \text{O} & \quad 153 \\
_8 \text{Eu} & \quad 63
\end{align*}
\]

isotopes

\[
\begin{align*}
10 & \quad 11 \\
B & \quad B \\
5 & \quad 5
\end{align*}
\]

80.2 % 19.8 % abundance's in nature

chemical mass = 10 (.802) + 11 (.198) = 10.80

note: nuclear stability favors \( \# n = \# p^+ \)

\[
N = Z
\]
Chadwick's Experiment (n discovery)

Particle

Be

α

n

neutrons? Target

p+ H+ N+

detector

① not affected by \( M \) or \( B \) field [no charge]

\( \gamma \) Photon (\( γ \)-ray), or neutral particle

need 55 MeV (too much energy)

\( n \) neutral particle \{ \( n \) - Rutherford proposal \} Chadwick discovery 1933
Energy Conservation
\[ \frac{1}{2} m_n v_n^2 = \frac{1}{2} m_n v'_n^2 + \frac{1}{2} m_T v_T^2 \]

Momentum Conservation
\[ m_n v_n = m_n v'_n + m_T v_T \]

2 different targets
\( ^{12} \text{C} \rightarrow H \quad m_H \)
\( ^{14} \text{N} \rightarrow N \quad m_N = 14 m_H \)

Chadwick found:
\[ \frac{V_H}{V_N} = \frac{[\frac{3m_n}{m_n + m_H}] v_n}{[\frac{2m_n}{m_n + 14m_H}] v_n} = \frac{m_n + 14 m_H}{m_n + m_H} \approx 7 \]

\[ 3.3 \times 10^7 \frac{\text{m/s}}{4.7 \times 10^6 \text{m/s}} \approx 7 \]

So:
\[ (m_n + 14 m_H) = 7 (m_n + m_H) \]

\[ \Rightarrow m_n = \frac{2}{b} m_H \approx 1.15 m_H \]
Strong Nuclear Force

Nuclear size

\[ V = \text{Volume} \propto A \]

\[ V = \text{Volume} \sim \left[ \frac{4}{3} \pi r^3 \right] \]

\[ r \propto V^{1/3} \]

\[ r \propto A^{1/3} \]

\[ r = R_0 A^{1/3} \]

\[ R_0 = 1.2 \times 10^{-15} \text{ m} \]

\[ \text{example } ^{197}\text{Au, } r = 7 \times 10^{-15} \text{ m} \]
- nucleons feel effective potential due to all other nucleons combined
- n help lend stability – dilute repulsive Coulomb force
- square well-like potential (3-dimensional)
- nucleon – quantized standing matter waves (recall QM square well)
- nucleon – quantized energy levels
n and p+ obey Pauli Exclusion Principal

- too many n, energy too high
- unstable $\Rightarrow$ decays to lower energy
  
  e.g. $n \Rightarrow p^+ + e^- + \bar{\nu}$
extra n but not too many

Locus of nuclear stability

$Z = N$

$N = \text{neutrons}$

$Z = \text{protons}$
\[ M_{^{4}He} < 2M_{H} + 2M_{n} \quad \text{Nuclear Binding} \]
\[ \therefore \Delta M \text{ is in binding energy} \]
\[ _{2}^{4}\text{He} \]

\[ E_{\text{binding}} = \Delta M \, c^2 \]

\[ E_{\text{binding}} = [(2m_{H}+2m_{n}) - M_{^{4}He}] \, c^2 \]

\[ 2m_{H} + 2m_{n} = 2.01560 + 2.017330 = 4.03293 \]

\[ M_{^{4}He} = \frac{4.002603}{4} \]

\[ \Delta M = 0.030377 \]

\[ E_{\text{binding}} = (0.03077)(931.5 \text{ MeV}) \]

\[ = 28.3 \text{ MeV} \]

This is 10^6 times atomic binding!!

Chemical reactions (Coulomb force) \sim 1 \text{ eV}

Nuclear reactions (strong nuclear) \sim 10^6 \text{ eV}
Nuclear Binding Energy per Nucleon (B/A, MeV) vs. Number of Nucleons (A = # nucleons)

- Fusion generates energy:
  - $^2\text{H} + ^2\text{H} \rightarrow ^4\text{He} + ^1\text{H}$

- Fission generates energy:
  - $^{235}\text{U} + ^0\text{n} \rightarrow (^{236}\text{U}^x) \rightarrow ^{140}\text{Xe} + ^{95}\text{Sr} + 2^0\text{n}$

- Most stable nuclei:
  - $^{56}\text{Fe}$

- Elements and isotopes:
  - $^{12}\text{C}$, $^{16}\text{O}$, $^{20}\text{Ne}$, $^{6}\text{Li}$, $^{2}\text{H}$, $^{3}\text{He}$, $^{56}\text{Fe}$, $^{140}\text{Xe}$, $^{95}\text{Sr}$, $^{235}\text{U}$, $^{236}\text{U}$, $^{138}\text{Xe}$, $^{200}\text{U}$, $^{100}\text{Mo}$, $^{120}\text{Te}$, $^{200}\text{Hg}$, $^{238}\text{U}$
A Massive Star at the End of its Life

700 million km ~Jupiter's orbit

$t = -7$ yrs
$T = 1.3$ billion $^\circ$K

Superstar died

$14 - 10$ SNZ

$t = -3$ days
$T = 3$ billion $^\circ$K

$H \rightarrow$ Ha shell
$C \rightarrow$ Ne shell
$Ne \rightarrow O$
Core.

$t = -1$ yr
$T = 1.9$ billion $^\circ$K

$O \rightarrow$ Si burning core
$Ne \rightarrow O$ shell
$C \rightarrow$ Ne shell

Nuclear synthesis in stars

13-9b
Relative Stopping Power

Pb better
Nuclear decay channels

\( ^{214}\text{Po} \rightarrow ^{210}\text{Pb} + ^{4}\text{He} \)

\( ^{235}\text{U} \rightarrow ^{231}\text{Th} + ^{4}\text{He} \)

\( ^{226}\text{Ra} \rightarrow ^{222}\text{Rn} + ^{4}\text{He} \)

\( ^{6}\text{Li} \rightarrow ^{6}\text{Li} + \gamma \)

\( ^{14}\text{C} \rightarrow ^{14}\text{N} + ^{0}\text{e} + \bar{\nu}_e \)

\( ^{12}\text{C} \rightarrow ^{12}\text{C} + \gamma \)

\( ^{12}\text{C} \rightarrow ^{12}\text{C} + \gamma \)
Quantum tunneling through energy barrier

- $E_{\text{particle}}$
- Particle wavefunction past the barrier

http://phet.colorado.edu/simulations/sims.php?sim=Alpha_Decay
Particle decay $\alpha$ and $\beta$ emission

M+m init. $\rightarrow$ M m final

momentum conservation

\[ 0 = MV - mv \] (1)

or

\[ V = \frac{m}{M} \] (1a)*

energy

\[ \Delta E = \frac{1}{2} MV^2 + \frac{1}{2} mv^2 \] (2)

(1a) into (2)

\[ \Delta E = \frac{1}{2} M \left( \frac{m}{M} \right)^2 + \frac{1}{2} mv^2 \]

\[ \Delta E = \frac{1}{2} mv^2 \left\{ 1 + \frac{m}{M} \right\} \]

nuclear energy change

energy of emitted m particle

Note: most of energy goes to KE of light (m) particle

\[
\frac{KE(M)}{KE(m)} = \frac{\frac{1}{2} MV^2}{\frac{1}{2} mv^2} = \frac{\frac{1}{2} mv^2 \left( \frac{m}{M} \right)}{\frac{1}{2} mv^2} \Rightarrow \frac{KE(M)}{KE(m)} = \frac{m}{M}
\]
Particle decay $\alpha$ and $\beta$ emission

$M + m$  
init.  
$M$  
final  

$\Delta E = \frac{1}{2} m v^2 \left[ 1 + \frac{m}{m_f} \right]$  

$\alpha$ emission

$^{210}_{84}\text{Po} \rightarrow ^{206}_{82}\text{Pb} + ^4_2\text{He}$

$\frac{m}{M} = \frac{4}{206} = 0.0194 \sim 2\%$

$\beta$ (e) decay  
$\beta^- = e^-$ emission

$^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + ^0_{-1}\text{e} + \bar{\nu}_e$

$\frac{m}{M} = \frac{5.5 \times 10^{-4}}{14} \sim 0.003\%$

neutrino complication
weak nuclear force in $\beta$ decay

$\Delta E(\text{observed})$
$\Delta E(\text{expected})$

$^{210}\text{Bi decay}$

$1^n \rightarrow ^{+1}_1\text{p} + ^0_{-1}\text{e} + \nu_e$
electron antineutrino

inverse $\beta$ decay
$^{+1}_1\text{p} + ^0_{-1}\text{e} \rightarrow ^0_0\text{n} + \nu_e$

$\beta$ (e) decay  $\beta^- = e^-$ emission
$^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + ^0_{-1}\text{e} + \bar{\nu}_e$

neutrino complication

http://phet.colorado.edu/simulations/sims.php?sim=Beta_Decay
\[ \Delta E = hf + \frac{1}{2} MV^2 \]

\[ \Delta E = hf \left[ 1 + \left\{ \frac{hf}{2Mc^2} \right\} \right] \]

Almost all energy to \( \gamma \)

\[ hf \sim< 1 \text{ MeV} \]

\[ 2Mc^2 \rightarrow 2A \left[ 1000 \text{ MeV} \right] \sim 200,000 \text{ MeV} \]

\[ A \sim 4 \text{ to } 300 \]
Tc used in nuclear stress tests to look at distribution of blood flow in heart

Activate Mo in reactor \[ {}_{42}^{98} \text{Mo} + {}_{0}^{1} \text{n} \rightarrow {}_{42}^{99} \text{Mo} \]

\[ {}_{42}^{99} \text{Mo} \rightarrow {}_{43}^{99m} \text{Tc} + {}_{-1}^{0} \text{e} + \bar{\nu} \]

\[ {}_{43}^{99m} \text{Tc} \rightarrow {}_{43}^{99} \text{Tc} + \gamma \]

\[ {}_{43}^{99m} \text{Tc} \text{ half-life of 6.01 hours} \{15/16 = 93.7\% \text{ done in 24 hr}\} \]

\[ {}_{43}^{99} \text{Mo has a half-life of 66 hours} \]

\[ \gamma \text{ Energy} = 140 \text{ keV (escapes body)} \]

Transport and inject in patient blood stream

Image gamma rays emanating from heart to measure blood flow
Example KE of

\[ \frac{232}{92}U \rightarrow \frac{228}{90}Th + \frac{4}{2}He + KE_{tot} \]

\[ m(U) \]
\[ m(Th) + m(He) \]
\[ 232.03713 \text{ u} \]
\[ 228.025716 \text{ u} \]
\[ 4.002602 \text{ u} \]
\[ 2.32 \times 10^{-13} \text{ MeV} \times 931.5 \left( \frac{\text{MeV}}{\text{u}} \right) = 5.4 \text{ MeV} \]

\[ KE_{Th} + KE_{He} = KE_{tot} = 5.4 \text{ MeV} \]
\[ \frac{KE_{He}}{KE_{Th}} = \frac{m_{He}}{m_{Th}} = \frac{4}{228} \]

\[ KE_{He} = \left( \frac{4}{228} \right) 5.4 \text{ MeV} = 5.3 \text{ MeV} \]
\[ KE_{Th} = \frac{5.4 \text{ MeV}}{0.1} = 0.1 \text{ MeV} \]
Radioactive decay: a stochastic statistical process
-a given nuclei decays randomly and independently of others
-constant statistical decay rate (probability per unit time)
  {short time compared to time when ~ nothing left)
⇒ 1) the more nuclei the more decays
   2) the longer the time the more decays.

1) ⇒ $N$ radioactive nuclei at time $t$, then $\Delta N \sim N$
2) ⇒ $\Delta N \sim \Delta t$

⇒ $\Delta N = -\lambda N \Delta t$
⇒ $dN = -\lambda N \, dt$
⇒ $\frac{dN}{dt} = -\lambda N$
⇒ $\frac{dN}{dt} + \lambda N = 0$

Have seen this before!!

Poisson process: every object has a fixed probability of decaying in a given time
[Remember the Fr. mathematician Siméon Denis Poisson (1781 – 1840) who was wrong about “Poissions’ bright spot”.]
Exponential Function

\[ f(t) = e^{-\frac{t}{\tau}} \]

\[ \tau = \text{time constant} \]

\[ f(t=\tau) = e^{-1} = \frac{1}{e} = \frac{1}{2.732} \]

\[ \frac{df}{dt} = -\frac{1}{\tau} f \]

or

\[ \frac{\Delta f}{\Delta t} = -\frac{1}{\tau} f \]

Note: gen. soln. \[ f(t) = f_0 e^{-\frac{t}{\tau}} \] (\(f_0 = \text{constant}\))
\[
T_{1/2} = 0.693 \frac{T_{1/2}}{\lambda} \\
\ln 2 = \lambda T_{1/2} \\
2 = e^{\lambda T_{1/2}} \\
\frac{N}{N_0} = \frac{1}{2} = e^{-\lambda T_{1/2}} \\
N = N_0 e^{-\lambda t} \\
N = N_0 \left(\frac{1}{2}\right)^{t/T_{1/2}}
\]

\[\begin{align*}
N &= N_0 e^{-\lambda t} \\
\frac{\Delta N}{\Delta t} &= -\lambda N \\
R &= \frac{\Delta N}{\Delta t} = \left(\frac{\Delta N}{\Delta t}\right)_0 e^{-\lambda t}
\end{align*}\]
Radioactivity illustration: carbon dating

Cosmic rays (at high altitudes)

\[ n + ^{14}_7 N \rightarrow ^{14}_6 C + ^1_1 p \]

\(^{14}_6 C\) is incorporated into CO\(_2\) in the atmosphere with stable \(^{12}_6 C\)

Photosynthesis incorporates \(^{14}_6 CO_2\) into plants

But \(^{14}_6 C \rightarrow ^{14}_7 N + e^- + \bar{\nu}_e\)

\(\tau_{1/2} = 5730\) years

\[^{14}_6 C\] is constantly decaying

So \(\frac{N(\text{^{14}C})}{N(\text{^{12}C})} = 1.3 \times 10^{-12}\)

Equilibrium isotope ratio in atmosphere and all living things

Organism dies \(\Rightarrow \text{^{14}_6 C}\) content decays as

\(\frac{N_{\text{^{14}C}}(t)}{N_{\text{^{12}C}}} = 1.3 (10)^{-12} \left(\frac{1}{2}\right)^{t/5700}\)
\[
\frac{N_{14_C}(t)}{N_{12_C}} = 1.3 \times 10^{-12} \ e^{-0.693 \frac{t}{5700}}
\]

suppose
\[
\frac{N_{14_C}}{N_{12_C}} = 1.3 \times 10^{-12} \left( \frac{1}{10} \right)
\]

\[
\Rightarrow \frac{1}{10} = e^{-0.693 \frac{t}{5700}}
\]

\[
\ln\left(\frac{1}{10}\right) = -0.693 \frac{t}{5700}
\]

\[
t = -\frac{5700}{0.693} \ln\left(\frac{1}{10}\right) \sim 3.3 \times 5700
\]

\[
t = 18,939 \text{ yrs}
\]

between

\[
\left(\frac{1}{2}\right)^0 = 1
\]

\[
\left(\frac{1}{2}\right)^1 = \frac{1}{2} = 0.5
\]

\[
1(5700) = 5700
\]

\[
\left(\frac{1}{2}\right)^2 = \frac{1}{4} = 0.25
\]

\[
2(5700) = 11400
\]

\[
\left(\frac{1}{2}\right)^3 = \frac{1}{8} = 0.125
\]

\[
3(5700) = 17100
\]

\[
\left(\frac{1}{2}\right)^4 = \frac{1}{16} = 0.0625
\]

\[
4(5700) = 22800
\]
Fission

Coulomb repulsion wins

excited

A' ~118

A ~95, ~137

Fraction

0.1

0.1

0.01

0.001

0.0001

0.00001

235\text{U} fission products

A (mass)

80 100 120 140 160

chain reaction

Critical mass reaction keeps going

13-16
Atomic weapons: fission bombs: U-bomb

$^{235}\text{U} \quad 0.7\% \text{ natural abundance} \quad \text{Weapons grade of enrichment} \quad 99\% \quad ^{235}\text{U}$

Reactor grade of enrichment $3-4\% \quad ^{235}\text{U}$

$\tau =$ time for spontaneous $^1\text{n}$ emission to initiate chain reaction

$\tau \sim 1 \mu s \quad \text{for} \quad ^{235}\text{U}$

time to assemble critical mass must be $\tau <$

uranium gun-type atomic bomb (Little Boy) - Hiroshima
Atomic weapons: fission bombs: Pu-bomb

$^{239}\text{Pu}$ man made in reactors

$\tau =$ time for spontaneous $^1\text{n}$ emission to initiate chain reaction

time to assemble critical mass must be $\tau <$

and WWII bomb $^{239}\text{Pu}$

$\tau -$ smaller must assemble faster

explosive

detonate simultaneously to implode $^{239}\text{Pu}$ into lump a critical mass.

Timing of explosive detonation crucial

implosion-type bomb (Fat Man) on the city of Nagasaki

13-17a
Heat → work
Note: T of reactor is low
→ low thermodynamic efficiency
→ large waste heat loss to surroundings

\[ {^1n + ^{235}U \rightarrow ^{236}U^*} \]
\[ ^{236}U^* \rightarrow ^{140}Xe + ^{94}Sr + 2 \, ^1n \]
\[ ^{236}U^* \rightarrow ^{141}Ba + ^{92}Kr + 3 \, ^1n \]
\[ ^{236}U^* \rightarrow ^{150}Nd + ^{81}Ge + 5 \, ^1n \]

1 eV slow $^1n$ best
Problems that can occur with nuclear reactors

\[ ^{92} \text{Kr} \] gas-radioactive-overpressure develops
released and controlled way (or blow out)

cooling system breakdown or coolant loss
“China syndrome” – fuel melts - concentrates
- burns through reactor containment floor
- molten fuel burns into earth below reactor
- hits ground water – blast of dirty radioactive steam emitted

Chernobyl (C-moderator- Russian design)
- test of reactors ability to run its own cooling system-
- undetected problems – local heating
- C- rods fracture – blocked at 33% insertion - steam blow outs
- C moderator ignited and burns
- fuel rods melt – steam explosion – C rod fire blow roof off
- smoke carries away radioactivity

Radioactive isotopes released
\[ ^{137} \text{Cs} \] particles - aerosol
\[ ^{92} \text{Sr} \] radioactive released - \( \text{Sr}^{2+} \) like \( \text{Ca}^{2+} \) -- concentrates in bones
\[ ^{129} \text{I} \] - long half life released I gets in grass – cows eat – into milk supply
Breeder Reactor takes advantage of fission fuel

\[
^1n + ^{238}U \rightarrow ^{239}U \rightarrow ^{239}Np \rightarrow ^{239}Pu \rightarrow
\]

\[
\text{fast} \quad \quad T_{1/2} = 23 \text{ min} \quad e^- \quad T_{1/2} = 2.3 \text{ d} \quad e^- \quad T_{1/2} = 24,000 \text{ yr}
\]

\[\therefore \text{ decrease moderator in reactor}\]

\[^{238}U : 15-30\% \quad ^{235}U \quad ^{239}Pu \quad \text{fuel created}\]

\[^{239}Pu \quad \text{fuel created}\]

\[^{1}n \rightarrow ^{235}U \quad \text{energy generated}\]

\[^{1}n \rightarrow ^{239}Pu \quad \text{energy generated}\]

reactor lasts 10-20 yr – creates enough fuel for another reactor

Common in Europe (France)

fear – generates \(^{239}Pu\) weapons product

What to do with nuclear waste?
Fusion

\[ ^1H + ^1H \rightarrow ^2H + e^+ + \nu \]

(proton) (deuterium)

\[ E = mc^2 \]

energy \( \uparrow \)

mass \( \uparrow \)

\[ E_{\text{fusion}} = m_{\text{in}} c^2 - m_{\text{out}} c^2 \]

- mass converted to energy
- \( c^2 \) is a big \( \uparrow \) i.e. little mass gives lots of energy!
Core of sun

High pressure & density ⇒ lots of $p^+ p^+$ collisions (opportunities to fuse)

High temperature: ~ 15 million K

High temperature ⇒ high $p^+$ velocity

\[ < \frac{1}{2} m v^2 > = \frac{3}{2} kT \]

\[ \therefore \text{very fast speeds} \]

\[ p^+ \xrightarrow{v} \quad \xleftarrow{v} \quad p^+ \]

Speed ($v$) high enough: overcome coulomb potential (repulsion). Nuclei get close enough for strong nuclear force to win & fusion to occur.

Nuclear reaction in sun

Proton - Proton Chain
Fusion bomb (H-bomb)

\[ ^2\text{H} + ^3\text{H} \Rightarrow ^4\text{He} + ^1\text{n} \]

*deuterium*  
*tritium*

(natural isotope)  
(1/2 life = 12.3 yr)  
Needs to be replenished every~ 12 yrs or so  
- bomb yield will decay

To drive this reaction high H velocities required  
(to overcome the coulomb repulsion)

T~ 1-10 million °K needed to get right H velocities

Use fission bomb (U or Pu) to trigger/heat-up fission bomb

It is this fission trigger that makes H-bomb dirty (radioactive)
1. Proton-Proton Chain

- Proton-Proton chain in Sun
- Energy out to heat up surroundings at each step
- 6 protons in \( \rightarrow \) \( ^4 \text{He} + 2 \) protons out
- Change in mass \( \rightarrow \) out
  - \( \Delta m \approx 0.07\% \)
  - \( E = mc^2 \left[ \text{Einstein} \right] \)
- Still lots of energy
- Fusion Energy source in Sun

<table>
<thead>
<tr>
<th>(proton)</th>
<th>( ^{1} \text{H} + ^{1} \text{H} \rightarrow ^{2} \text{H} + e^+ + \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kinetic Energy out</td>
</tr>
<tr>
<td></td>
<td>Gamma</td>
</tr>
<tr>
<td>( ^{2} \text{H} + ^{1} \text{H} \rightarrow ^{3} \text{He} + e^+ + \nu )</td>
<td>Energy out</td>
</tr>
<tr>
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<td>Energy out</td>
</tr>
</tbody>
</table>
Fusion bomb (H-bomb) cont.

\[ ^2\text{H} + ^3\text{H} \rightarrow ^3\text{He} + ^1\text{n} \]

nuclear weapon needs to keep lump of nuclear reacting material together long enough to react (like to blow apart with partial reaction)

T(H-fusion-reaction)~ 1-10 million ⁰K –nothing strong enough to contain (even steel turns to vapor ~ 1/10,000’ th of this temperature)

inertial confinement

high Z material resists expansion by virtue of the inertia of its mass (tamper)

“bright idea”- use left over “scrap” \(^{238}\text{U}\) for tamper

Actually - \(^{238}\text{U}\) tamper used to get more “bang for $”

nuclear reaction activated

results—they get a bigger dirtier blast

Tsar Bomb- 1961 largest test 50 to 58 megatons of TNT used Pb tamper – so one of the “cleanest” nuclear explosions
Fusion bomb (H-bomb) cont.

\[ ^2\text{H} + ^3\text{H} \rightarrow ^3\text{He} + ^1\text{n} \]

**Castle Bravo** a dry fuel hydrogen bomb, 1954, at Bikini Atoll, Marshall Islands

- Fuel: \( ^6\text{Li}^2\text{H} = ^6\text{LiH} \)
- Natural Li: 7.5\% \( ^6\text{Li} \) + 92.5\% \( ^7\text{Li} \)

Bomb enriched to 40\% \( ^6\text{Li} \) + 60\% \( ^7\text{Li} \)

\[ ^6\text{Li} + ^1\text{n} \rightarrow ^4\text{He} + ^3\text{H} \]

Expected \( ^6\text{Li} \) to yield fusion fuel

\[ ^7\text{Li} + ^1\text{n} \rightarrow ^8\text{Li} \rightarrow \text{e}^- + ^8\text{Be} \]

\[ ^8\text{Be} \rightarrow 2 ^4\text{He} \]

Expected \( ^7\text{Li} \) to do

With fast n they got

\[ ^7\text{Li} + ^1\text{n} \rightarrow ^8\text{Li} \rightarrow ^4\text{He} + ^3\text{H} + ^1\text{n} \]

- increased fast n flux!
- more fission fuel!

- Fireball ~ 4.5 mi (~7 km) across within ~1 s
- Mushroom cloud – 1 min height 14 km, diameter 11 km
  - 10 min 40 km height, 100 km diameter

Expected 5 M ton – got 15 M ton yield
Fusion energy burns out – star collapses violently
– gravitational energy heats core to 13 billion K – tremendous pressures

Fe nuclei cook apart – decompose (photo dissociate)

\[ \gamma + ^{56}\text{Fe} \rightarrow 13 \alpha + 4 n. \]

Electrons capture occurs and nuclei decompose to neutrons (neutronization)

\[ e^- + p \rightarrow n + \nu_e, \quad \text{This neutrino blast escapes !!!!} \]

Collapsing star rebounds off of hard core of neutron star and explodes in supernova
(if massive enough neutron core collapses to gravitational black hole)
Electrons capture occurs and nuclei decompose to neutrons (neutronization)

\[ e^- + p \rightarrow n + \nu_e , \]  \hspace{1cm} \textbf{This neutrino blast escapes !!!!}

Collapsing star rebounds off of hard core of neutron star and explodes in supernova
(if massive enough neutron core collapses to gravitational black hole)

Neutrino’s from Supernova 1987A (Shelton)
$^{210}\text{Po}$

1897 discovered Marie & Pierre Curie - named after Marie's home Poland
mg $^{210}\text{Po}$ emits as many alpha particles as 5 g of radium
1/2 g quickly reaching a temperature above 750 K.
$^{210}\text{Po}$ emit a blue glow by excitation of surrounding air.
1 g $^{210}\text{Po}$ generates energy at the rate of 150 watts
applications: space craft – antistatic
lethal dose of only 0.12 micrograms

1934 \[ n + ^{209}\text{Bi} \Rightarrow ^{210}\text{Bi} \]
mg amounts producible using high n flux nuclear reactors -100 g/yr

\[ n + ^{209}\text{Bi} \Rightarrow ^{210}\text{Bi} \]
\[ ^{210}\text{Bi} \Rightarrow \beta^- + ^{210}\text{Po} \quad \tau = 5.01 \text{ days.} \]
\[ ^{210}\text{Po} \Rightarrow \alpha + ^{206}\text{Pb} \quad \tau = 138.38 \text{ days.} \]

$^{206}\text{Pb}$ non-radioactive

13-25
\[ ^{222}\text{Rn} \Rightarrow \alpha + ^{218}\text{Po} \quad \tau = 3.824 \text{ days.} \]
\[ ^{218}\text{Po} \Rightarrow \alpha + ^{214}\text{Pb} \quad \tau = 3.05 \text{ minutes.} \]
\[ ^{214}\text{Pb} \Rightarrow \beta^+ + ^{214}\text{Bi} \quad \tau = 26.8 \text{ minutes.} \]
\[ ^{214}\text{Bi} \Rightarrow \beta^- + ^{214}\text{Po} \quad \tau = 19.8 \text{ minutes.} \]
\[ ^{214}\text{Po} \Rightarrow \alpha + ^{210}\text{Pb} \quad \tau = 164 \text{ microseconds.} \]
\[ ^{210}\text{Pb} \Rightarrow \beta^- + ^{210}\text{Bi} \quad \tau = 22.3 \text{ years.} \]
\[ ^{210}\text{Bi} \Rightarrow \beta^- + ^{210}\text{Po} \quad \tau = 5.01 \text{ days.} \]
\[ ^{210}\text{Po} \Rightarrow \alpha + ^{206}\text{Pb} \quad \tau = 138.38 \text{ days.} \]
\[ ^{206}\text{Pb} \text{ stable} \]
\[ ^{206}\text{Pb} \text{ non-radioactive} \]
Liquid Metal cooled Fast Breeder Reactors (LMFBR)

"Pool" Design

- Control Rods
- Flow Baffle
- Coolant Level
- Fissile Core
- Breeder Blanket
- Reactor Pool Pump
- Biological Shielding
- Liquid metal coolant
- Heat exchanger
- Steam generator

- Steam (to power turbine)
- Water (from power turbine)

"Loop" Design

- Control rods
- Fissile Core
- Breeder Blanket
- Biological Shielding
- Liquid metal coolant
- Heat exchanger
- Steam generator

- Reactor loop (primary coolant)
- Intermediate loop
- Power-generation loop
- Intermediate loop
- Reactor loop (primary coolant)