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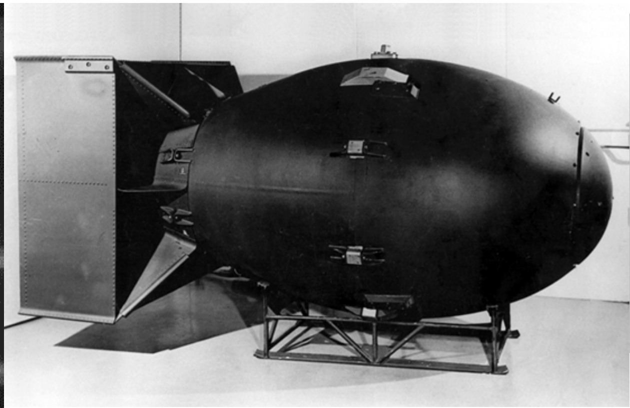

What is a Nuclear Weapon?

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Slim Pickens Courtesy of Columbia Pictures

Objectives

- Describe what constitutes a generic nuclear weapon.
- Discuss nuclear properties and physics associated with nuclear weapon operation.
- Discuss important differences between nuclear reactors and nuclear weapons.
- Compare and contrast energy release in weapons throughout human history.
- Explain basic nuclear weapon designs and function.

What is a Nuclear Weapon?

- Explosive Device
- Destructive force is derived from the release of binding energy in the nucleus
  - Fission
  - Fission and Fusion
- Commonly referred to as:
  - Atomic Bombs or Weapons
  - Thermonuclear Weapons or Hydrogen Bombs

Properties and Mechanisms that Support Nuclear Weapon Operation

NUCLEAR FISSION

Fission Process

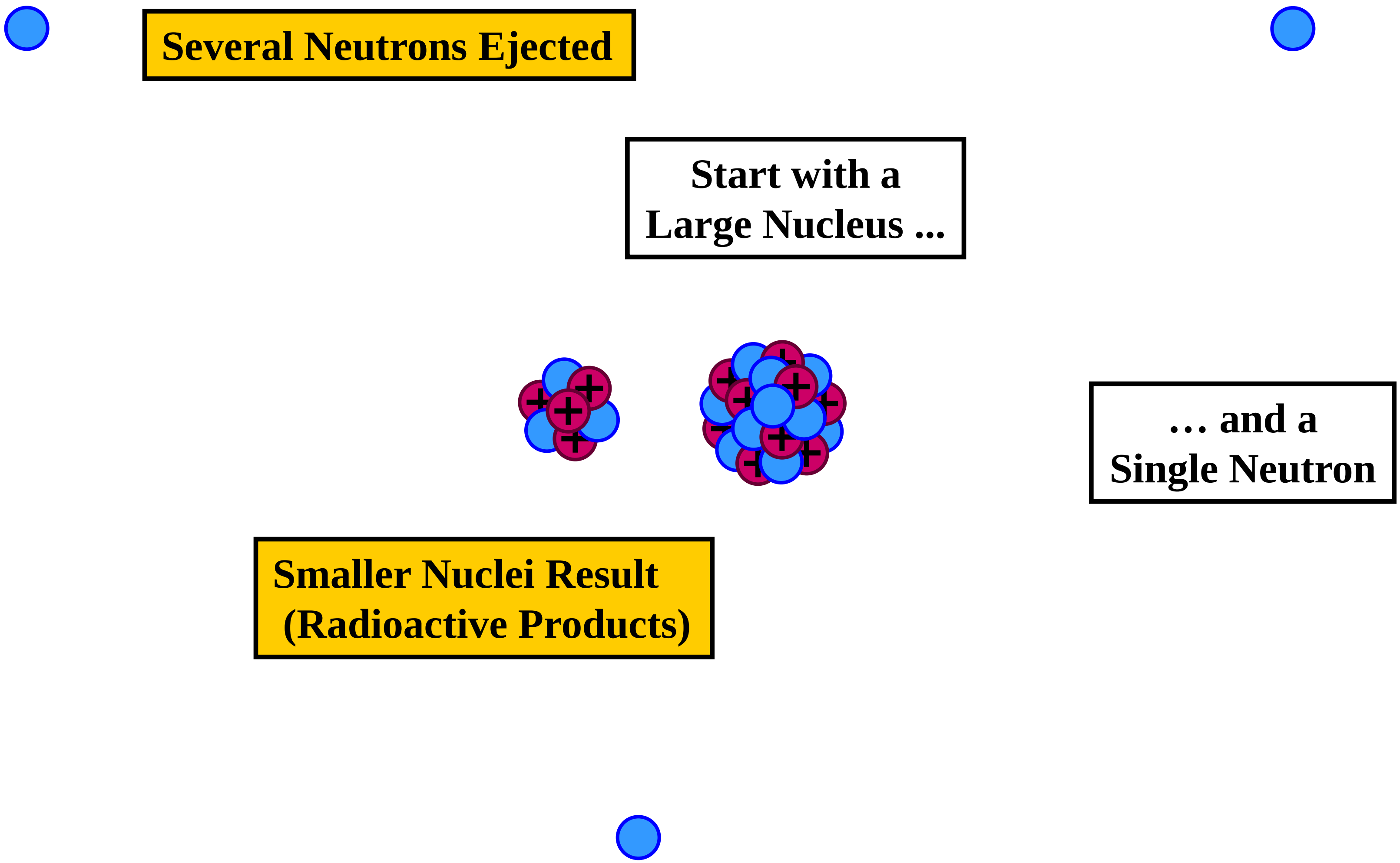
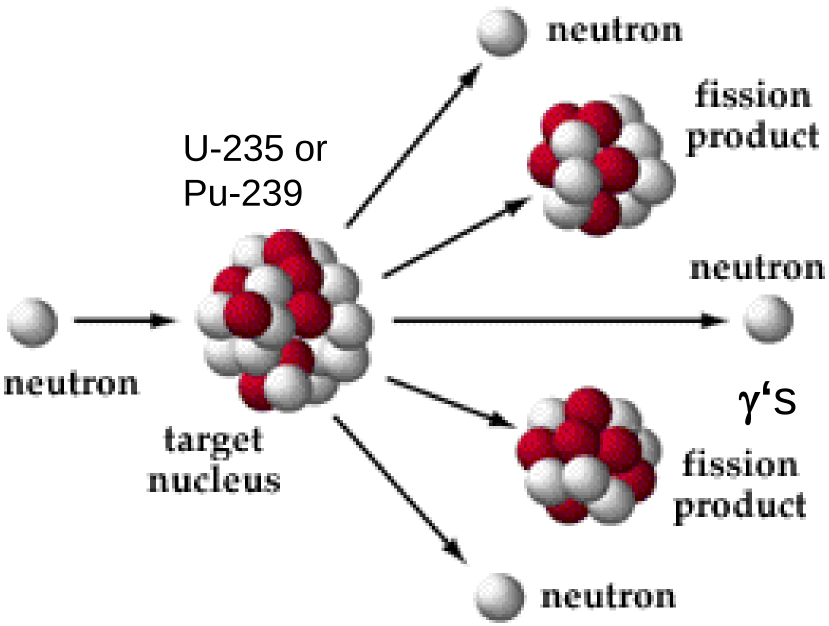


Image courtesy of Scottie Walker

Fission Products



Average Energy Release ~ 200 MeV (180 MeV, prompt).

Average number neutrons emitted per fission:

- $\bar{\upsilon}$ = 2.5 (^{235}U)
- $\bar{\upsilon}$ = 2.9 (^{239}Pu)

Neutrons are emitted with an average KE of ~ 1 MeV

- $1.4E7\,\frac{m}{s}$
- $14\,\frac{m}{\mu s}$

Fission Energy Density (J/gm)

$$\frac{6.02\cdot 10^{23}\ fissions}{236\ grams}\cdot\frac{180\ MeV}{fission}\cdot\frac{1\ Joule}{6.24\cdot 10^{12}\ MeV} = 74\ GJ/g = \ \ 74\ TJ/kg$$

Image courtesy of Scottie Walker

Suitable Nuclear Materials

- Special Nuclear Materials
  - Pu
  - ^{233}U
  - ^{235}U
  - ^{3}H (tritium)
- Fissile Materials
  - Fissionable
  - Neutron requires no kinetic energy
  - e.g. ^{239}Pu
- Fissionable Materials
  - Fissionable
  - Neutrons requires a threshold kinetic energy
  - e.g. ^{238}U

Critical Mass

- The least amount of fissionable material that will allow a self-sustaining nuclear chain reaction, or criticality.
- The critical mass depends on
  - Isotope
  - Chemical form
  - Geometry
    - Material
    - Reflector
  - Density

Energy and Mass Equivalence

- Einstein's Relation
  - $E = mc^2$
  - We're more interested in $\Delta E = \Delta mc^2$
  - 1 amu = 931.5 MeV

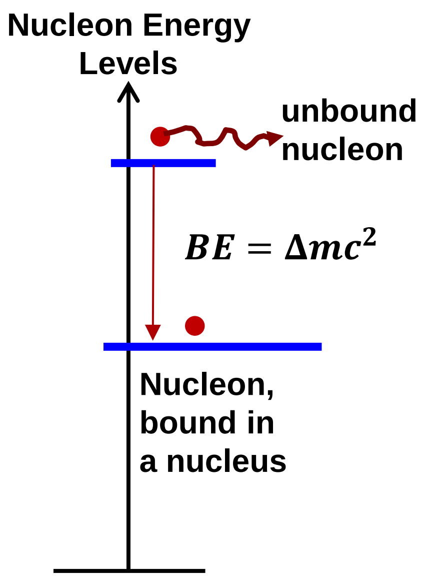
- Mass difference produces energy release

$$\Delta M = M_{parent} - \left(M_{fission\ frags} + M_{ejected\ neutrons}\right)$$

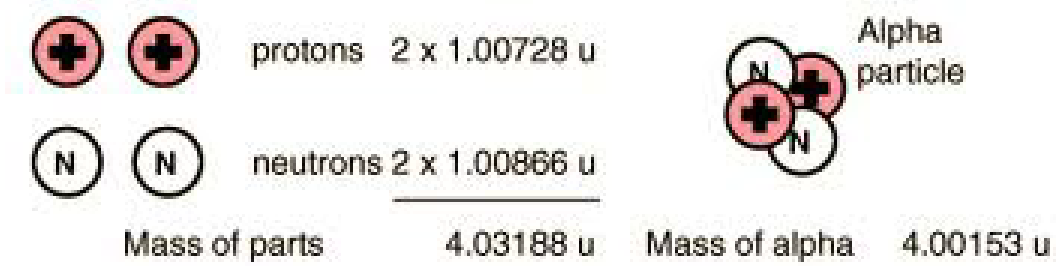
- Total fission (or fusion) energy released is called the *Q-value* of the reaction

$$Q = \Delta mc^2$$

Binding Energy – Splitting or Forming the Nucleus



Unbound nucleons **He-4 nucleus**



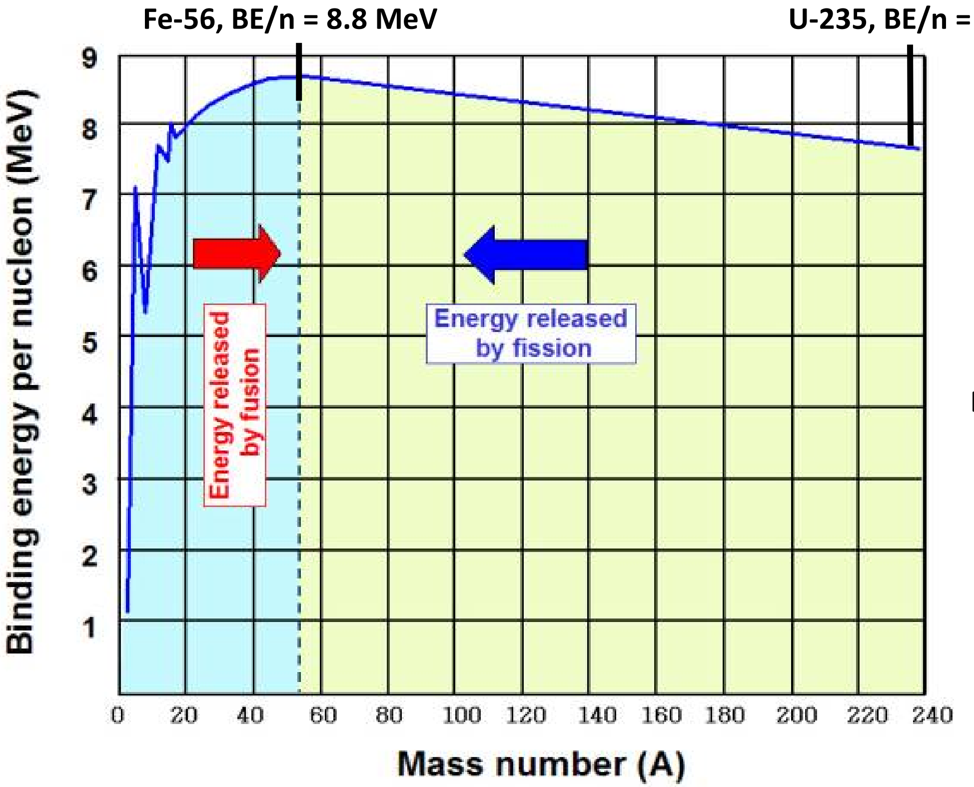
BE = (4.03188 – 4.00153) u x 931.5 MeV per u = 28.3 MeV

BE/n = BE per nucleon = 28.3 MeV/4 nucleons = 7.08 MeV/nucleon

- When the nucleus is formed, some of their mass is converted to energy and released.
- This energy released is called the Binding Energy (BE) of the nucleus.
- It's reversible--to completely disassociate the nucleus, you need to supply Energy = BE
  - The higher the BE, the lower the energy state on the diagram above

Image: http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/radact.html

Curve of Binding Energy



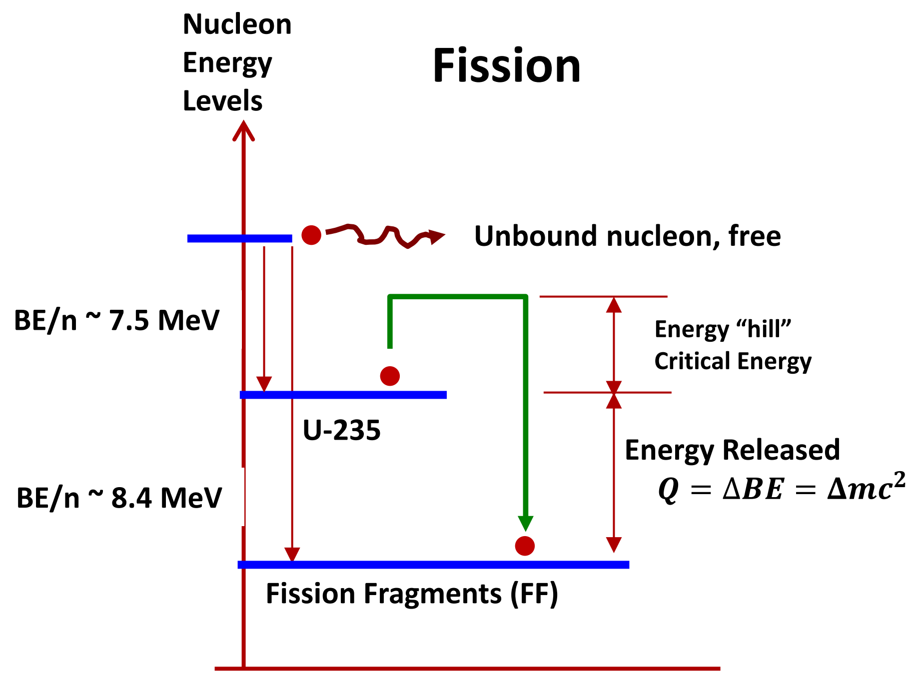
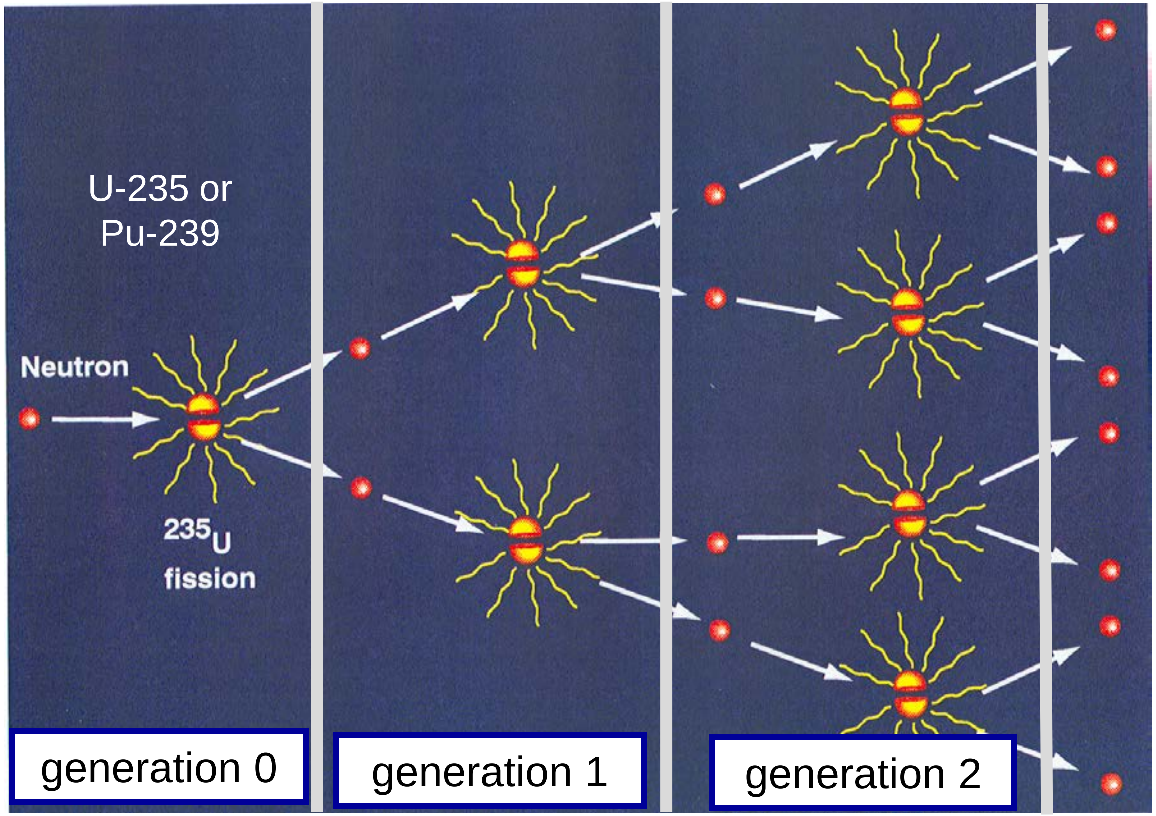


Image: http://www4.nau.edu/meteorite/meteorite/Images/BindingEnergy.jpg

Fission Chain Reaction



Relate to population “explosions”
Fission = birth

ν ~ fertility = 2-3 for stable pop.

Capture = death w/o fission

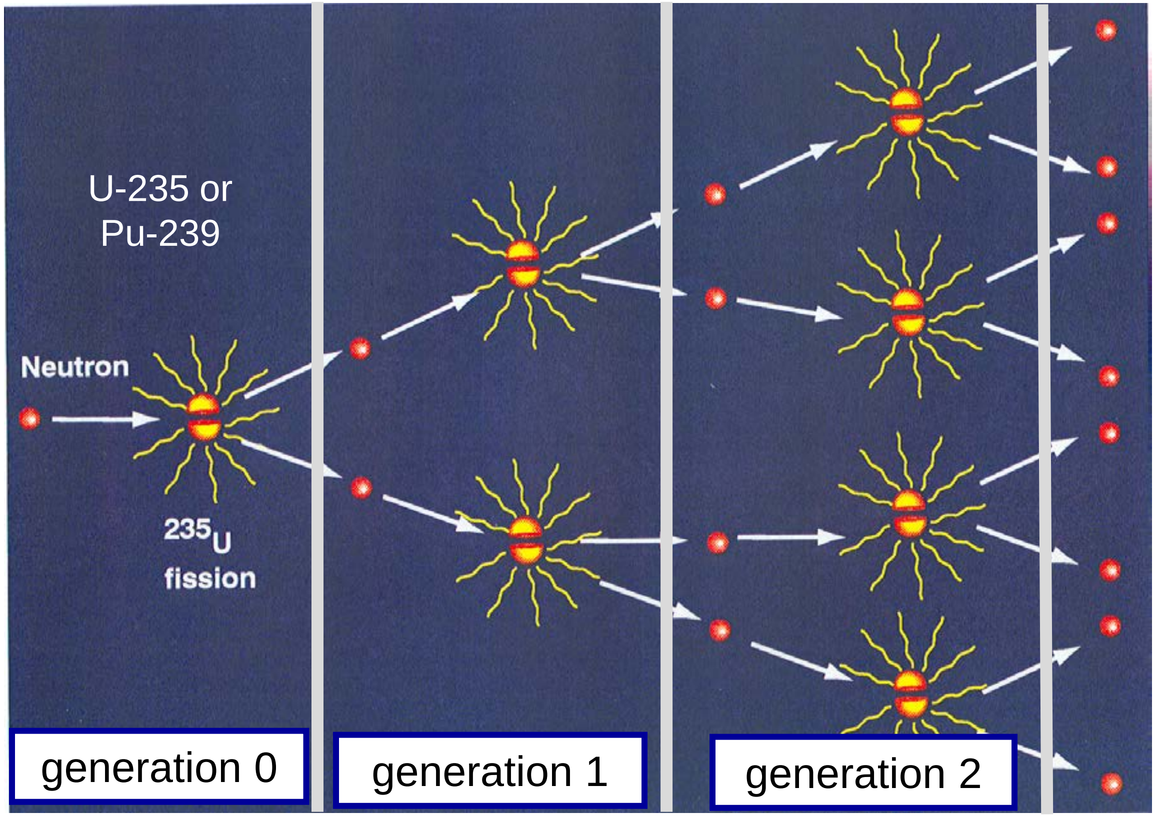
Leakage = system loss

In a nuclear bomb the total number of fissions grows exponentially

- generation = one birth – death cycle of the neutrons
- Since the fission process creates ν neutrons per fission, an explosive chain reaction is possible.

Image: DOE Office of Nonproliferation and National Security, 1995

Multiplication Factor (k)



k = # of fissions per fission in the previous generation

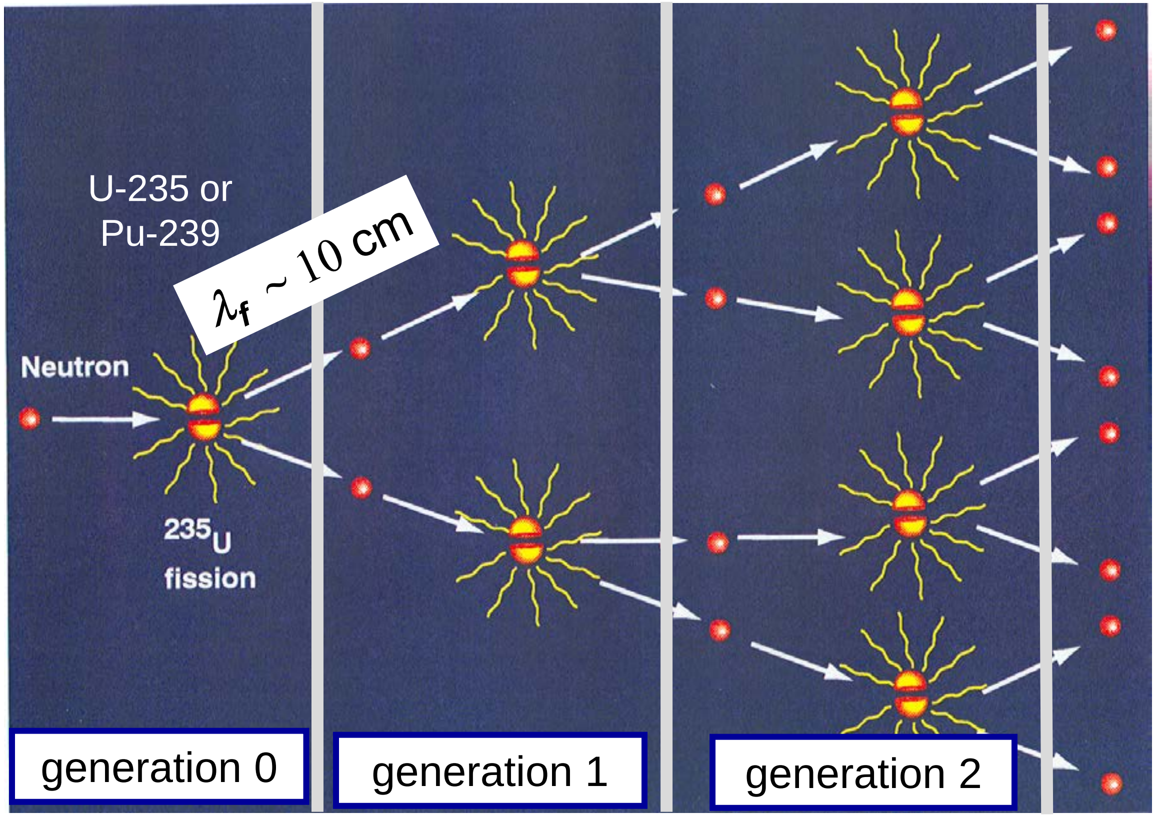
k = 2 in the picture

k – depends on material and geometry of system

- 3 possible situations for k
  - K < 1 subcritical
  - K = 1 critical
  - K > 1 supercritical

Image: DOE Office of Nonproliferation and National Security, 1995

Fission Chain Time



Key difference between a nuclear reactor and nuclear weapon is the generation time:

- Reactor power τ ~tens of seconds
- Weapon τ ~10's μs

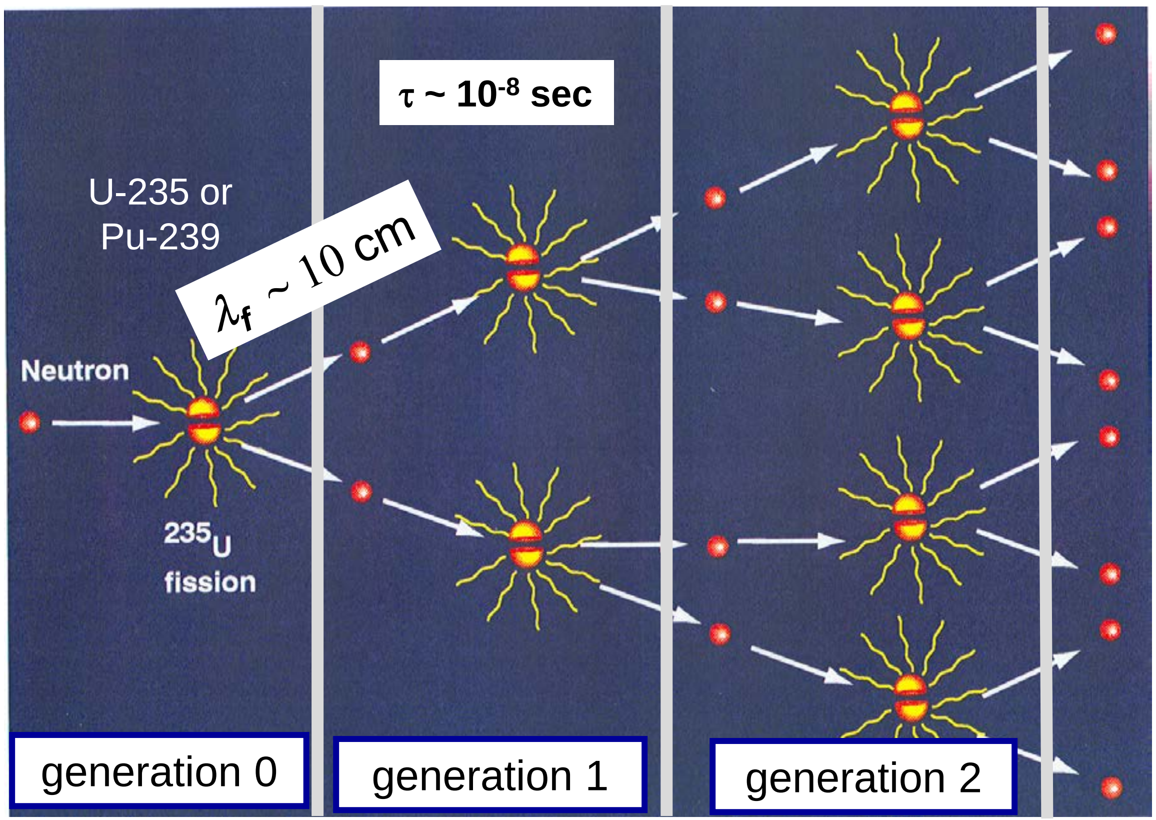
Mean fission generation time (τ) - the average time between when a neutron is "born" in fission and when it causes another fission in the next generation.

$\tau = 10^{-8}$ sec (1 shake) for weapons.

Image: DOE Office of Nonproliferation and National Security, 1995

Fission Generation Rate Factor (α)

- Alpha (α) measures the "potential" growth rate, $\dot{N}$, in the neutron population.
- But you need a starting, free neutron to initiate the chain!



α = the net increase in number of fission neutrons per fission neutrons in the previous generation per unit time:

$$\alpha = \frac{k-1}{\tau}$$

So the growth rate at any instant is just alpha times the neutron population at that instant:

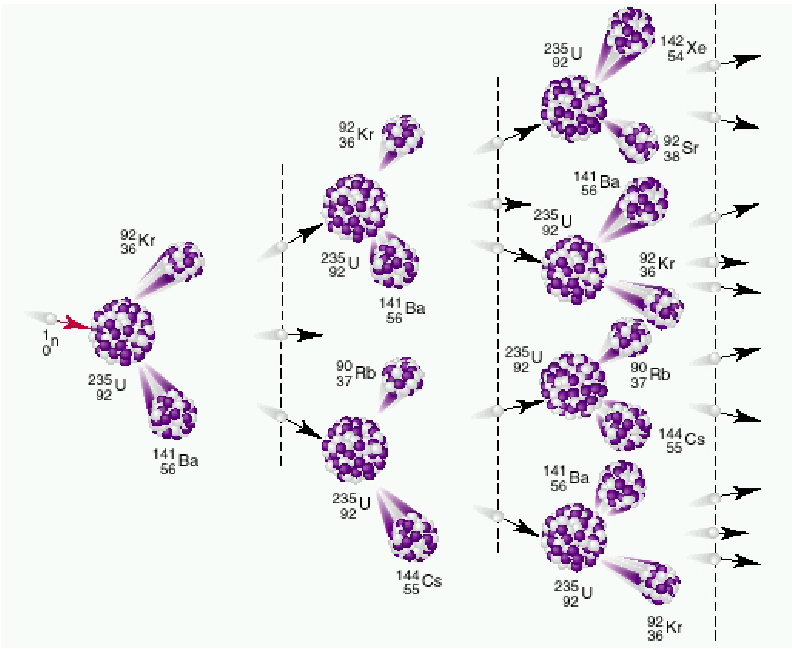
$$\dot{N} = \alpha \cdot N$$

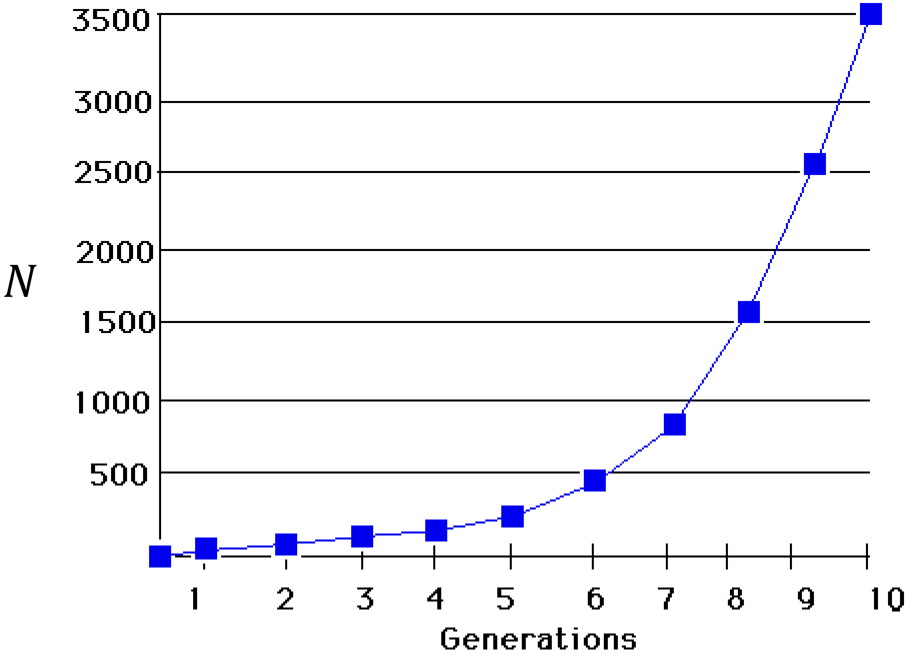
Image: DOE Office of Nonproliferation and National Security, 1995

Fission Growth

$$\dot{N} = \alpha \cdot N \quad \Rightarrow \quad N = N_0 \cdot e^{\alpha \cdot t}$$

$\alpha \cdot t$ = number of generations (g)





http://utahthoriumenergy.org/wp-content/uploads/2013/10/chain-reaction-picture.jpg

Energy Buildup in a Fission Device

$$E(g) = 7.5 \cdot 10^{-21} \cdot e^{g} \text{ (tons of TNT equiv.)}$$

Number of Generations	Fissions $N = e^g$	Energy (TNT eq.)	Energy "density" (J/g)	Comments
0	1	0	0	
10	2.2E4	--	--	
20	4.8E8	--	--	
35	1.6E15	--	0.7	
39	8.7E16	--	39	
40	2.3E17	--	106	
42	1.7E18	--	784	
44	1.3E19	0.1 tons	6750	TNT ~ 4200 J/g
46	9.5E19	0.7 tons	4.3E4	
48	7.0E20	5.2 tons	3.2E5	Plasma
50	5.2E21	39 tons	2.3E6	
52	3.8E22	290 tons	1.7E7	
54	2.8E23	2.1 kT	1.3E8	
56	2.1E24	15.7 kT	9.4E8	1.4 %
58	1.6E25	116 kT	6.9E9	11 %
60.3	1.5E26	1.1 MT	74E9	100 %

Assuming α = 1 g/shake

Most of the energy is released in the final few generations!

Properties and Mechanisms that Support Nuclear Weapon Operation

NUCLEAR FUSION

Fusion Process

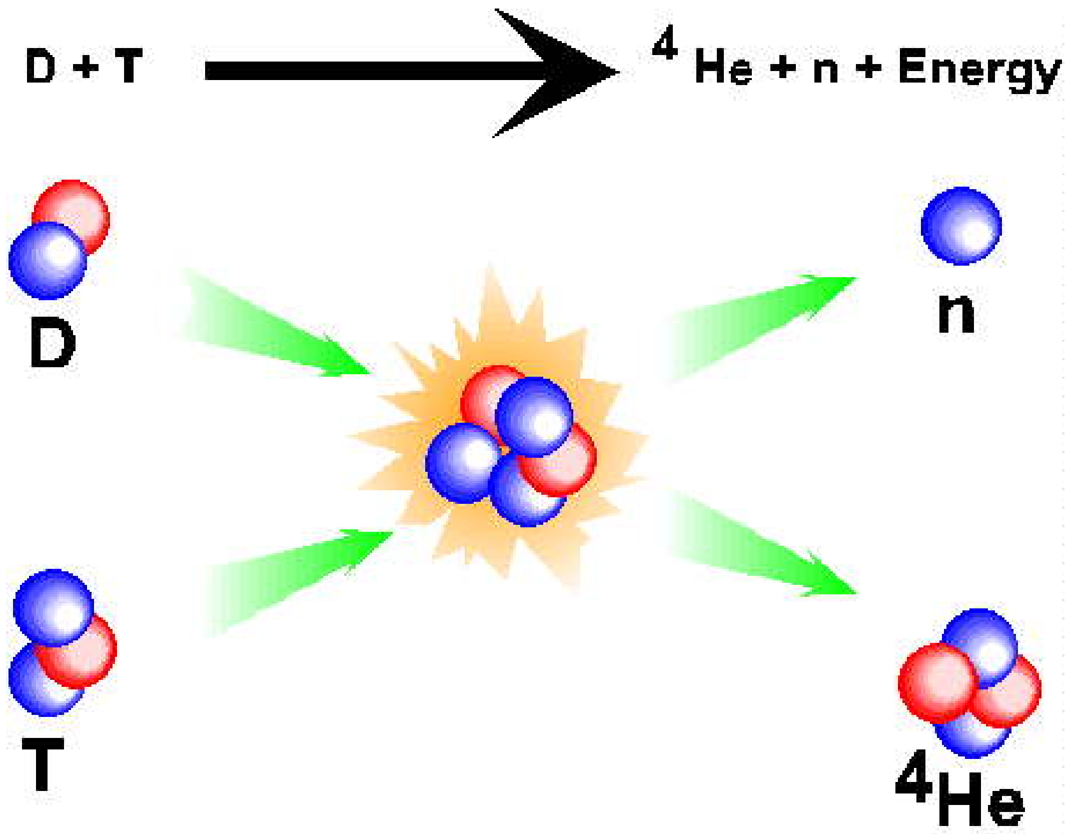
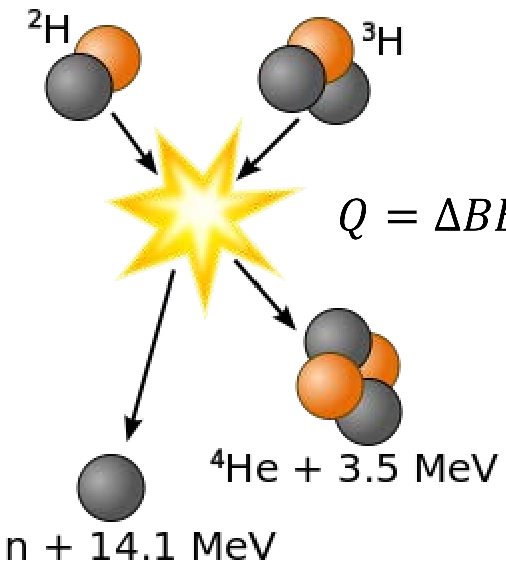


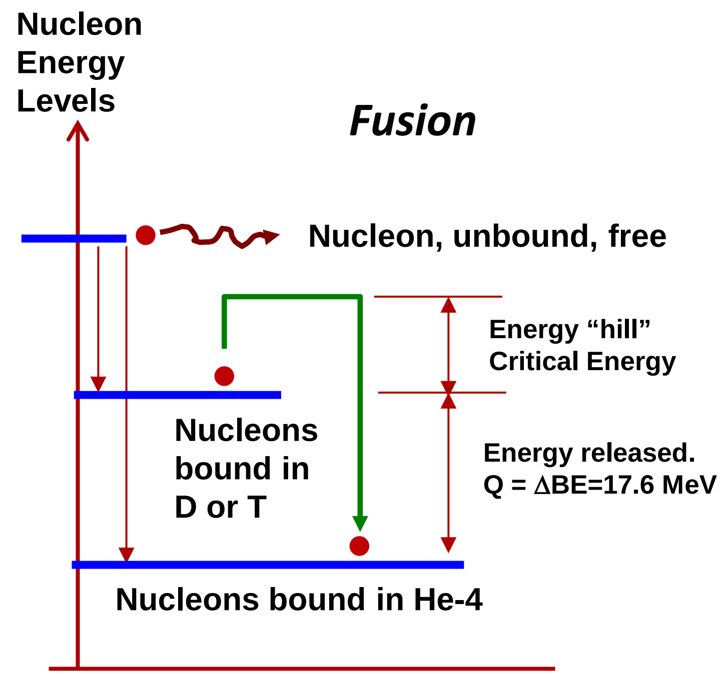
Image courtesy of Scottie Walker

Energy from Nuclear Fusion

Smaller Q value, but greater energy density



$$Q = \Delta BE = 17.6\ MeV$$



Fusion Energy Density (J/gm)

$$\frac{6.02 \cdot 10^{23}\ fusions}{5\ grams} \cdot \frac{17.6\ MeV}{fusion} \cdot \frac{1\ Joule}{6.24 \cdot 10^{12}\ MeV} = 340\ GJ/g = \ \ 340\ TJ/kg$$

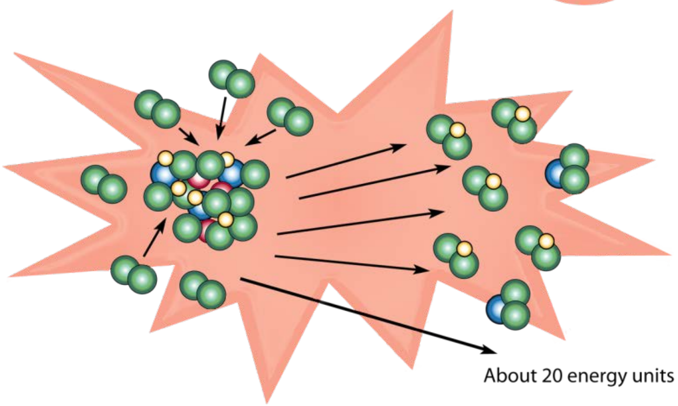
Image: http://upload.wikimedia.org/wikipedia/commons/5/5d/Checker-16x16.png

ENERGY RELEASE COMPARISONS

Conventional High Explosives (TNT)

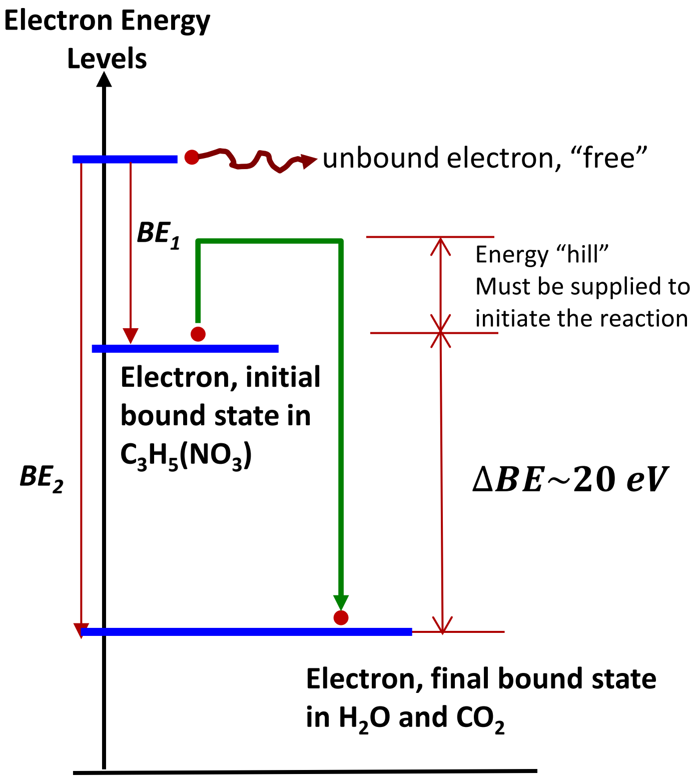
Change in electron binding energy

$C_3H_5(NO_3)_3 + nO2 \rightarrow CO_2 + H_2O + NOx + \ldots + \text{~20eV}$



- About 20 eV per chemical reaction
- Energy density about 4.2 MJ/kg

MOAB ~ 10 tons TNT eq. 3.3 ft x 40 ft



Energy Density and Yield

- Energy density of TNT = 4.2 MJ/kg
- Energy density of fission (^{235}U, ^{239}Pu or SNM) = 74 TJ/kg
- Ratio: $\dfrac{74x10^{12}\dfrac{J}{kg\ SNM}}{4.2x\ 10^{6}\dfrac{J}{kg\ TNT}}$ = 17.6 x 10^6 kg of TNT per kg of SNM
- Complete fission of 1 kg SNM = 17.6 kT of TNT

Energy Density (J/g) Over Time

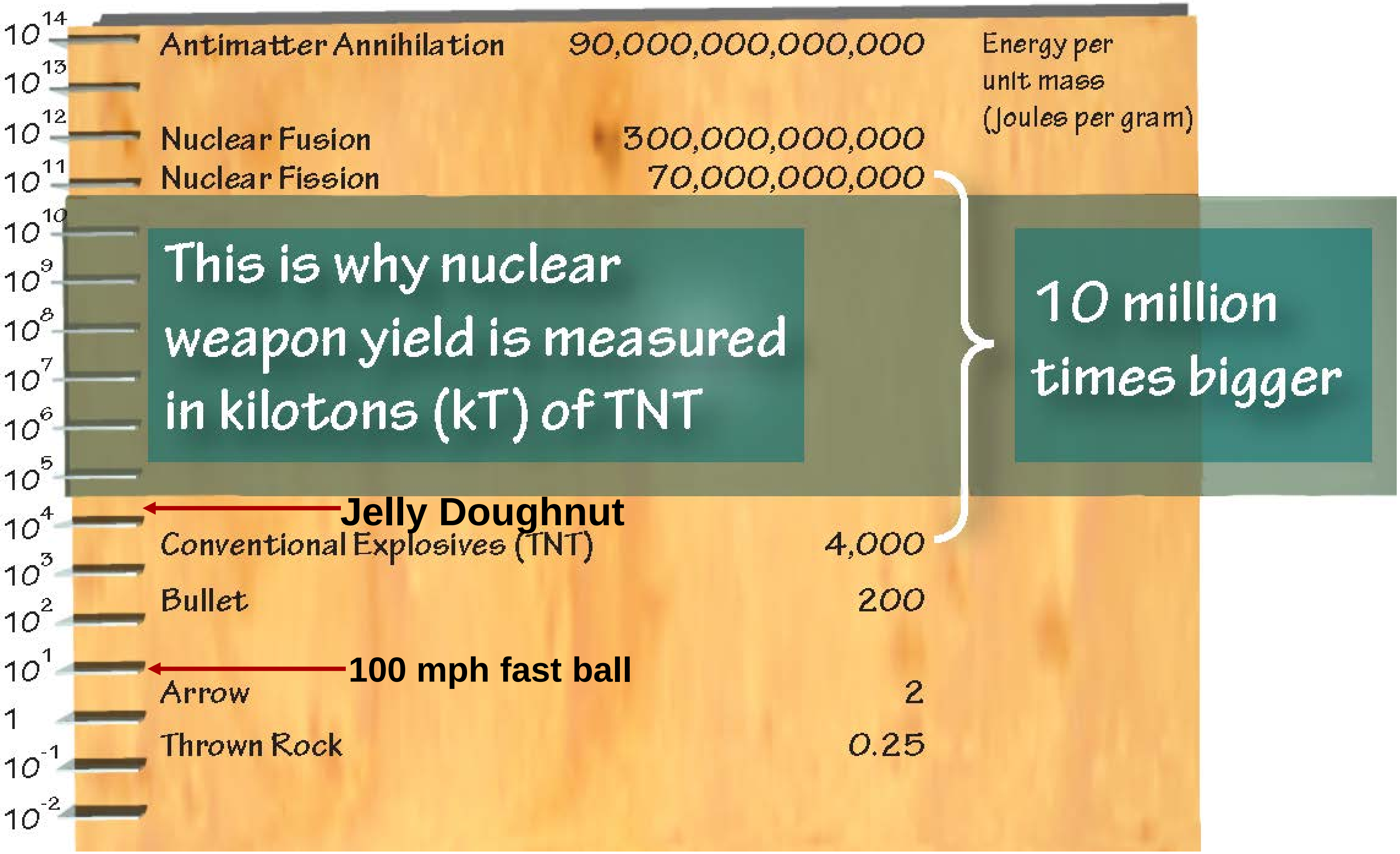
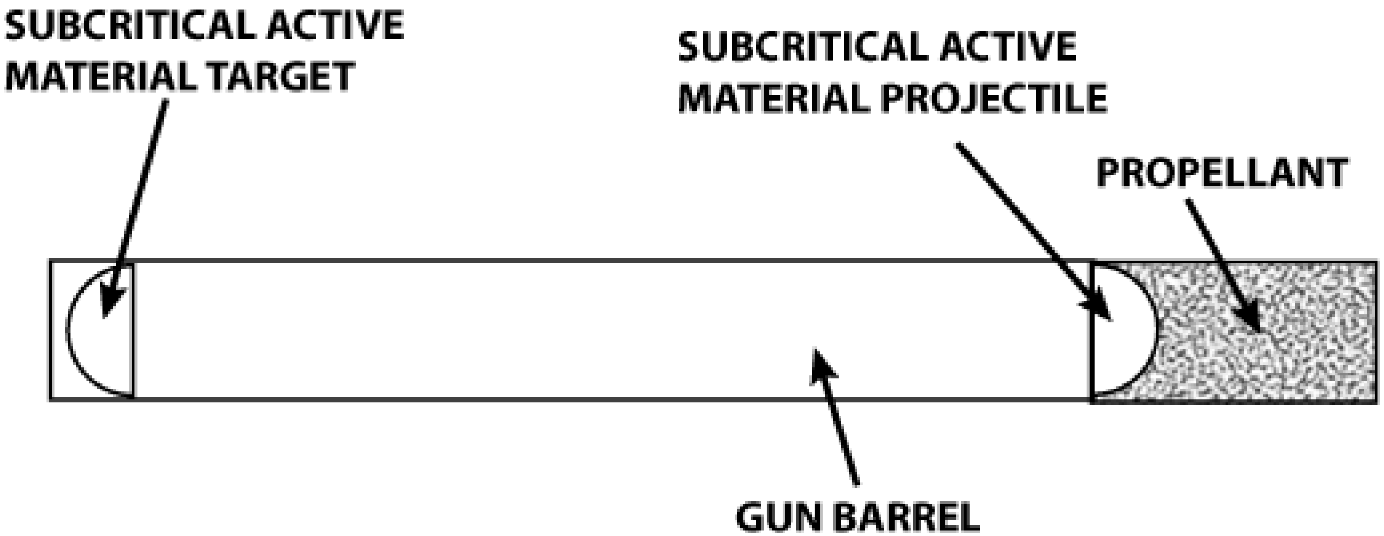


Image courtesy of Scottie Walker

BASIC NUCLEAR WEAPON DESIGNS

Gun-Type Nuclear Weapon



Mk-I "Little Boy"

Width: 0.71 m

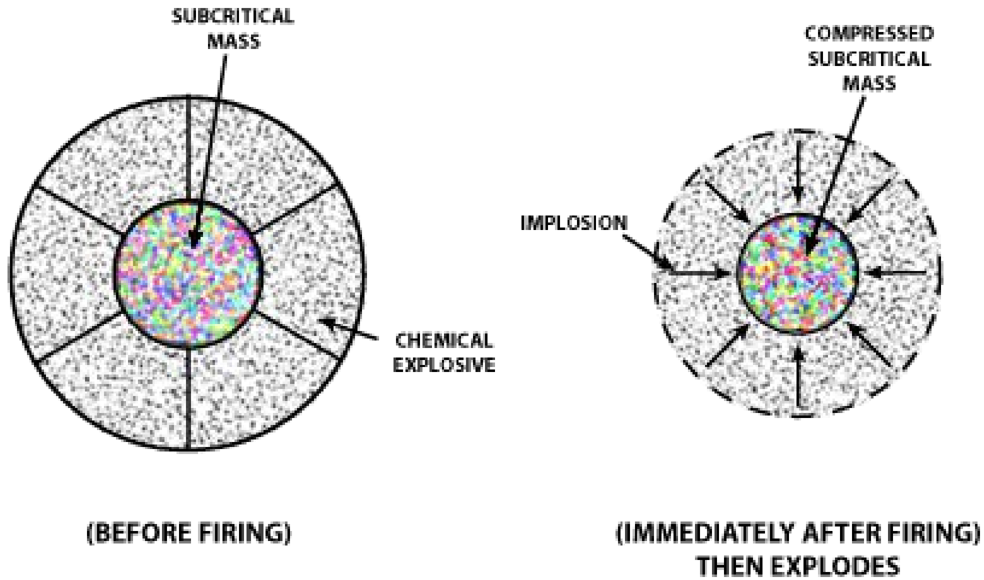
Length: 3.05 m

Weight: 4045 kg

Yield 15-16 kT

Photo Courtesy of Sandia National Laboratories

Implosion Type Nuclear Weapon



Mk-II "Fat Man"

Width: 1.53 m

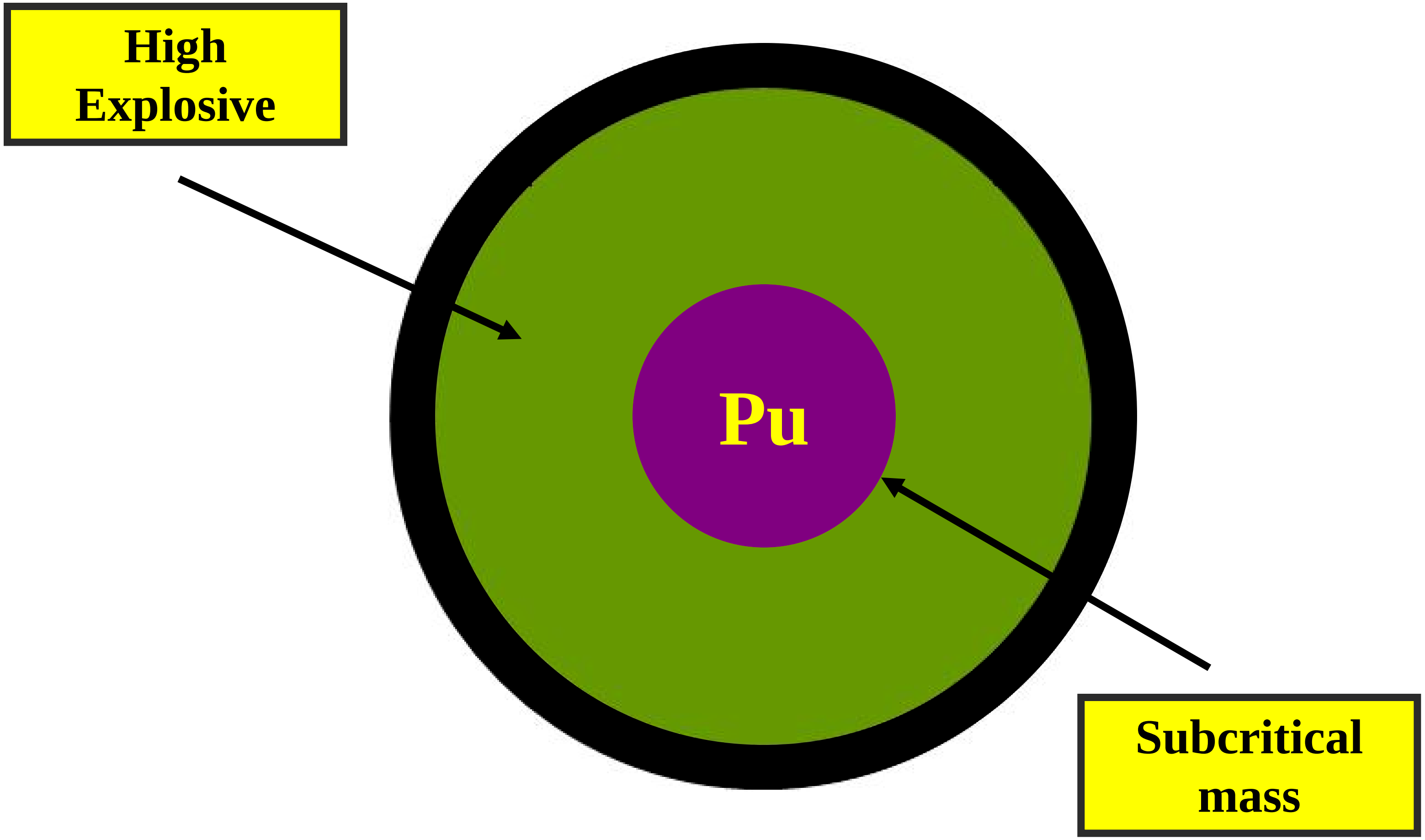
Length: 3.25 m

Weight: 4680 kg

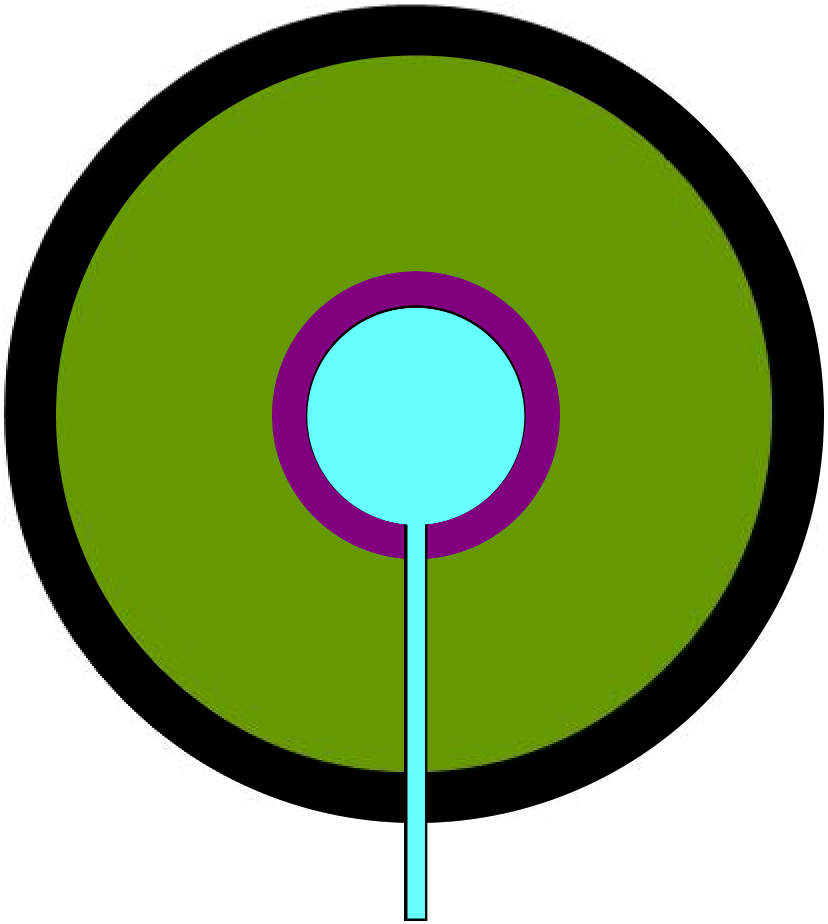
Yield: 21 kT

Photo Courtesy of Sandia National Laboratories

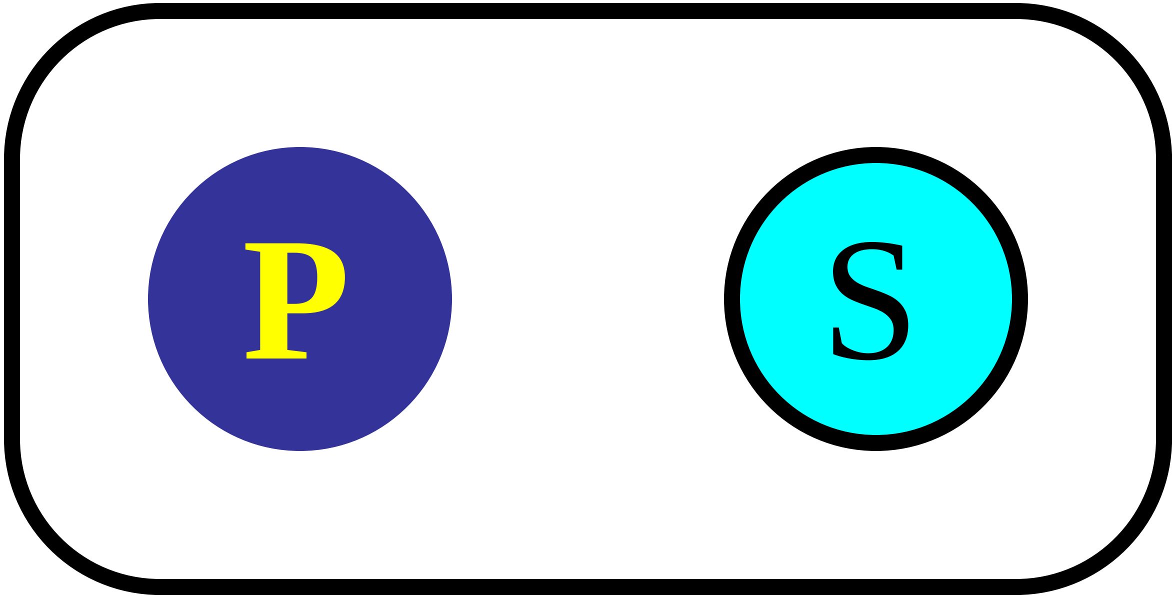
Implosion Warhead



Boosted Warhead



2-Stage Thermonuclear



EXAMPLE WARHEAD DESIGNS AND EQUIPMENT

Bomb and Warhead Shapes

Cruise Missile Warhead

Davy Crockett

Slim Pickens
Riding a B-15

Warheads Mounted on a
Reentry System

Gravity Bomb Components

Photos Courtesy of Sandia National Laboratories
Slim Pickens Courtesy of Columbia Pictures

The End

QUESTIONS (THAT I'M ALLOWED TO ANSWER)?