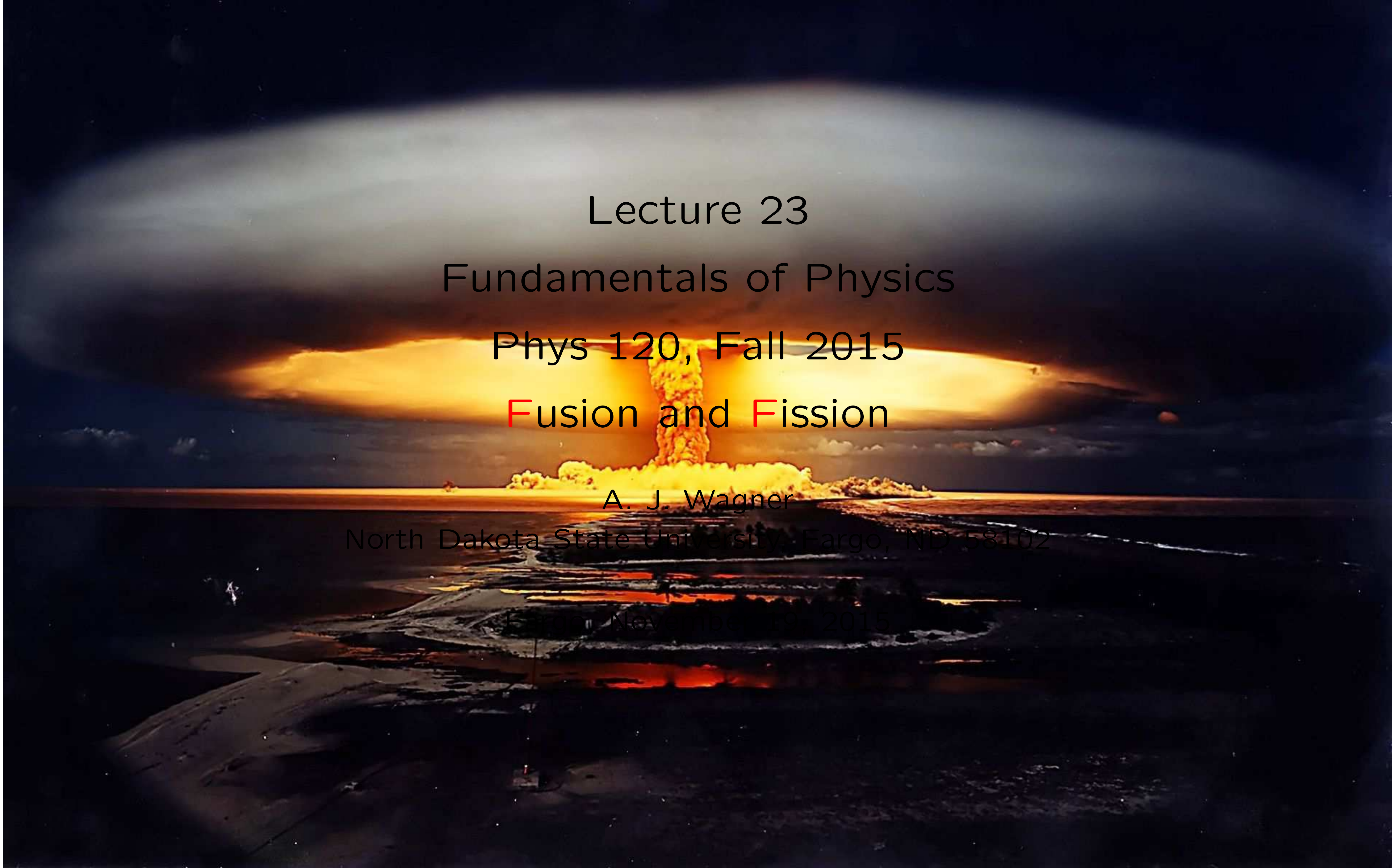

Lecture 23

Fundamentals of Physics

Phys 120, Fall 2015

Fusion and Fission

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Overview

- Review of The Nuclear Energy curve
- Bombarding matter with alpha radiation and neutrons
- One natural fissionable element $^{235}_{92}U$
- Chain reactions
- Nuclear bomb design

Concept Check

How do we know what the energy contained in a nucleus is?

(Remember, we discussed the nuclear energy curve last lecture, and we gave an example of how the different energies of the nuclei are determined)

a) We fuse the nuclei and measure the released energy.
b) We examine the chemical properties of the Elements.
c) We weigh the Elements.
d) We bombard the Elements with neutrons and examine the energy released/absorbed.

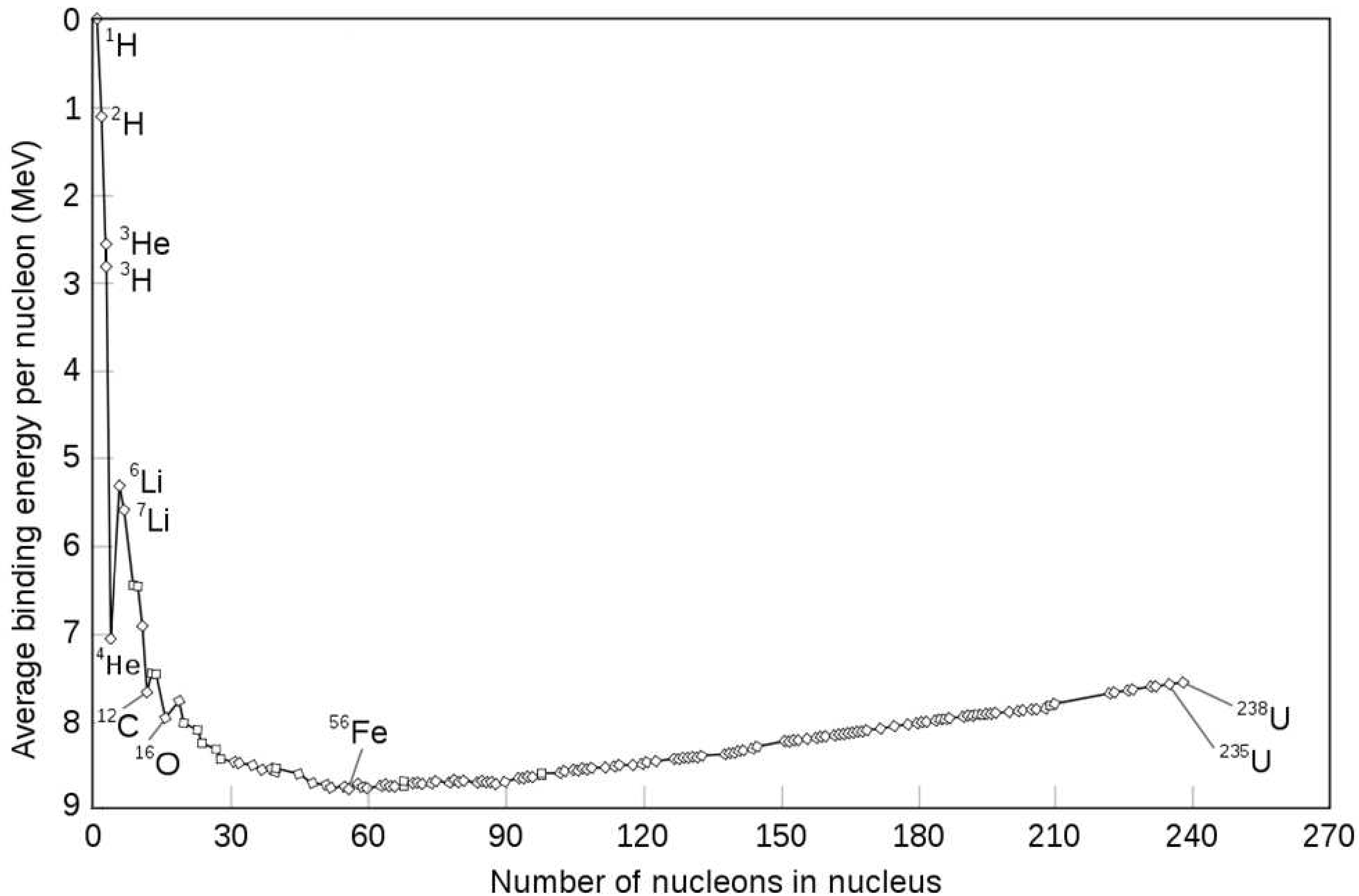
Answer

The best way of determining the energy of an Element is to weigh it and then use Einstein's

$$E = mc^2 \tag{1}$$

to determine the Energy of the atoms!

The nuclear energy curve



The origin of elements

Big bang: ‘^1_1H,^2_1H,^3_2He,^4_2He,^7_3Li and ^3_1H,^7_4Be.

Sun: First $H \rightarrow He$ then heavier elements up to Fe.

Super novae: bombarding elements with neutrons and alpha particles to generate higher-energy nuclei.

Man-made nucleosynthesis

1933: Irene Joliot-Curie bombarded aluminum foil with alpha particles and generated a new form of radioactive phosphorus

$$^{27}_{13}Al +^{4}_{2} He \rightarrow^{30}_{15} P +^{0}_{1} n$$

In nature we find $^{31}_{15}P$ which is stable. The new $^{30}_{15}P$ decays to $^{30}_{14}Si$ with a half-life of 2.5 min. The Alchemist's dream of transmuting elements has been realized for the first time!

1934: Enrico Fermi started bombarding nuclei with the newly discovered neutrons. He built up larger and larger atoms.

But in the neighborhood of uranium the recipe strangely failed (sometimes)

Ida Noddack suggested that the nucleus could be thought of as a drop and might break up during the capture of neutrons

Hahn and Meitner show that uranium can be broken up in this way (fissioned).

Hitting Uranium with neutrons

The largest stable element that is found abundantly on earth is Uranium. When one bombards uranium with a neutron it either absorbs it to give

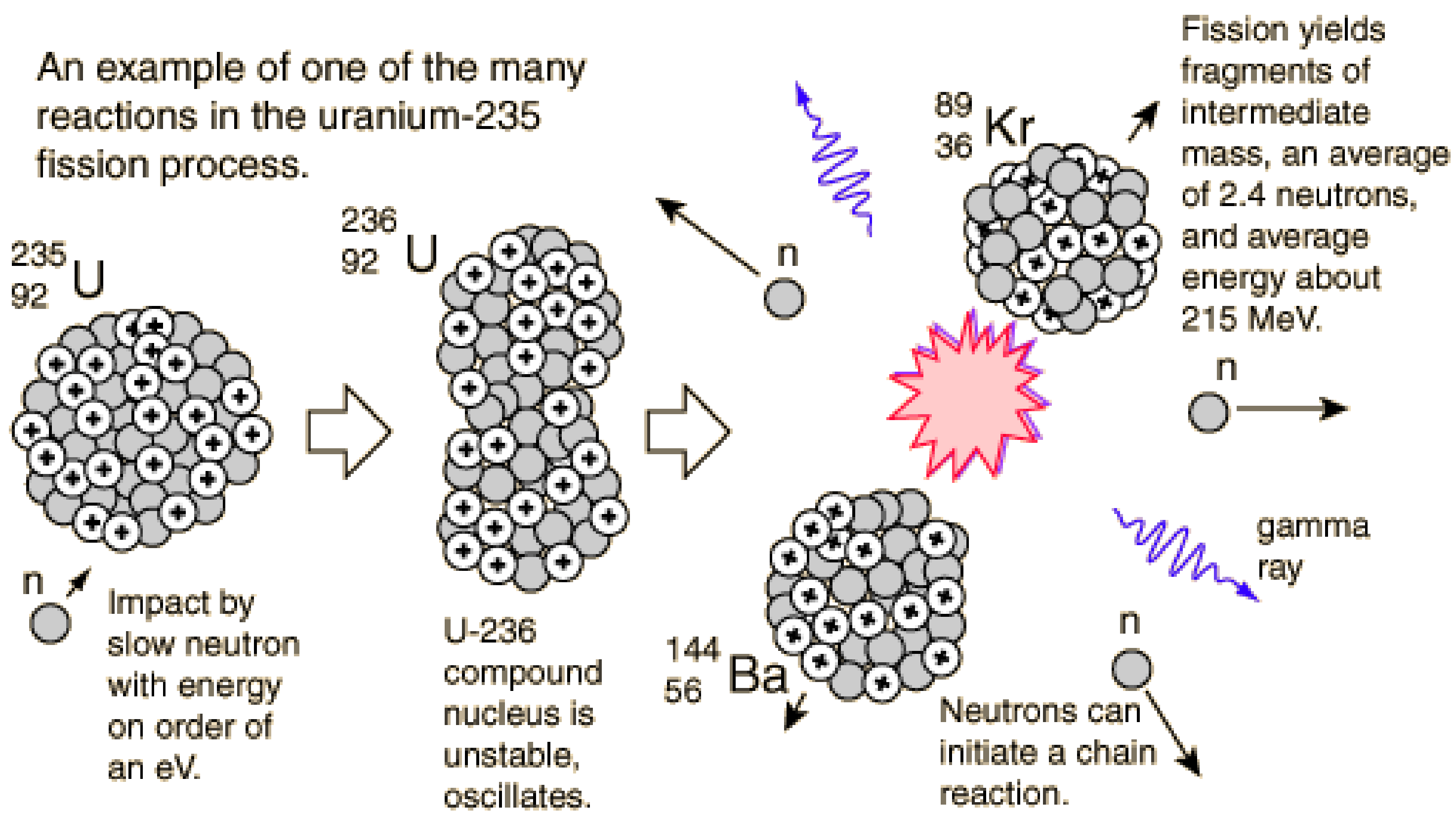
$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U \stackrel{\beta}{\rightarrow} {}^{239}_{93}Np \stackrel{\beta}{\rightarrow} {}^{239}_{94}Pt$$

and two new elements Neptunium 239 (2.4 day half-life) and Plutonium 239 (24,000 y) are created.

However, a small fraction ($\approx$ 1%) of naturally occurring uranium is $^{235}_{92}U$. When it is hit by a neutron it can reach an excited state that breaks up into two smaller nuclei in a process called fission.

Uranium fission

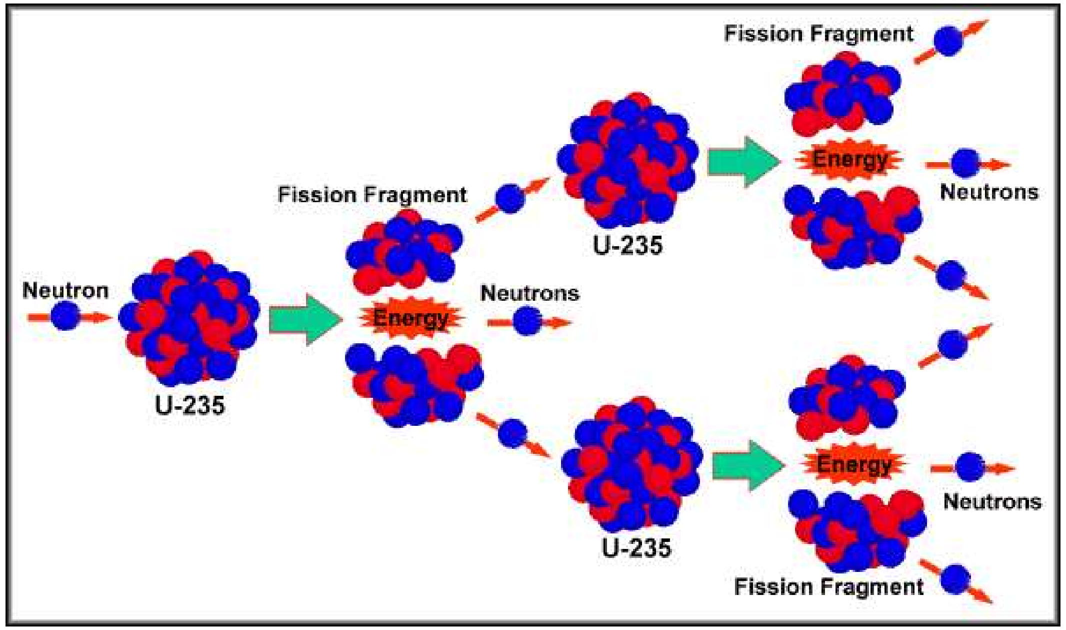
When $^{235}_{92}U$ is hit by a neutron it has a high likelihood of breaking up roughly in half. There are many possible daughter nuclei, but all of them have fewer neutrons, so two or three neutrons are typically released in the fission event.



Chain reaction

If this happens in normal uranium these neutrons will be absorbed by the abundant $^{238}_{92}U$. However, if only had $^{235}_{92}U$ these neutrons could act as driving forces for new fission events.

This opens the possibility of a chain reaction in which the splitting of one $^{235}_{92}U$ causes the splitting of more than one $^{235}_{92}U$. The number of split atoms then increases exponentially.



Since each fission event is associated with a release of energy, this gives the potential for a potent bomb.

The development of gunpowder in the 9th century in China led to the invention of bombs as military devices in the 11th century. Original bombs consistest of gunpowder enclosed in bamboo. Later versions included iron casings that increased the explosive power significantly.

Knowledge about gunpowder reached the Islamic states around 1250. The very first time gunpowder was used in the Western world for military purposes was in 1262, when king Alfonso X of Castile set siege to the city of Niebla in Spain whose Spanish-Arab inhabitants used some sort of primitive gun against the Spaniards.

..The Arabs threw many (iron) balls launched with thunder, the Christians were very afraid of, as any member of the body hit was severed as if with a knife; and the wounded man died afterwards, because no surgery could heal him, in part because the balls were hot as fire, and apart of that, because the powders used were of such nature that any ulcer done meant the death of the injured man...

.. and he was hit with a ball of the thunder in the arm, and (the arm) was cut off, and died next day: and the same happened to all of those injured by the thunder. And even now the story is being told amongst the host...

How bombs work

Simplest bomb: take a closed container partially filled with water and heat it up. As the water begins to boil the pressure inside the container increases until it finally breaks apart. Since this mechanical failure of the container is a run-away process (the partially fractures container is less stable than the whole container) the container disintegrates quickly and the compressed gas inside expands rapidly.

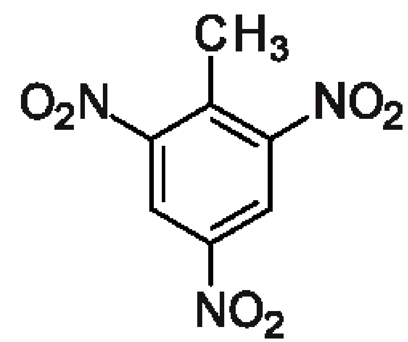
Damage: The damage caused by this bomb has three causes:
I: the shockwave of pressure can cause significant damage as it interacts with materials or living organisms.
II: shrapnel from the container accelerated to high velocities can cause significant damage.
III: the heat can cause damage.

This is a quite general cause of damage from explosions of bombs.

Chemical bombs

Low explosives materials like gunpowder, that don't react quickly enough, will not react in an explosive manner. These materials have to be contained and the heating and outgassing have to build up a high pressure which in turn will rupture the container (like in the previous example).

High explosives materials like plastic explosives where the reaction proceeds through the material faster than the speed of sound do not require the casing to achieve an explosive combustion. However, sometimes a casing is added to provide shrapnel projectiles. The standard for high explosives is Trinitrotoluene (TNT)



Next we will talk about using uranium as a fuel for a bomb.

Enriching uranium

For the chain reaction to happen we need to have more neutrons created then are absorbed (or lost to the outside). This means there cannot be a lot of $^{238}_{92}U$ around.

One needs to separate the uranium isotopes, and that is the difficult step in building a nuclear bomb. Chemistry does not help and there is only a slight difference in weight.

However, it can be done using centrifuges in a repeat process.

Concept check

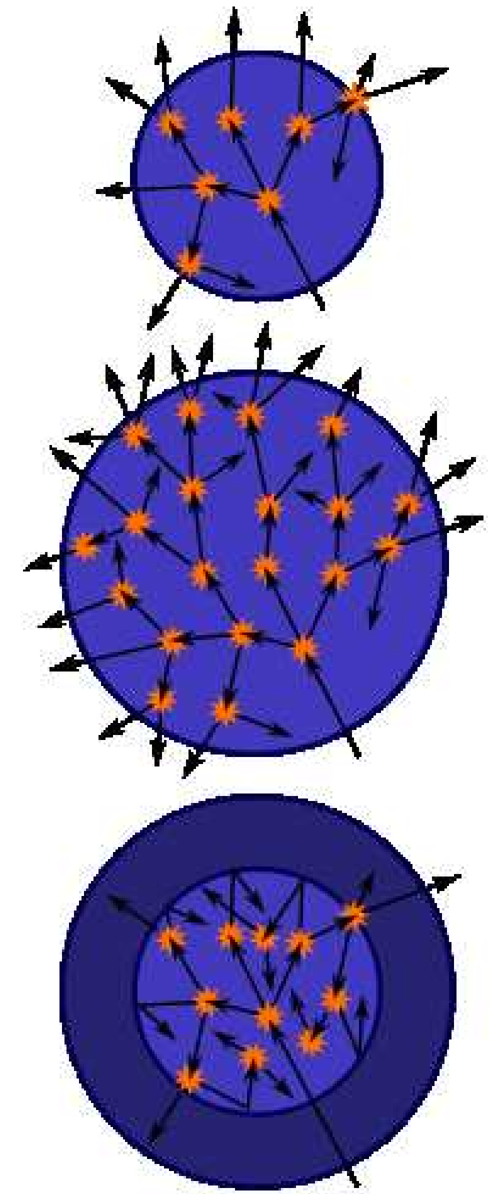
If you want to build a uranium bomb, you can use an ultracentrifuge to separate heavier from lighter elements. If you use a gas molecule containing uranium and you put it in an ultracentrifuge, which part of the centrifuge do you want to siphon off to get the "good stuff"?

a) the heavy part at the bottom

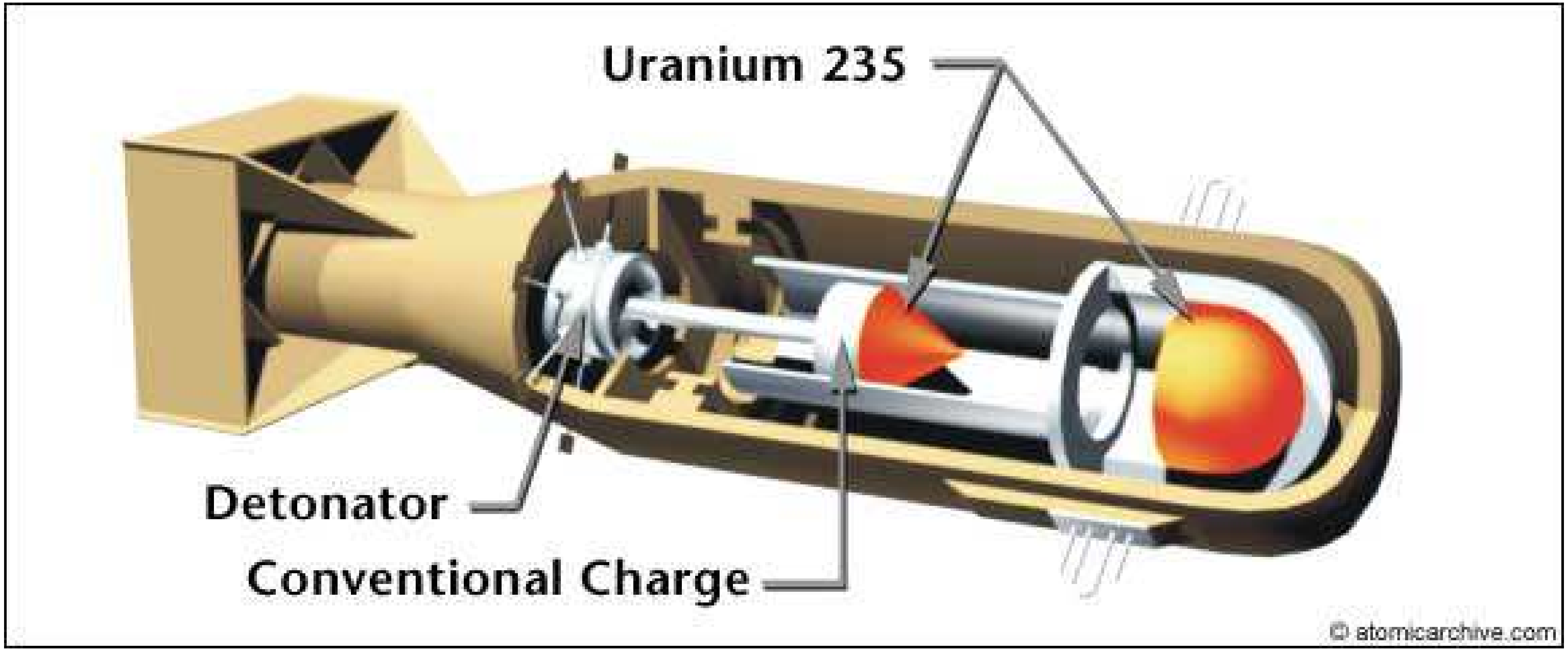
b) the light stuff at the top.

Critical mass

For a small amount of uranium many neutrons are lost through the surface. However by making the mass bigger the neutrons remain long enough inside the uranium to generate (on average) more than one neutron before they are lost. Then the number of neutrons steadily increases, leading to the chain reaction.
Two halves of a sphere of less than critical mass can be handled safely, but as soon as they are brought together the chain reaction begins. For uranium the critical mass is about 25kg.



Building a bomb



Little boy

The destructive power of such a bomb is amazing: 18,000 tons TNT equivalent.

A chemical bomb can carry maybe a quarter ton of explosive.

Hiroshima

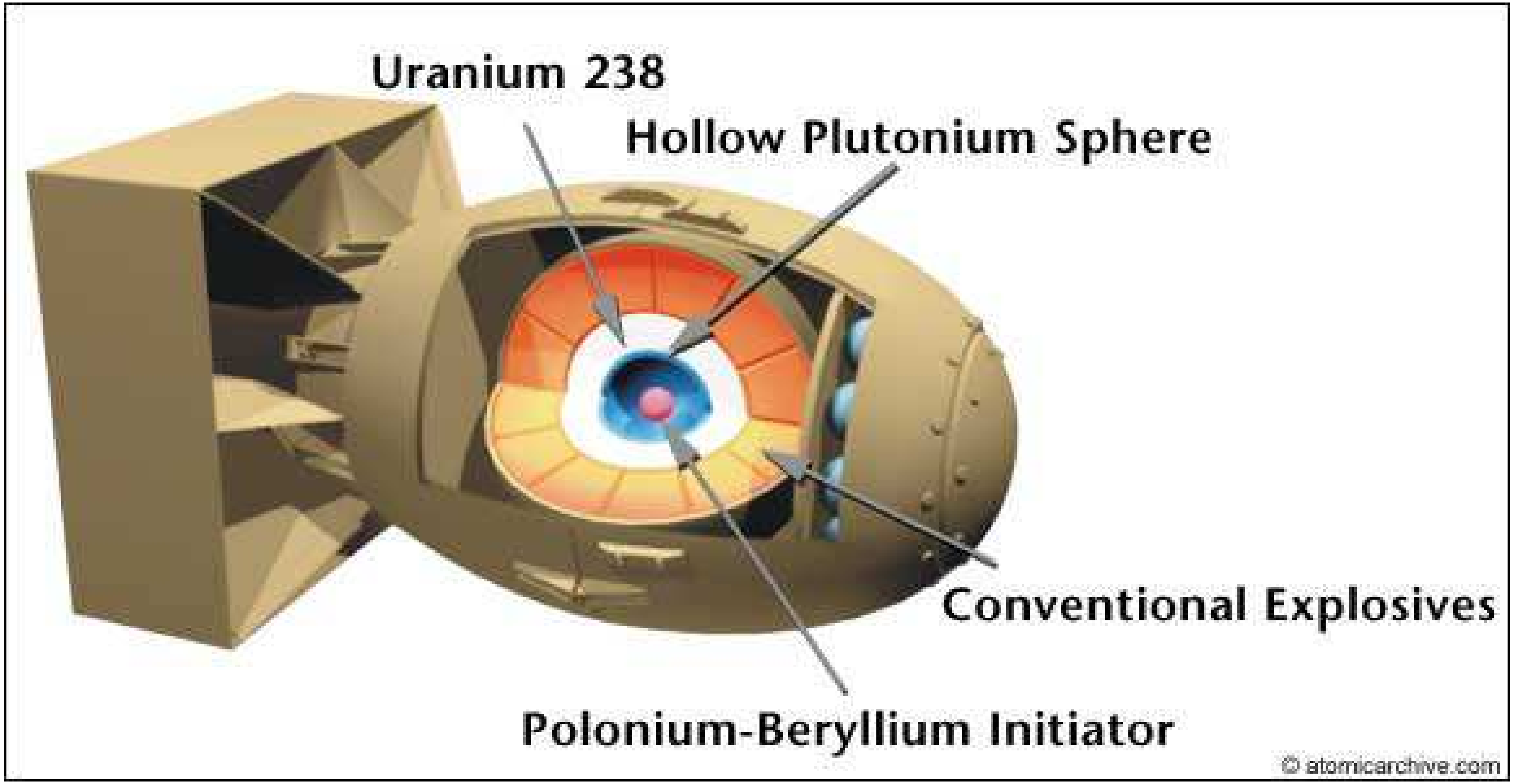
Watch little boy in action:

The plutonium bomb

It turns out that the element plutonium is also suitable for fission. We saw that plutonium can be created by exposing $^{238}_{92}U$ to neutrons. This can be done effectively in Nuclear reactors (we will talk about those later).

The critical mass for plutonium is only about 8kg, but the uranium bomb design won't work because the plutonium will be blown apart before it is properly brought together. A different design is necessary that compresses the plutonium to reach a critical density:

Plutonium bomb design

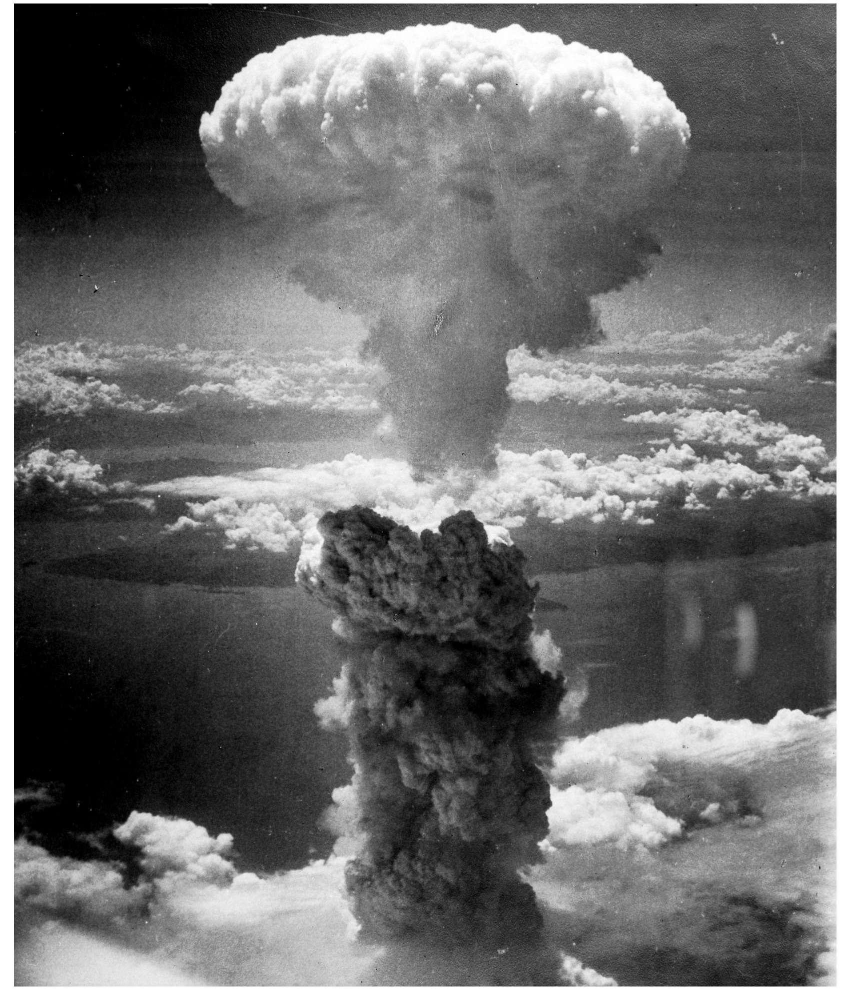


Explosive power: 22,000 tons TNT

Concept Check

How many World War II heavy bombers (5-ton bomb capacity) would be needed to carry enough high-explosive chemical bombs to equal the power of the nuclear bomb dropped on Nagasaki?

a) Less than 1000
b) 1000 - 2000
c) 2000 - 4000
d) 4000 - 6000
e) more than 6000

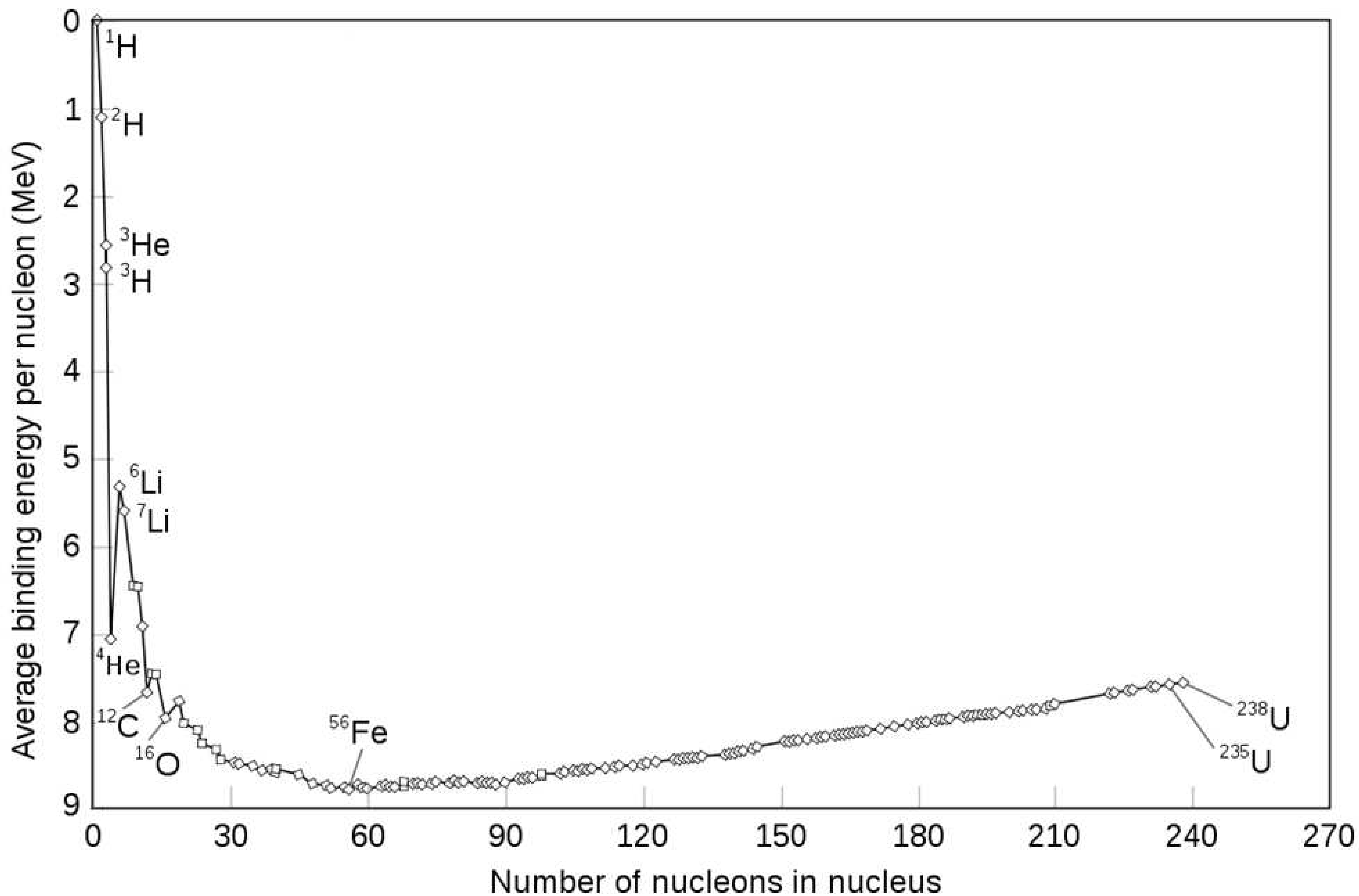


Answer:

The plutonium bomb used over Nagasaki had an explosive power of 22,000 tons TNT. Each plane can carry 5 tons of bombs, so the total number would be

$$\frac{22,000}{5} = 4,400 \tag{2}$$

A bigger bang? The nuclear energy curve again



Clearly there is much more energy per nucleon to be had if on fuses hydrogen into helium, but this is not easily done.

How to make fusion work

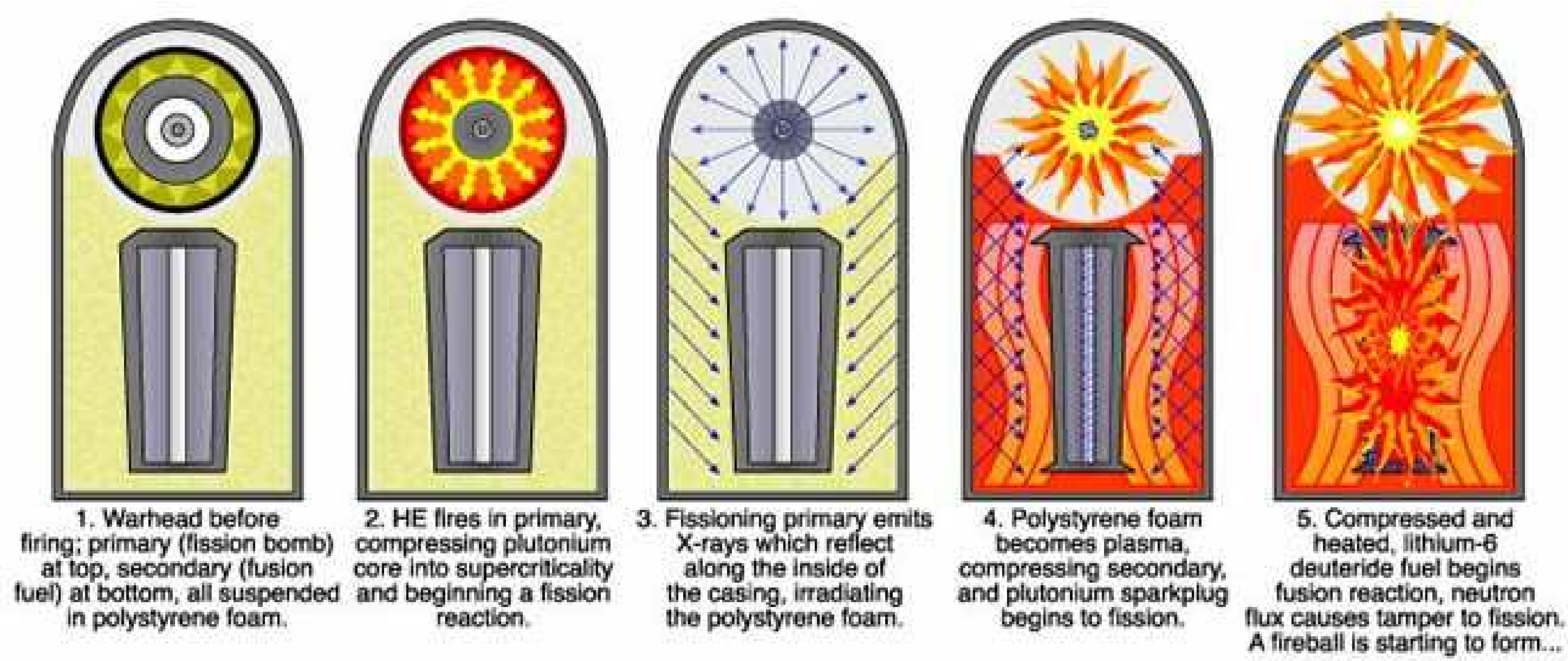
We saw that the processes used in the sun to generate fusion are very slow and generate only a low energy density.

The main trick to make this feasible is to use ^2H and ^3H instead of just H.

Fusion bombs

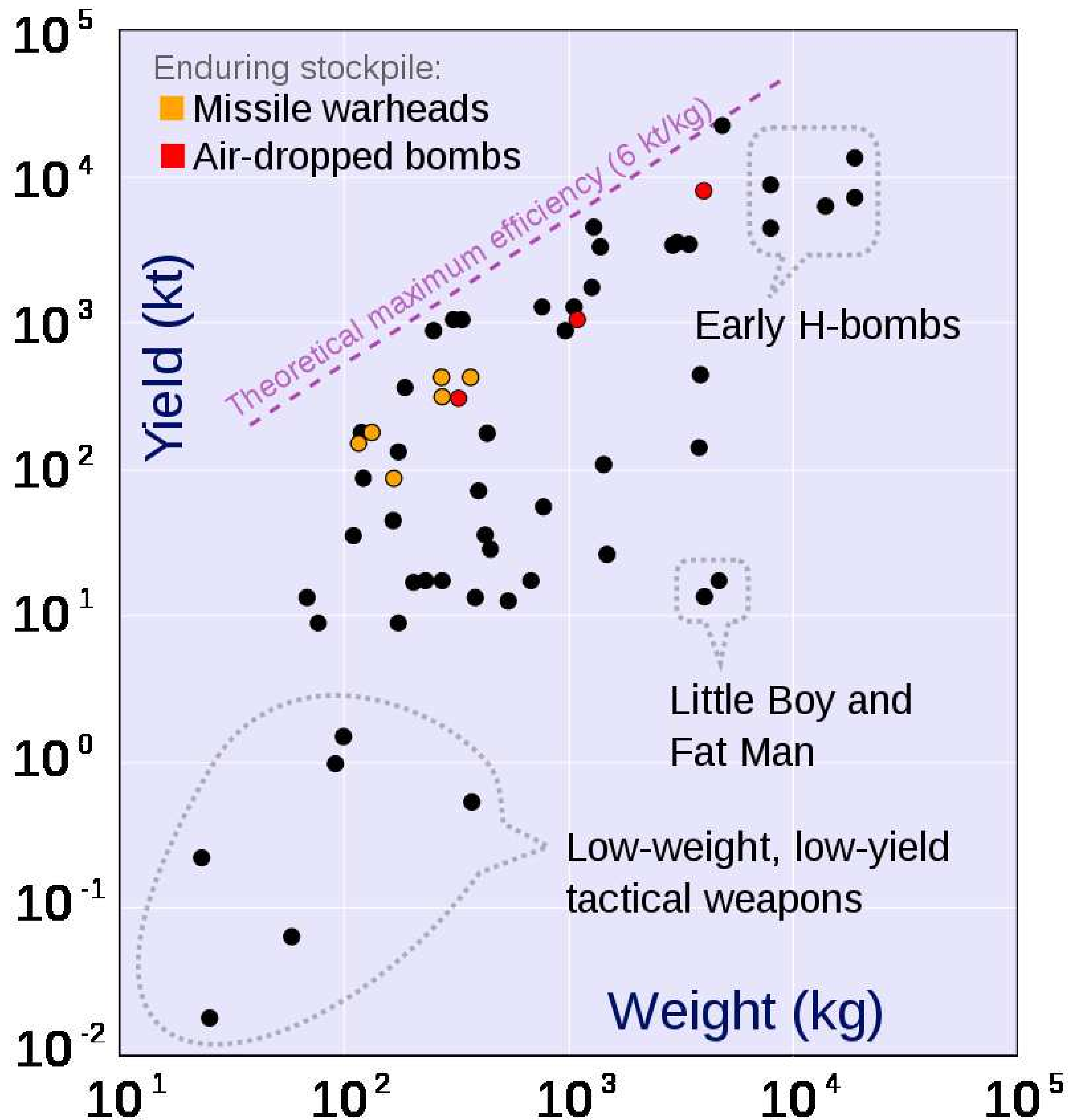
We can get even more energy per kg if we use

$$^2H +^3 H \to^4 He +^1 n$$



Much about the detailed design remains classified. They give a yield of about 50,000 tonnes TNT. This is the design of most currently used nuclear weapons.

Yield of US nuclear devices



Larges explosion: Tsar Bomba

See this for all the nuclear explosions so far.

Summary

- Nuclear fission
- Basic theory of bombs
- Physics of uranium, plutonium and hydrogen bombs.