Plan for This Session

Announcements about the course

Questions about the course

News

Module 2: Nuclear weapons

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Physics 280: Session 4

Announcements About The Course

Please read

- **the reading assignments**
- **the slides from the previous session**

before **coming to the lecture-discussion and writing lab!**

also don’t forget to read the essay prompts prior to the writing labs. Make sure you ask your TA in case you have questions concerning a prompt!

Questions About The Course

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News and Discussion: January 28th State of Union Address

"American diplomacy has rallied more than fifty countries to prevent nuclear materials from falling into the wrong hands, and allowed us to reduce our own reliance on Cold War stockpiles."

"And it is American diplomacy, backed by pressure, that has halted the progress of Iran's nuclear program – and rolled parts of that program back – for the very first time in a decade. As we gather here tonight, Iran has begun to eliminate its stockpile of higher levels of enriched uranium. It is not installing advanced centrifuges. Unprecedented inspections help the world verify, every day, that Iran is not building a bomb. And with our allies and partners, we're engaged in negotiations to see if we can peacefully achieve a goal we all share: preventing Iran from obtaining a nuclear weapon."

"These negotiations will be difficult. They may not succeed. We are clear-eyed about Iran's support for terrorist organizations like Hezbollah, which threaten our allies; and the mistrust between our nations cannot be wished away. But these negotiations do not rely on trust; any long-term deal we agree to must be based on verifiable action that convinces us and the international community that Iran is not building a nuclear bomb. If John F. Kennedy and Ronald Reagan could negotiate with the Soviet Union, then surely a strong and confident America can negotiate with less powerful adversaries today."

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News and Discussion: January 29th, New IAEA Inspections in Iran

SWI swissinfo.ch

Swiss news in 10 languages

IAEA visits Iranian mine as part of nuclear transparency pact

Reuters

January 29, 2014 - 13:21

DUBAI (Reuters) - U.N. nuclear inspectors visited an Iranian uranium mine for the first time in nearly a decade on Wednesday, Iranian media reported, as Tehran gradually opens up its disputed nuclear programme to greater international scrutiny.

A three-member team from the International Atomic Energy Agency (IAEA) went to the Gchine mine near the southern Gulf port city of Bandar Abbas, a spokesman for Iran's atomic energy organisation said. The IAEA was last there in 2005.

Going to Gchine would allow the IAEA to know the amount of uranium mined there, making it "harder for Iran to generate a secret stock of natural uranium", the U.S. Institute for Science and International Security (ISIS) said last month.

As the first step to be implemented under the Iran-IAEA agreement, U.N. inspectors went in December to the Arak heavy-water production facility, a plant that is linked to a nearby reactor under construction that the West fears could yield plutonium for nuclear bombs once operational.

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News and Discussion:
January 28th State of Union Address

theguardian

Iran dismisses Barack Obama's claim that sanctions prompted nuclear talks

US president's State of the Union assertion that US pressure rolled back Tehran's nuclear programme called 'delusional'

Iran has said comments in Barack Obama's State of the Union speech about how sanctions linked to its nuclear programme had forced Tehran to the negotiating table were "unrealistic and unconstructive".

"The delusion of sanctions having an effect on Iran's motivation for nuclear negotiations is based on a false narration of history," Iran's foreign ministry spokeswoman Marzieh Afkham was quoted as saying by state broadcaster IRIB.

President Obama, in his address on Tuesday, said US and international pressure had led to the interim deal struck in November between Iran and six global powers, under which Tehran agreed to scale back uranium enrichment in return for sanctions relief.

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iClicker Question

What was (approximately) the maximum number of nuclear weapons in the U.S. and Soviet Union had during the Cold War and when was the maximum reached?

A	55,000 in 1995
B	70,000 in 1985
C	70,000 in 1980
D	55,000 in 1975
E	90,000 in 1985

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Physics 280: Session 4

iClicker Answer

What was (approximately) the maximum number of nuclear weapons in the U.S. and Soviet Union had during the Cold War and when was the maximum reached?

A 55,000 in 1995

B 70,000 in 1985

C 70,000 in 1980

D 55,000 in 1975

E 90,000 in 1985

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Module 2: Nuclear Weapons

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Why should we be interested in the basic physics and design of nuclear weapons?

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Physics of Nuclear Weapons

A basic understanding of the nuclear physics and design of nuclear weapons is required to have informed opinions about —

- How easy or difficult is it for countries or non-state groups to develop nuclear weapons?
- Are there any important secrets left?
- Is it significantly more difficult to develop a thermonuclear weapon (“H-bomb”) than a fission weapon?
- What is the likelihood of the U.S. making a “breakthrough” in nuclear weapon design?
- What are the likely costs and benefits of nuclear testing?

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Physics of Nuclear Weapons

Topics covered in this module —

- Atoms and nuclei
- Fission and fusion
- Nuclear reactors and nuclear bombs
- Fission weapons (“A-bombs”)
- Thermonuclear weapons (“H-bombs”)
- Production of nuclear explosive material (NEM)
- Implications for nuclear testing and proliferation

Do not be overly concerned! This is by far the most technical part of the course.

It’s important to know about this material, but the remainder of the course will *not* be this technical.

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Introduction ➔

Atoms and Nuclei

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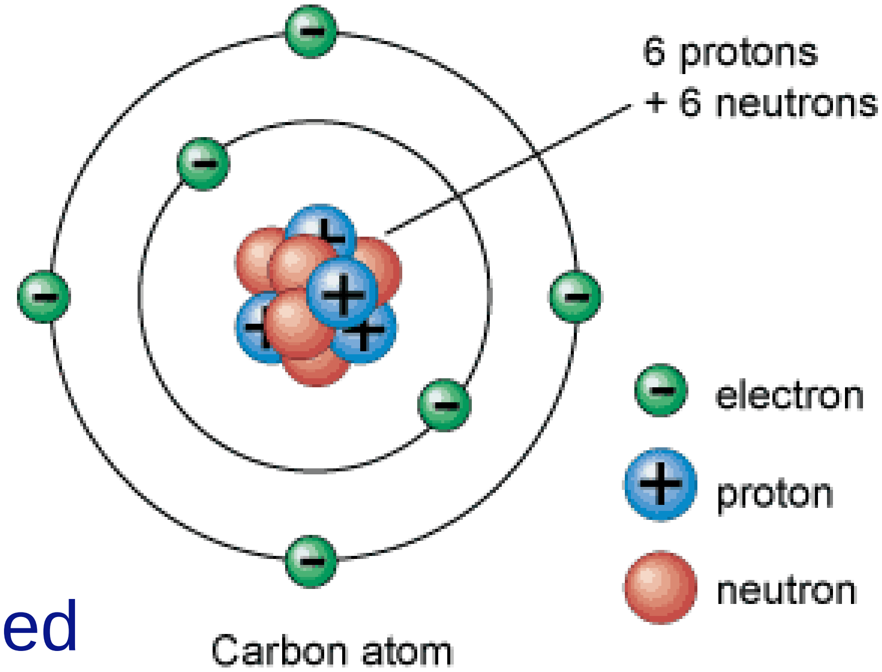
Atomic Nature of All Matter



- Everything is made of atoms
- Atoms have a tiny nucleus surrounded by a very much larger electron cloud
- Every nucleus is composed of protons and neutrons; both are called “nucleons”
- Protons and neutrons are made of smaller particles (this fact is unimportant for nuclear weapons)

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Fundamental Forces of Nature – 1

Nature has four basic forces that govern the structure of Matter —

1. Gravitational force (structure of solar systems and galaxies)

- Always attractive, weakest but first to be discovered
- Strength decreases as $1/r^2$ (“long-range”, r -> distance between objects)

2. Electromagnetic force (structure of atoms and molecules)

- Can be attractive or repulsive
- Classical electrical force decreases as $1/r^2$ (“long-range”)
- Both are described by the theory of electromagnetism, which was developed in the latter part of the 19th Century
- The quantum theory of electromagnetism is called Quantum Electrodynamics

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Fundamental Forces of Nature – 2

3. Weak nuclear force (radioactivity)

- Extremely short range (smaller than the diameter of a nucleon), responsible for radioactive beta decay
- No classical approximation: a quantum mechanical description is required

4. Strong nuclear force ("strong force") (structure of nuclei)

- The strongest known force, it holds protons and neutrons together in the atomic nucleus
- Nuclear binding energies are about 1,000,000 times larger compared to atomic binding energies
- Short-range (reaches approximately the diameter of a proton, vanishes at larger distance)
- Has no classical approximation, a quantum description is required
- The quantum theory of the strong force is called Quantum Chromodynamics

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Fundamental Forces of Nature – 3

Luke, the Force is Strong with you …

… yeah, all four! They keep me on the ground and hold my molecules, atoms and nuclei together!

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iClicker Question

Do the two nuclear forces play a significant role in chemical reactions?

A Yes, chemical reactions between atoms depend on the number of protons held by the strong nuclear force inside the nucleus.

B No, the range of the nuclear forces does not reach beyond the surface of the nucleus and therefore cannot impact atomic processes or the chemistry between two atoms.

C For neutrons, no, as they don't carry electric charge, for protons, yes, as they do carry electric charge.

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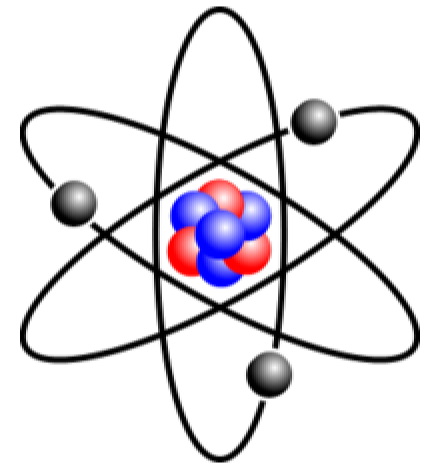
Lithium-Atom



Atoms and Nuclei

Sizes of atoms and nuclei —

- The size of an *atom* is defined by the extent of its electron cloud (~10^{-8} cm = 10^{-10} m).
- The size of a *nucleus* is defined by the size of a nucleon (~10^{-13} cm = 10^{-15} m) and the number of nucleons it contains.

$$\text{Size of an Atom: } r_{atom} \approx 10^{-8}\ \text{cm} = 10^{-10}\ \text{m} = 0.1\ \text{nm}$$
$$\text{Size of a nucleus : } r_{nucleus} \approx 10^{-12}\ \text{cm} = 10^{-14}\ \text{m} = 10\ \text{fm}$$

Masses of subatomic particles —

$m_p \approx m_n \approx 10^{-27}$ *kg*, $m_p = 1836\ m_e \approx 2000\ m_e$

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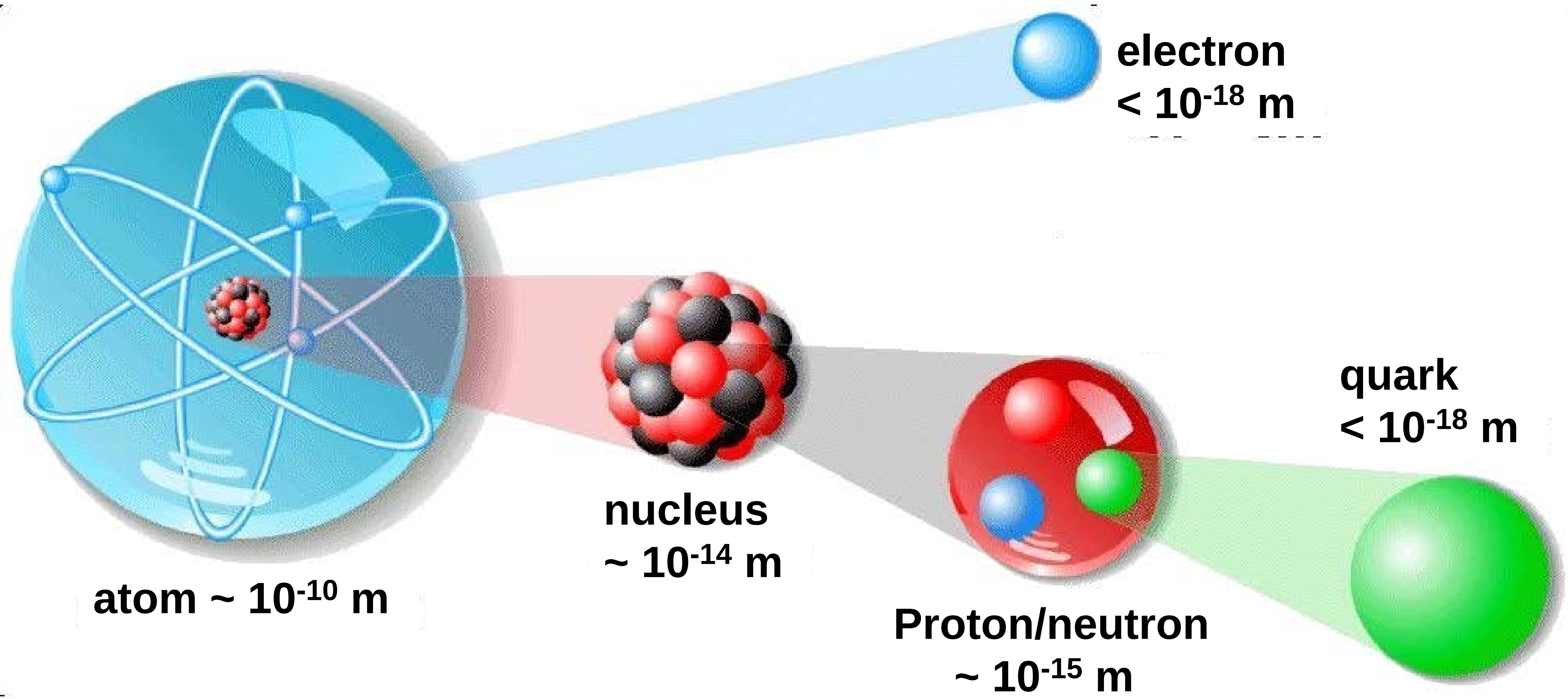
Atomic Structure and Length Scales



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Atomic Nuclei

- A distinct atomic nucleus ("nuclide") is specified by

  —its number of protons (denoted Z – always an integer) and

  —its number of neutrons (denoted N – always an integer)

- Protons and neutrons are both called "nucleons".
- Z is called the "proton number" or "atomic number".
- N is called the "neutron number".
- The total number $N+Z$ of nucleons in the nucleus is denoted A and is called the "atomic weight" of the nucleus ($A = Z + N$).

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Chemical Properties of Atoms

- The **chemical properties of an atom** (i.e., to what other atoms it can bind to form molecules and compounds, with what strengths, and in what geometries) **are determined by the number of electrons** in its electron cloud.

- The electron cloud of **a *neutral* atom has *Z* electrons**: the positive charge of the *Z* protons in its nucleus is *exactly* offset by the negative charge of *Z* electrons in its electron cloud.

- **The mass of an atom is determined by the total number $A = N + Z$ of the nucleons in its nucleus**, because the mass of a proton is almost equal to the mass of a neutron and both are about 2,000 times more than the mass of an electron. Recall *A* is called the “atomic weight” of the atom.

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Atoms with Different Nuclei: Isotopes and Isotones

Several notations are in common use for nuclides –

$$ {}^{A}_{Z}X_{N} = {}^{A}_{Z}X = {}^{A}X = X(A) $$

Here X is the chemical symbol

Isotopes are different nuclides with the same number of *protons* —

- Z is the same for all, but N varies
- **All isotopes of a particular element are chemically indistinguishable**
- Examples: ${}^{238}_{92}\mathrm{U} = {}^{238}\mathrm{U} = \mathrm{U}(238)$, ${}^{235}_{92}\mathrm{U} = {}^{235}\mathrm{U} = \mathrm{U}(235)$

Isotones are different nuclides with the same number of *neutrons*

- N is the same for all, but Z varies
- Isotones are nuclei of different chemical elements

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iClicker Question

A reactor core contains Uranium Isotopes $^{238}_{92}U$, $^{235}_{92}U$ and Plutonium Isotopes $^{239}_{94}Pu$, $^{240}_{94}Pu$. Most of the material is $^{238}_{92}U$ which cannot be used for nuclear weapons. Which statement is correct?

A $^{235}_{92}U$ can be extracted from the material using chemical analysis

B $^{239}_{94}Pu$ and $^{240}_{94}Pu$ can be extracted together using chemical analysis

C Once extracted from the core, $^{239}_{94}Pu$ and $^{240}_{94}Pu$ can be separated using chemical analysis

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iClicker Answer

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Facts About Naturally Occurring Chemical Elements

- 91 chemical elements are found in nature
- 82 of these have one or more stable isotopes
- 9 of these have only unstable isotopes and decay radioactively
- Hydrogen (H) is the lightest (Z = 1)
- Every naturally occurring element beyond Bismuth (Z = 83) has only unstable isotopes
- Uranium (U) is the heaviest (Z = 92)
- Only 91 elements are found in nature because the element Technetium (Z = 43) is not found in nature
- Over 20 *transuranic* (Z > 92) elements have been created in the laboratory; all their isotopes are unstable

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Radioactivity

Radioactivity is a *spontaneous* process in which one nuclide changes into another, either a different isotope of the original chemical element or a different chemical element, *without any outside influence*.

All radioactive decays are *probabilistic:* the exact moment at which a given nuclide will decay cannot be predicted.

The lifetime of a given radioactive nuclide is described by its *half life* $\tau_{1/2}$ or, equivalently, its *mean life* = 1.44 $\tau_{1/2}$

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There are Four Types of Radioactive Decay

1. Alpha decay

Parent —> Daughter + alpha particle (^{4}He)

2. Beta decay

Parent —> Daughter + electron (+ anti-neutrino)

Parent —> Daughter + anti-electron (+ neutrino)

3. Gamma decay

Parent —> Daughter + gamma-ray

4. Spontaneous fission

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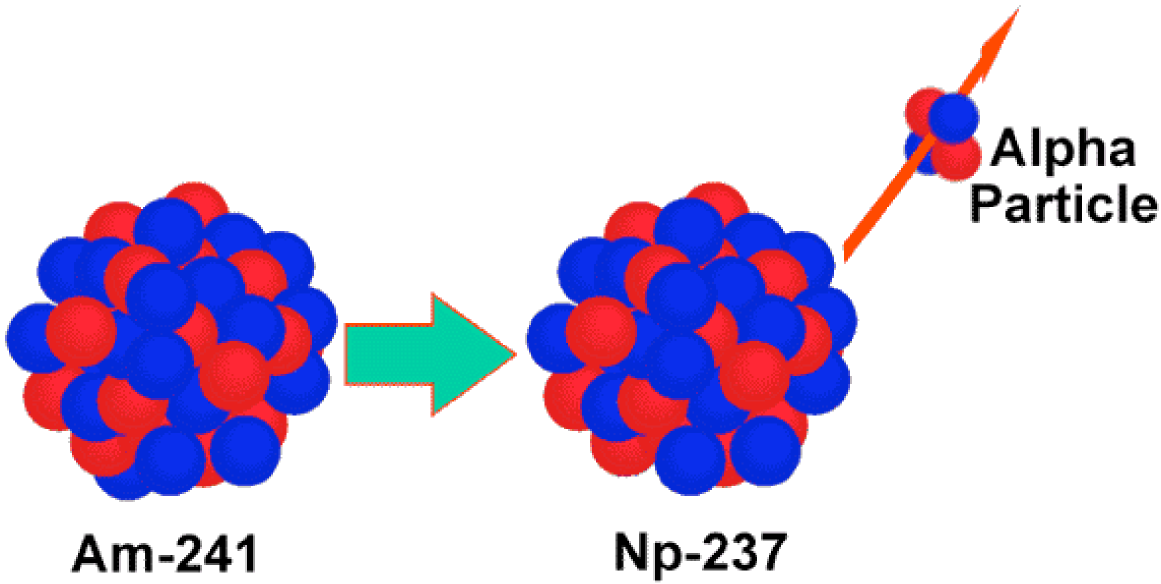
Illustration of Alpha Decay



Americium as 95 protons and 136 neutrons

An alpha particle is a helium nucleus and has 2 protons and 2 neutrons

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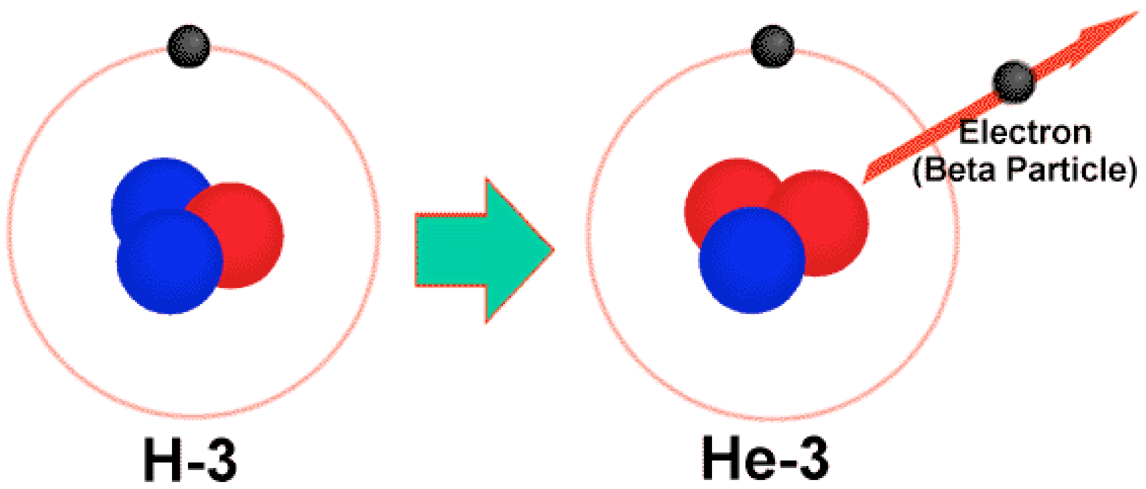
Illustration of Negative Beta Decay (Electron Emission)



Tritium is a hydrogen isotope and decays into He-3, a helium isotope

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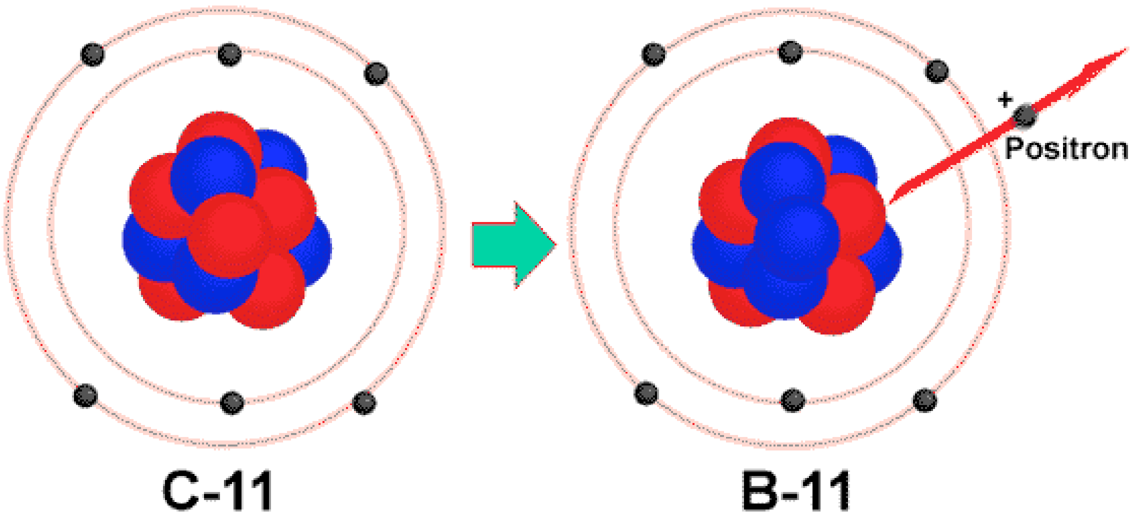
Illustration of Positive Beta Decay (Positron Emission)



The positron from a positive beta decay is the anti-particle to the electron!

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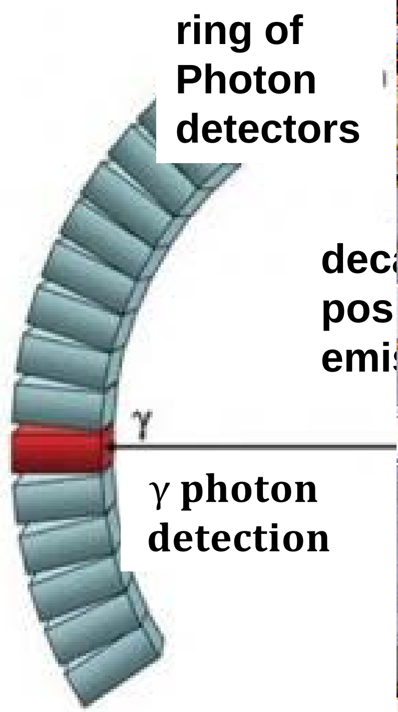
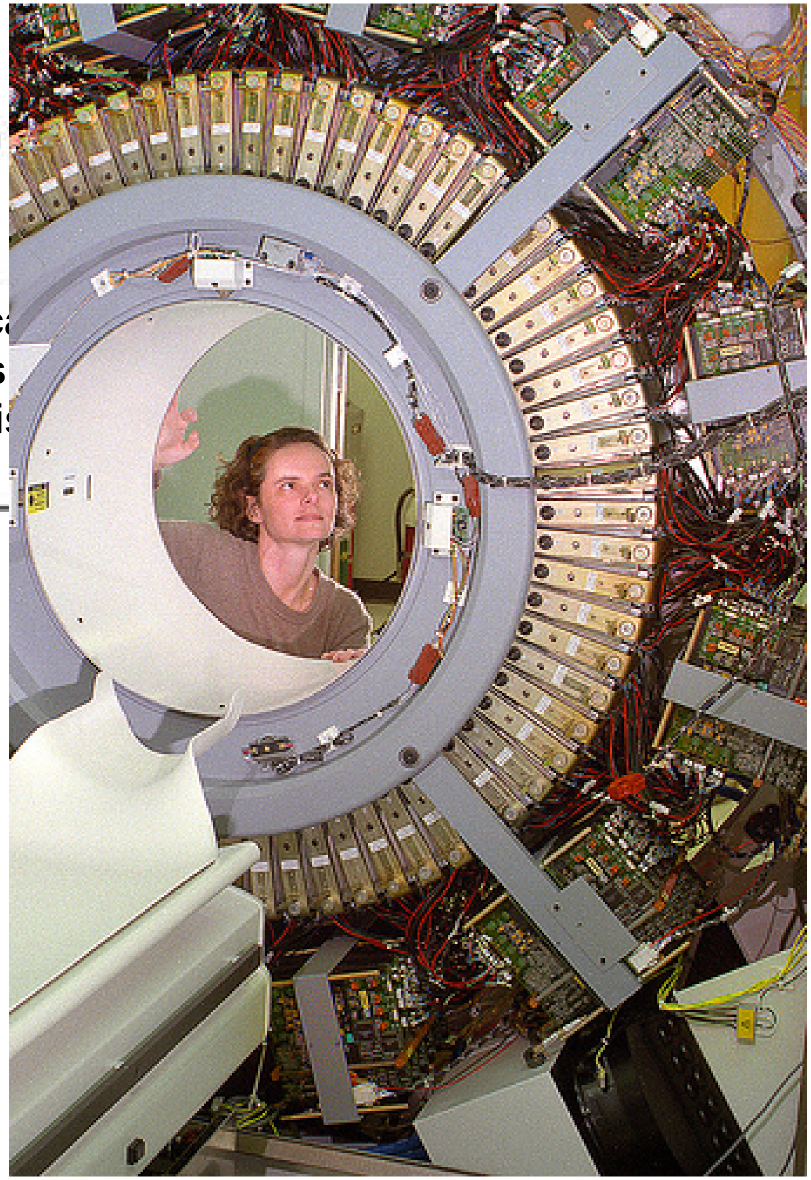
Use of Anti-Electrons, the Positron in Positron Emission Tomography, PET





Positron emitting radioactive isotopes and gamma rays from Electron-positron annihilation are used for medical imaging

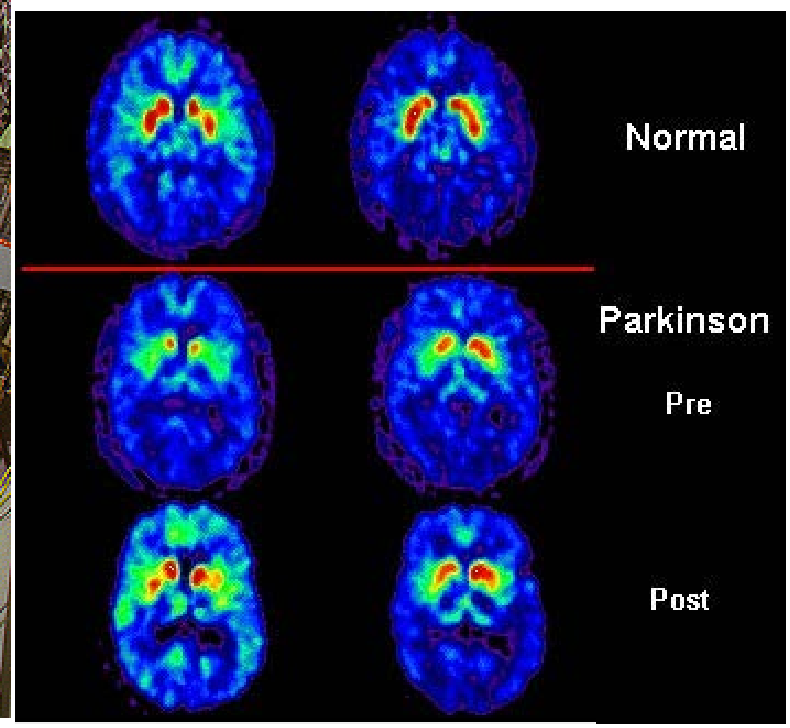


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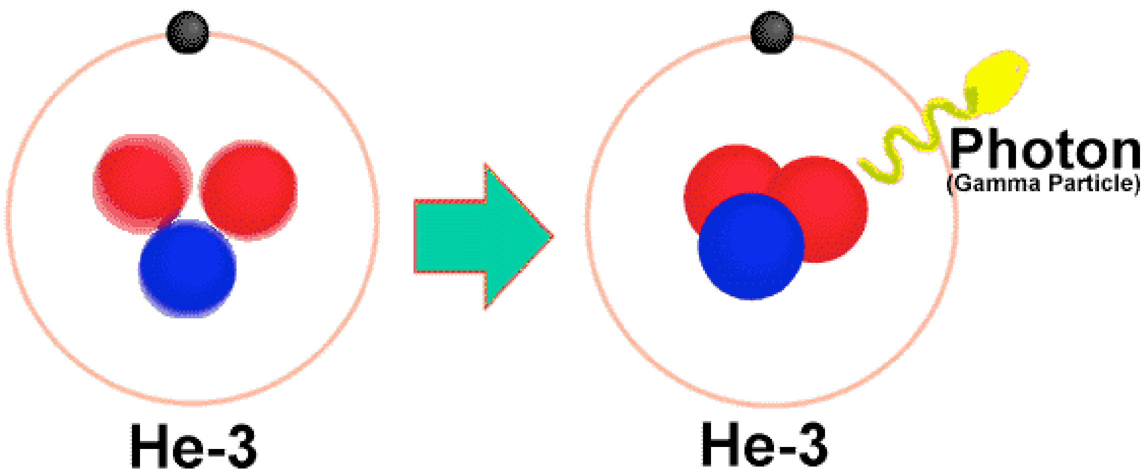
Illustration of Gamma-Ray Emission



If a nucleus is in a higher energy (excited) state it returns to a lower energy state by emitting a photon.

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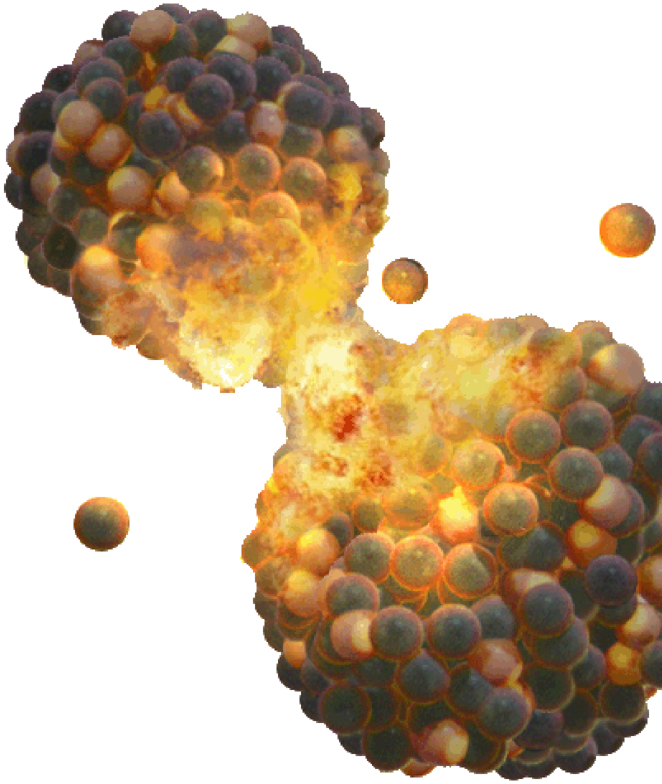
Illustration of Spontaneous Fission of a Californium, Cf-252 Nucleus



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iClicker Question

How does the explosive power of a given mass of nuclear-explosive material compare with the explosive power of an equal mass of conventional high explosives?

A. About the same

B. 10 times more

C. 100 times more

D. 1,000 times more

E. 1,000,000 times more

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iClicker Answer

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iClicker Question

Which radioactive decay increases the number of protons, Z, in the nucleus?

A. Positive Beta Decay

B. Negative Beta Decay

C. Gamma Decay

D. Spontaneous Fission

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iClicker Answer

Which radioactive decay increases the number of protons, Z, in the nucleus?

A. Positive Beta Decay

B. Negative Beta Decay

C. Gamma Decay

D. Spontaneous Fission

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Fission and Fusion

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The Two Types of Fission

Spontaneous fission —

- The process in which an *isolated* nucleus undergoes fission, “splitting” into two smaller nuclei, typically accompanied by emission of one to a few neutrons
- The fission fragments are typically unequal in mass and highly radioactive (β^- and γ)
- Energy is released in the form of kinetic energy of the products and as excitation energy of the (radioactive) fission fragments

Induced fission —

- The process in which capture of a neutron causes a nucleus to become unstable and undergo fission
- The fission fragments are similar to those for spontaneous fission

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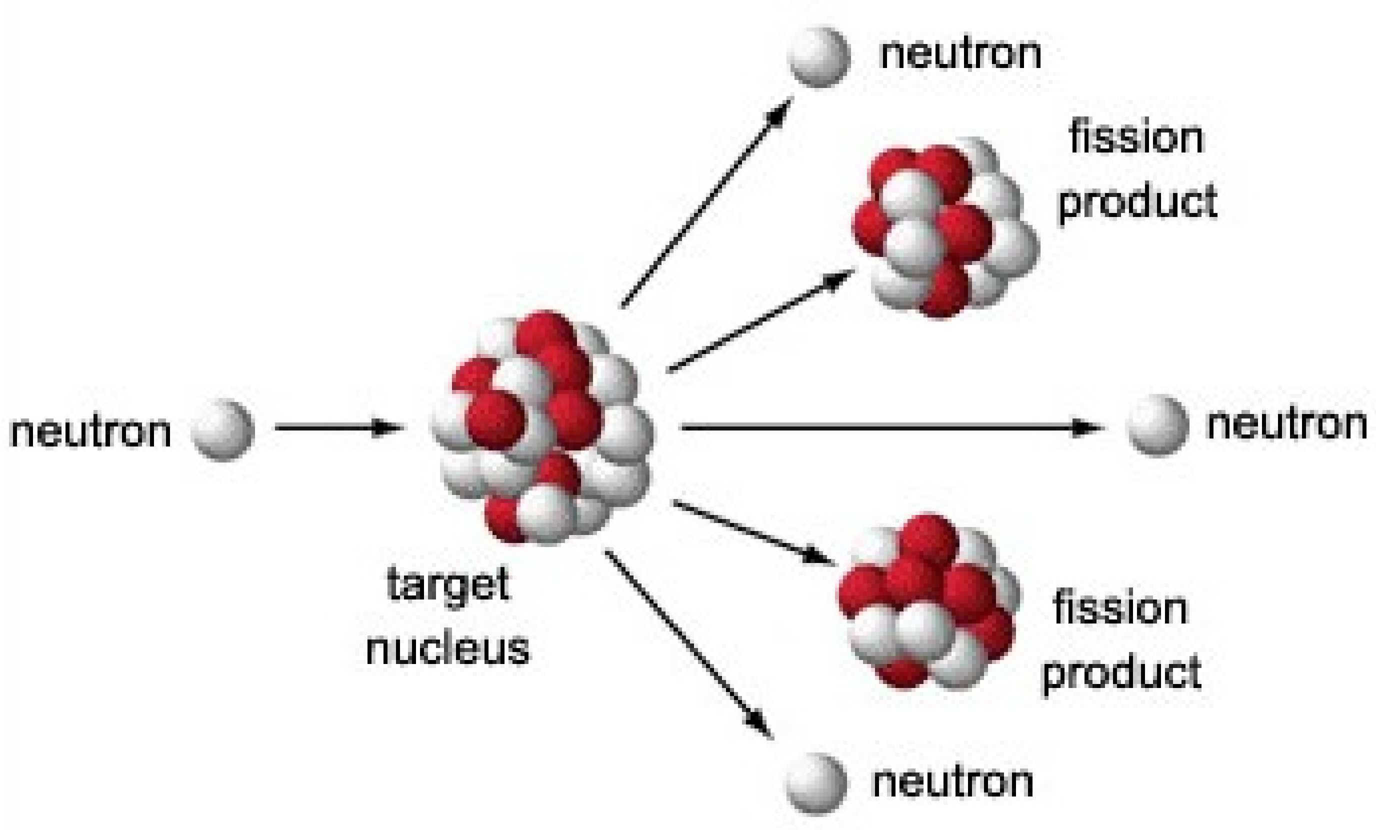
Induced Fission



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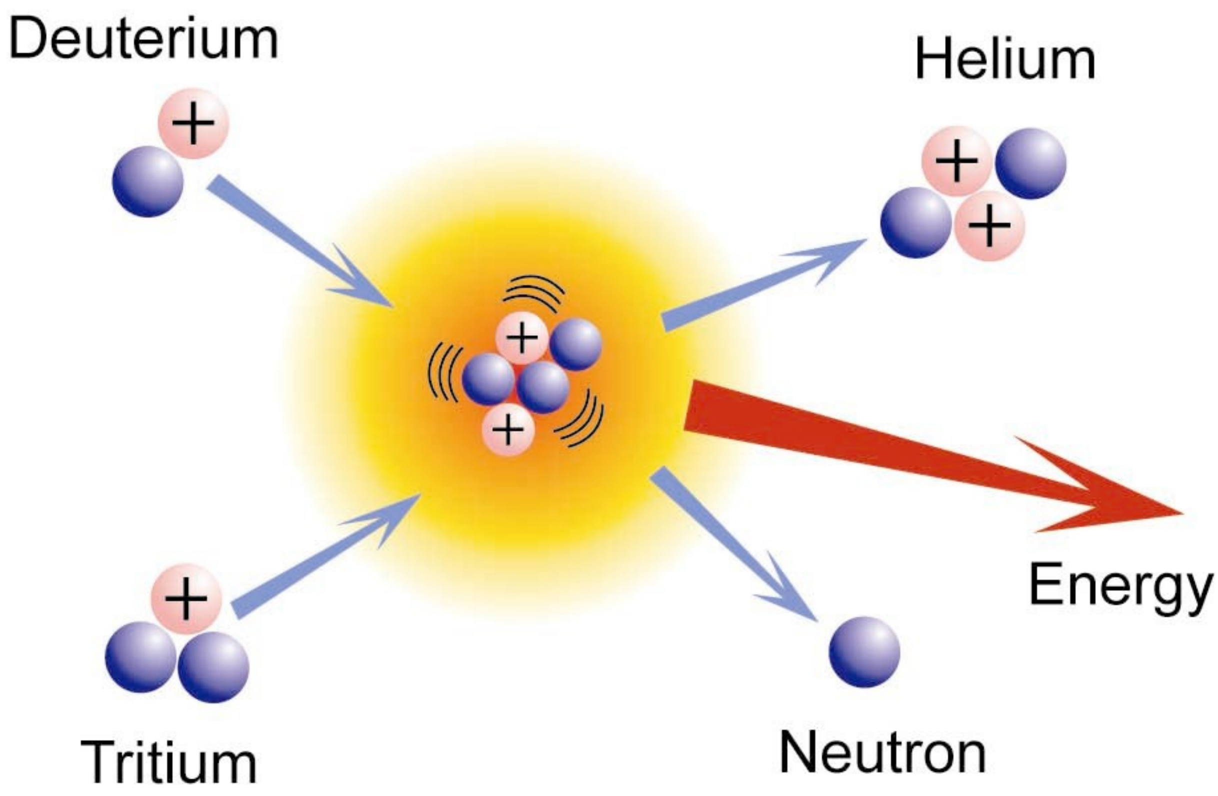
Fusion



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Plan for This Session

Announcements about the course

Questions about the course

Module 2: Nuclear weapons cont'd

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Physics 280: Session 5

Announcements About The Course

RE2v1 will be due Thursday, 2-6

o printed copy (in class) + electronic submission (**1pm**)

https://my.physics.illinois.edu/login.asp?/courses/upload/index.asp

o prompt is posted on course web-page

http://courses.physics.illinois.edu/phys280/sp2014/assignments/re2v1.html

o follow all instructions stated in the student handbook

o MGP office hour today 5-6pm in Loomis 469 (not at 4:30pm)

Questions About The Course

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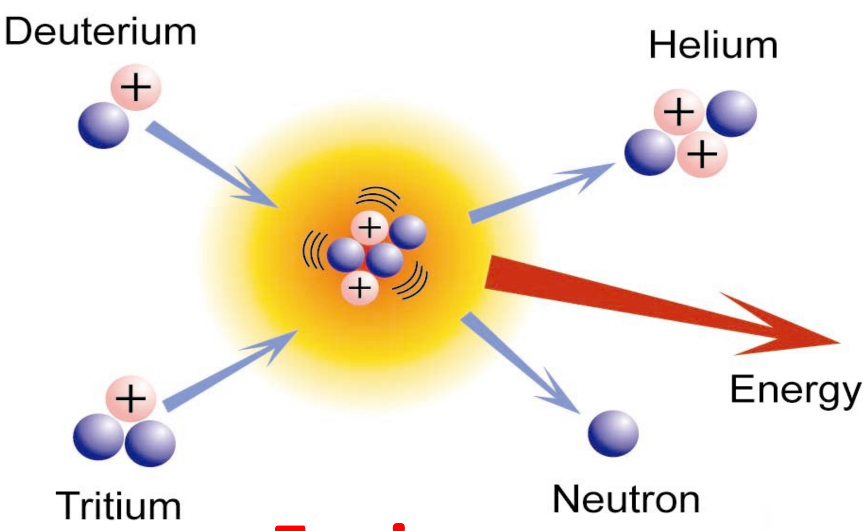
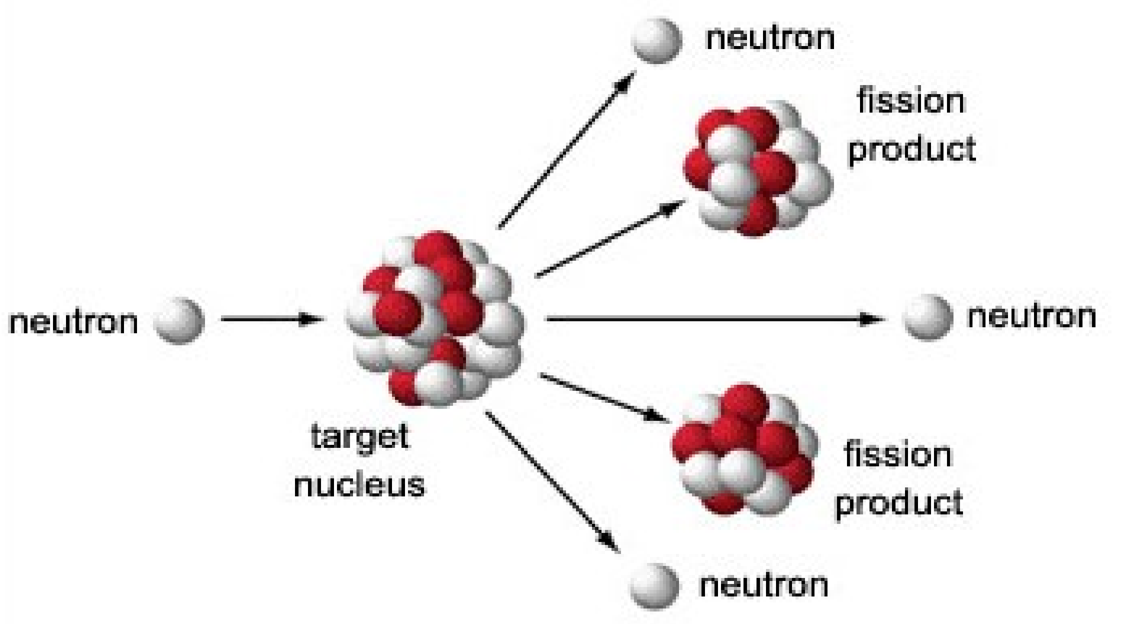
Re-call Both Fission and Fusion Reactions Can Yield Energy



Fusion

Fission



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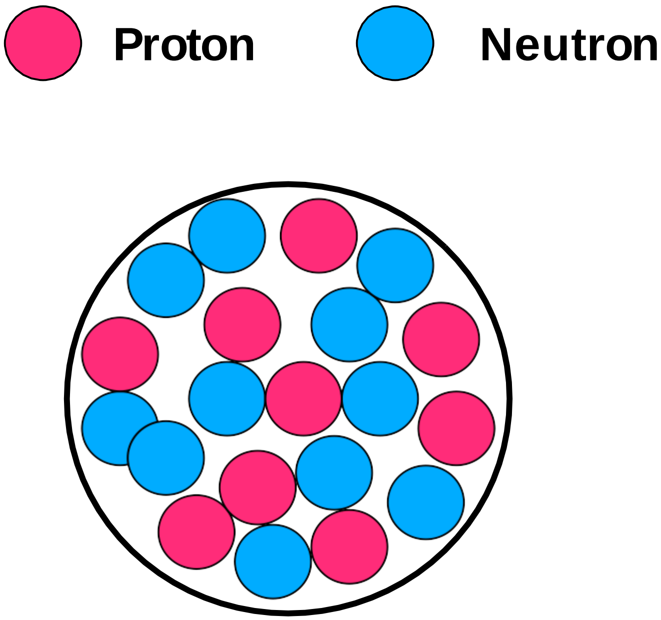
Binding Energy of Nucleons in a Nucleus



Nucleus: *N*, *Z*

(1) Attractive nuclear force between nearest neighbor nucleons (short range)

(2) Repulsive electric forces between all protons (long range)

Competition between (1) and (2) determine **total binding energy of a nucleus B_T**:

$$B_T = \text{const} \times (N + Z) - \text{const} \times Z^2$$

Nuclear Force — Electrical Force

Nuclear Binding Energy is the source of nuclear energy utilized in nuclear reactors and released in nuclear bomb explosions !

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The Binding Energy Per Nucleon

- The easiest way to understand how fission and fusion liberate energy is by considering the *average binding energy B* of the nucleons in a nucleus —

$$B \equiv \frac{B_T}{A} = \frac{B_T}{(Z+N)}$$

- The plot of *B* vs. *A* is called “the curve of the binding energy”
- A nuclear reaction that increases the binding energy of nucleons in the nucleus is “exothermic” and releases energy.

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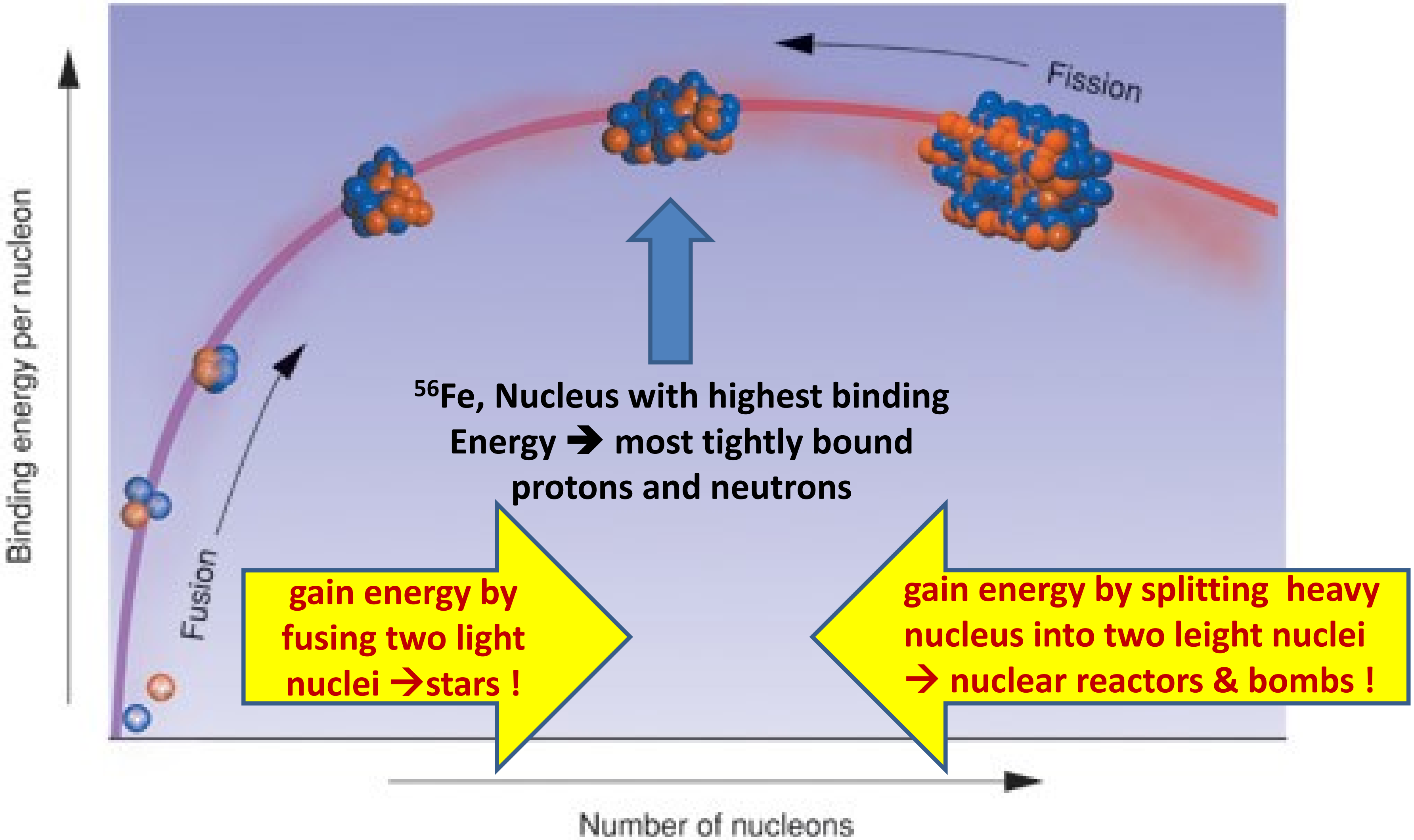
The Curve of Binding Energy (Important)



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Nuclides Important for Fission Bombs

Heavy elements (high Z) —

$$^{238}_{92}U = {}^{238}U = U(238) \quad ***$$

$$^{235}_{92}U = U(235) \quad ***$$

$$^{233}_{92}U = U(233) \quad *$$

$$^{239}_{93}Np = Np(239)$$

$$^{239}_{94}Pu = Pu(239) \quad ***$$

$$^{240}_{94}Pu = Pu(240) \quad **$$

*, **, *** denotes increasing importance

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Nuclides Important for Fusion Bombs

Light elements (low Z) —

$^{1}_{1}H$ = P (proton)

$^{2}_{1}H$ = D (deuteron), stable * * *

$^{3}_{1}H$ = T (triton), unstable * * *

$^{4}_{2}He$ = He(4) = α (alpha particle), very stable

$^{3}_{2}He$ = He(3) , stable (indirectly relevant to NWs) *

$^{6}_{3}Li$ = Li(6) , stable * *

$^{7}_{3}Li$ = Li(7), stable (no relevance to NWs)

$^{9}_{4}Be$ = Be(9) stable (lighest metal) *

*, **, *** denotes increasing importance

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The Neutron

- The discovery of the neutron in 1932 was the single most important discovery in nuclear physics after the discovery of the nucleus itself.
- Until the neutron was discovered, physicists could not understand nuclei, in particular how A could be greater than Z.
- The discovery of the neutron made it possible to understand for the first time that $A = Z + N$ and could therefore be greater than Z.
- Neutrons are not repelled by the positive charge of a nucleus and therefore can approach and penetrate a nucleus without having to overcome an electrical energy barrier.
- The nuclear force between neutrons and protons, and between neutrons and nuclei, is generally attractive. Hence if a neutron gets close enough, it will be attracted by and become bound to a nucleus.
- Neutron bombardment of nuclei quickly became a tool for probing the structure of nuclei and the properties of the nuclear force.

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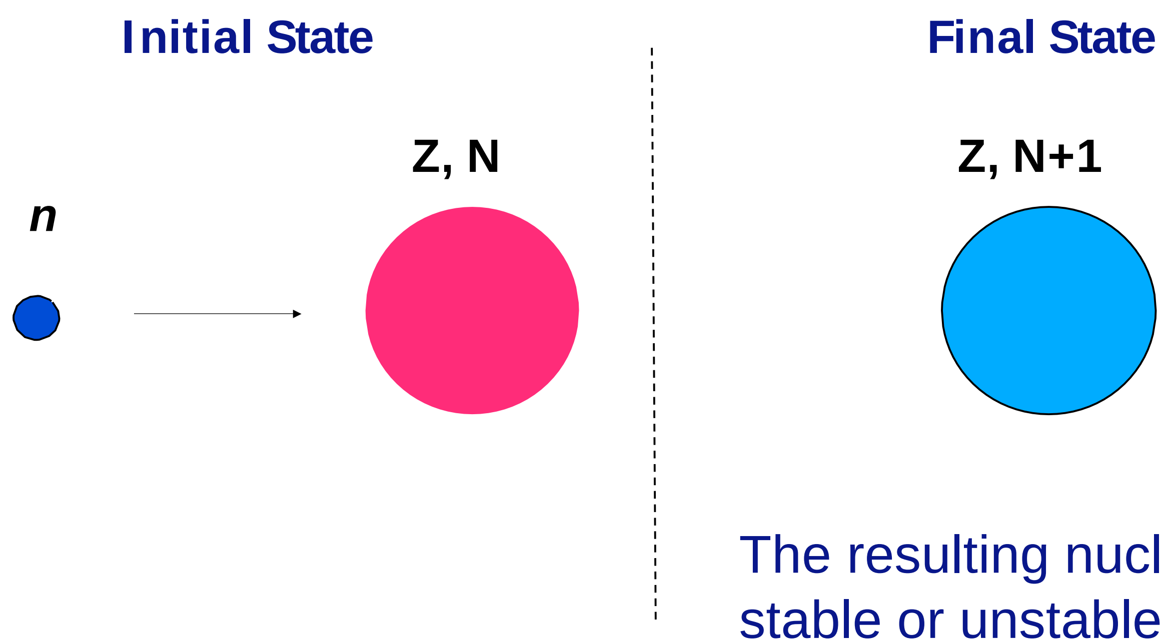
Neutron Capture



The resulting nucleus may be stable or unstable.

If unstable, we call this process *neutron activation*. It typically results in a β-decay.

$$ {}^{1}_{0}n + {}^{238}_{92}U \rightarrow {}^{239}_{92}U \rightarrow {}^{239}_{93}Np + e^{-} + \overline{\nu}_{e} $$

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iClicker Question

Which reaction produces $^{239}_{94}Pu$ in Nuclear Reactors?

A. $^{239}_{94}Pu$ cannot be made in Nuclear Reactors!

B. $^{243}_{96}Cm \rightarrow ^{239}_{94}Pu + \alpha$

C. $^{239}_{93}Np \rightarrow ^{239}_{94}Pu + e^{-} + \overline{\nu}_e$

D. None of the above

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D. None of the above

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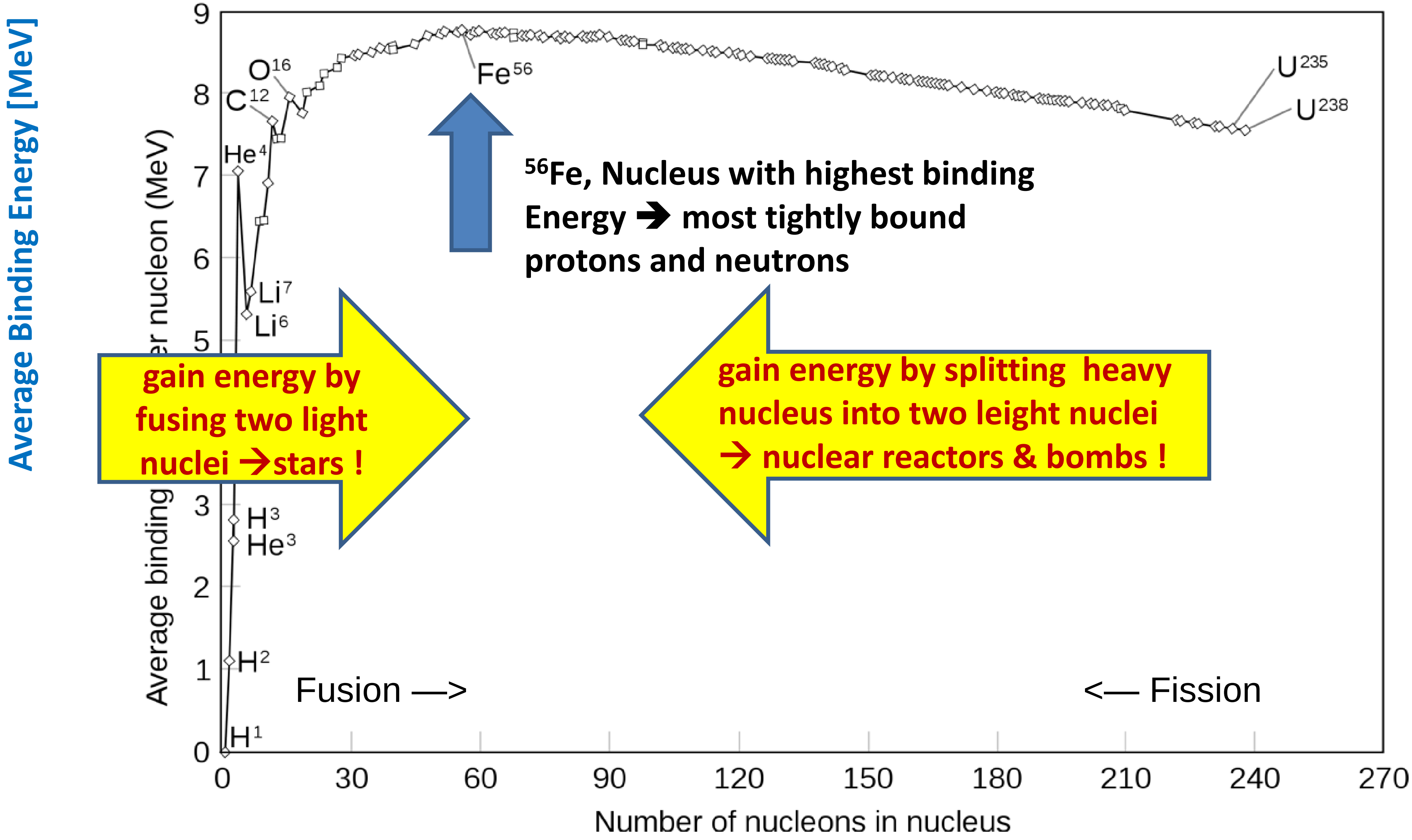
Average Nucleon Binding Energy → Amount of Energy Released if 1 Neutron is Captured in Nucleus



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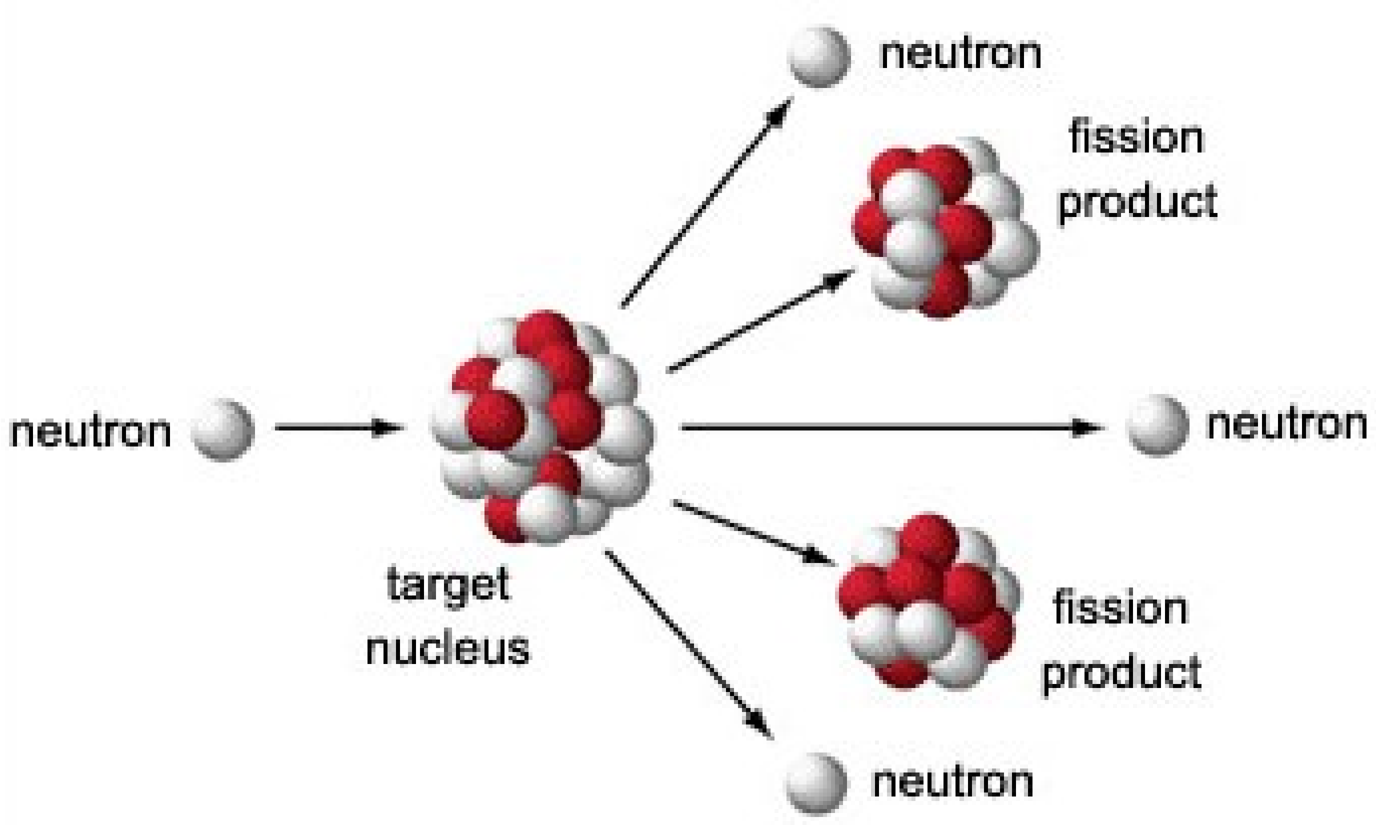
Induced Fission – 1



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Induced Fission – 2

The discovery of induced fission was a great surprise!

Many groups studying neutron capture by Uranium had induced fission without realizing what was happening.

Lise Meitner, a brilliant Jewish scientist who had fled from Germany to the Netherlands in 1938, was the first person to understand what was happening in the experiments.

Unfortunately, *she was not included* in the Nobel Prize awarded for the discovery! A shameful omission.

Element 109, Meitnerium, is named in her honor.

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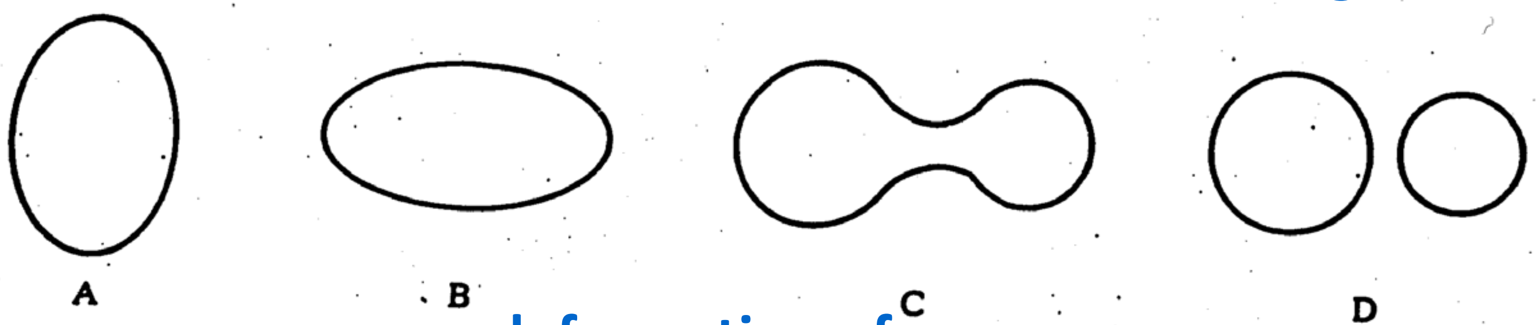
Lisa Meitner's Concept of Fission

parent nucleus

daughter nuclei



deformation of parent nucleus

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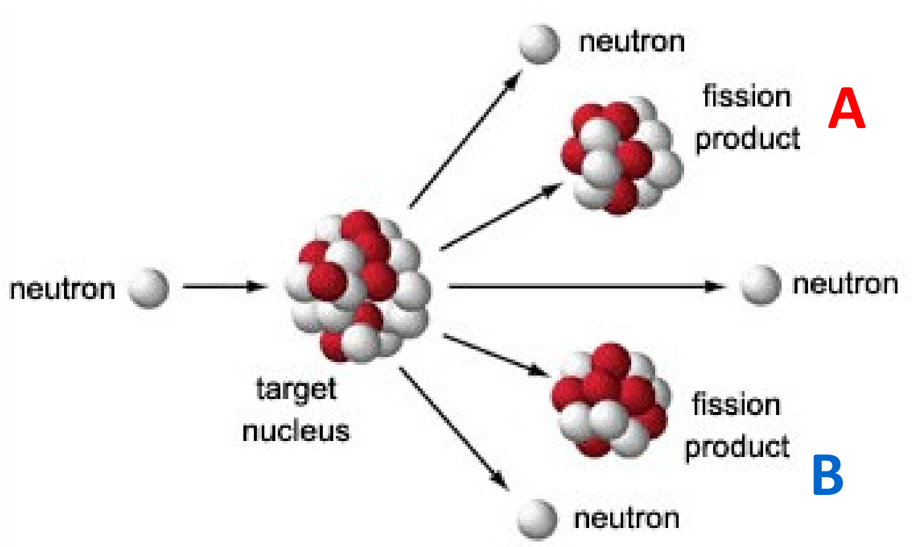
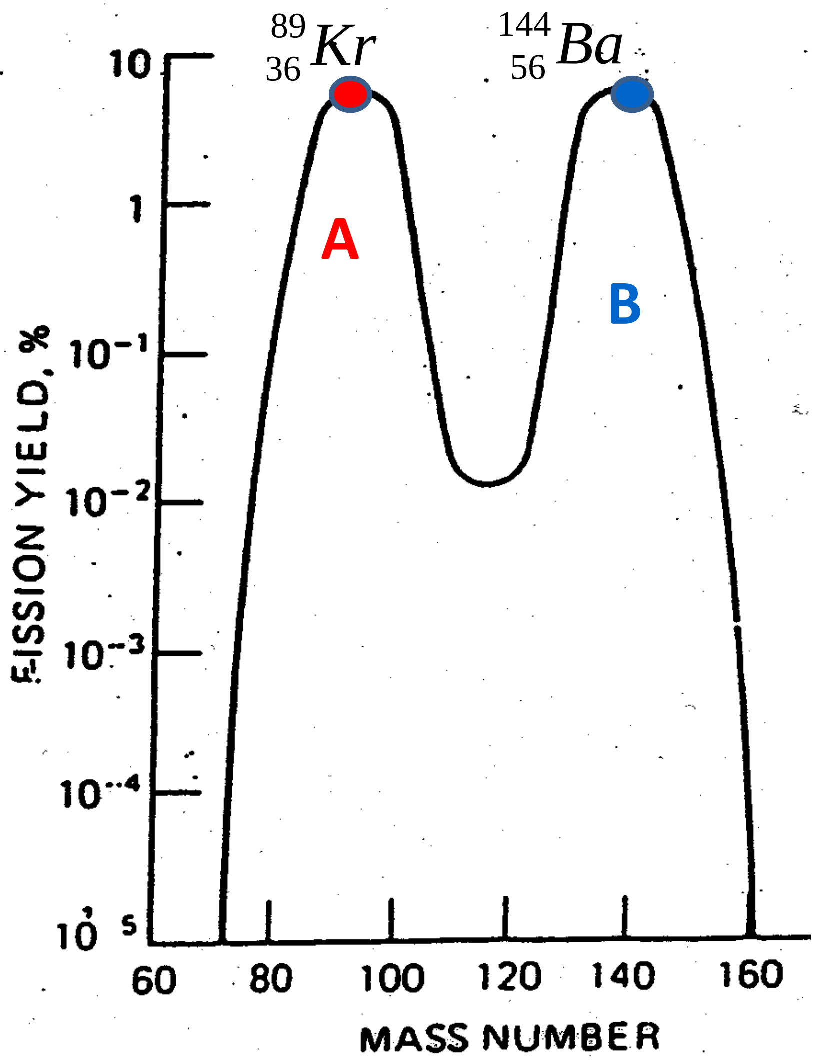
Distribution of Fission Fragment Masses





$$^{235}_{92}U \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3n + 177\,MeV$$

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Induced Fission – 3

- Soon after it was realized that induced fission itself produces neutrons, many scientists realized that
  - —a nuclear fission chain reaction might be possible
  - —the energy released would be many thousands of times greater than the energy released by chemical reactions
  - —a fission reactor (steady chain reaction) might be possible
  - —a fission bomb (explosive chain reaction) might also be possible
- There was great fear in the Britain and the U.S. that Germany would be the first to develop a nuclear bomb
- British scientists played important early roles in showing that a nuclear bomb was possible
- The U.S. was slow to start, but eventually became the center of nuclear bomb development (the Manhattan Project)

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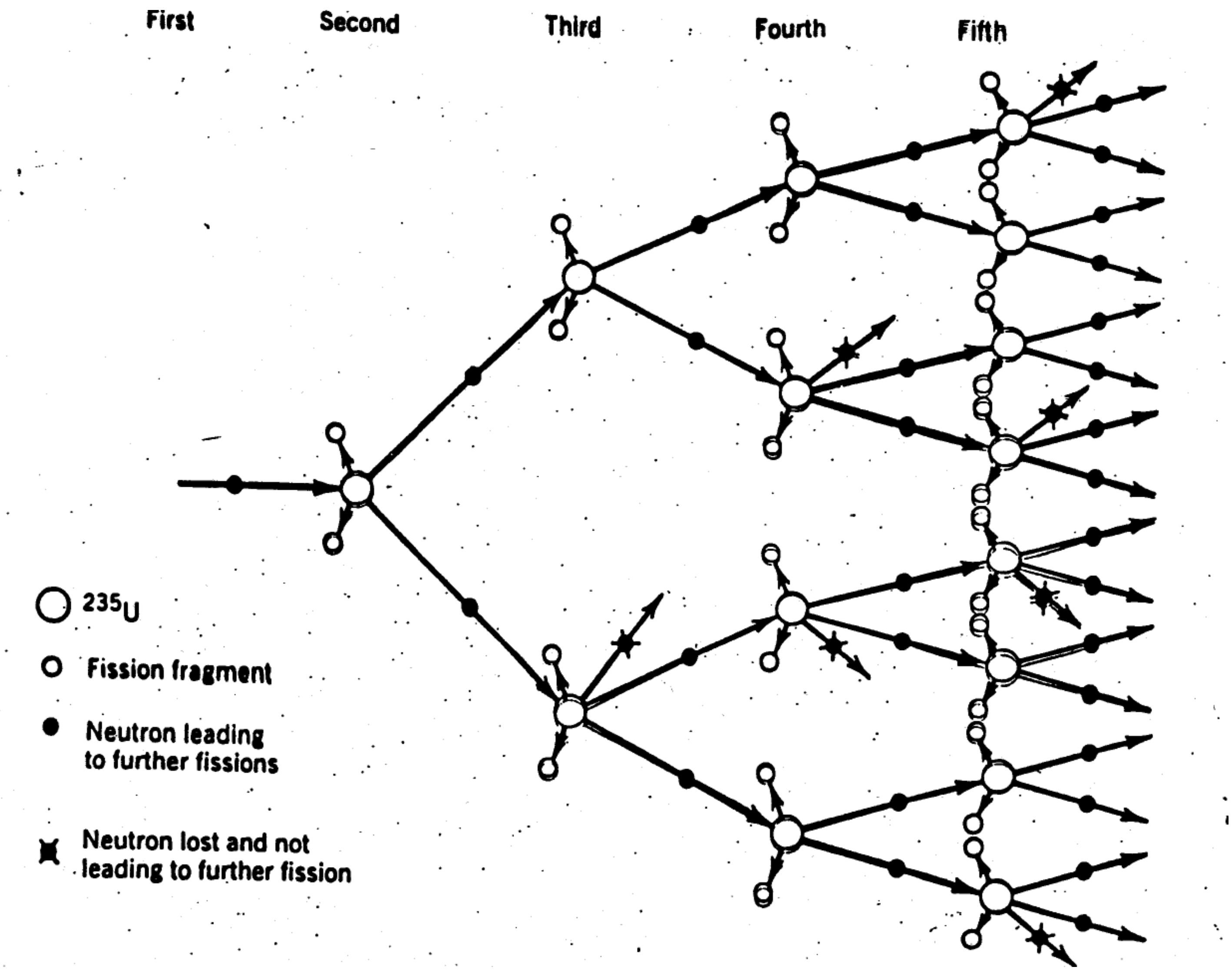
Chain Reaction



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iClicker Question (Use Channel C-C)

Which of the following is an example of radioactive decay?

A. Alpha decay

B. Beta decay

C. Gamma decay

D. Spontaneous fission

E. All of the above

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iClicker Answer

Which of the following is an example of radioactive decay?

A. Alpha decay

B. Beta decay

C. Gamma decay

D. Spontaneous fission

E. All of the above

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iClicker Question (Use Channel C-C)

The symbol “U-238” is sufficient to specify

A. The chemical element to which this nucleus corresponds

B. The number of neutrons in this nucleus

C. The number of protons in this nucleus

D. The number of neutrons and protons in its nucleus

E. All of the above

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iClicker Answer

The symbol “U-238” is sufficient to specify

A. The chemical element to which this nucleus corresponds

B. The number of neutrons in this nucleus

C. The number of protons in this nucleus

D. The number of neutrons and protons in its nucleus

E. All of the above

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Nuclear Reactors and Nuclear Bombs

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What Is a Critical Configuration?

A critical configuration is an assembly of fissionable nuclear material in an arrangement for which the rate of fissions in the assembly is steady.

The rate of fissions in the assembly will be steady if, on average, the neutrons released in each fission event initiate one new fission event.

The quantity of a given nuclear material needed to produce a steady rate of fissions depends on —

- The average number of neutrons released by each fission
- The fraction of the neutrons released that cause a subsequent fission

These depend on the composition, density, chemical form, etc., of the nuclear material and its arrangement (geometry, surroundings, etc.).

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What is the “Neutron Multiplication Factor”?

The number of neutrons released by each fission that cause a subsequent fission in a configuration of nuclear material depends on what fraction —

- Escape from the system
- Are captured but do not cause a fission
- Are captured and cause a fission

The ratio R of the number of neutrons present in fission generation *n* + 1 to the number present in fission generation *n* is called the *neutron multiplication factor* of that nuclear material configuration.

If R < 1, the configuration is *subcritical* and the rate of fissions in it will die out (usually quickly) as time goes on. Such a configuration is of little use.

If R = 1, the configuration is *critical* and the rate of fissions in it will remain the same as time goes on. Such configurations are used in nuclear reactors.

If R > 1, the configuration is *supercritical* and the rate of fissions in it will grow exponentially (usually quickly) with time. Such configurations are used in nuclear bombs.

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Nuclides Useful in Nuclear Reactors Versus Useful in Fission Bombs

Nuclear reactors require nuclides that can be fissioned by neutrons of any energy. Such nuclides are called "fissile".

The reason is that in a nuclear reactor, the neutrons emitted by fission events lose most of their kinetic energy (i.e., "slow down") by interacting with surrounding material before inducing a further fission.

A steady chain reaction can be created under these circumstances if fissile nuclides are used.

Nuclides that can be fissioned only by neutrons with energies above a certain threshold energy are called "fissionable but not fissile".

Fissionable but not fissile nuclides cannot be used in a nuclear reactor but some can be used in nuclear bombs.

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Relationship of Non-fissionable, Fissionable, Fissile, and Non-fissile Nuclides

All nuclides (fissionable and non-fissionable)

- Non-fissionable nuclides (most)
- Fissionable nuclides
  - Non-fissile (can be fissioned only by neutrons with energies above a certain threshold energy)
  - Fissile (can be fissioned by neutrons of any energy)

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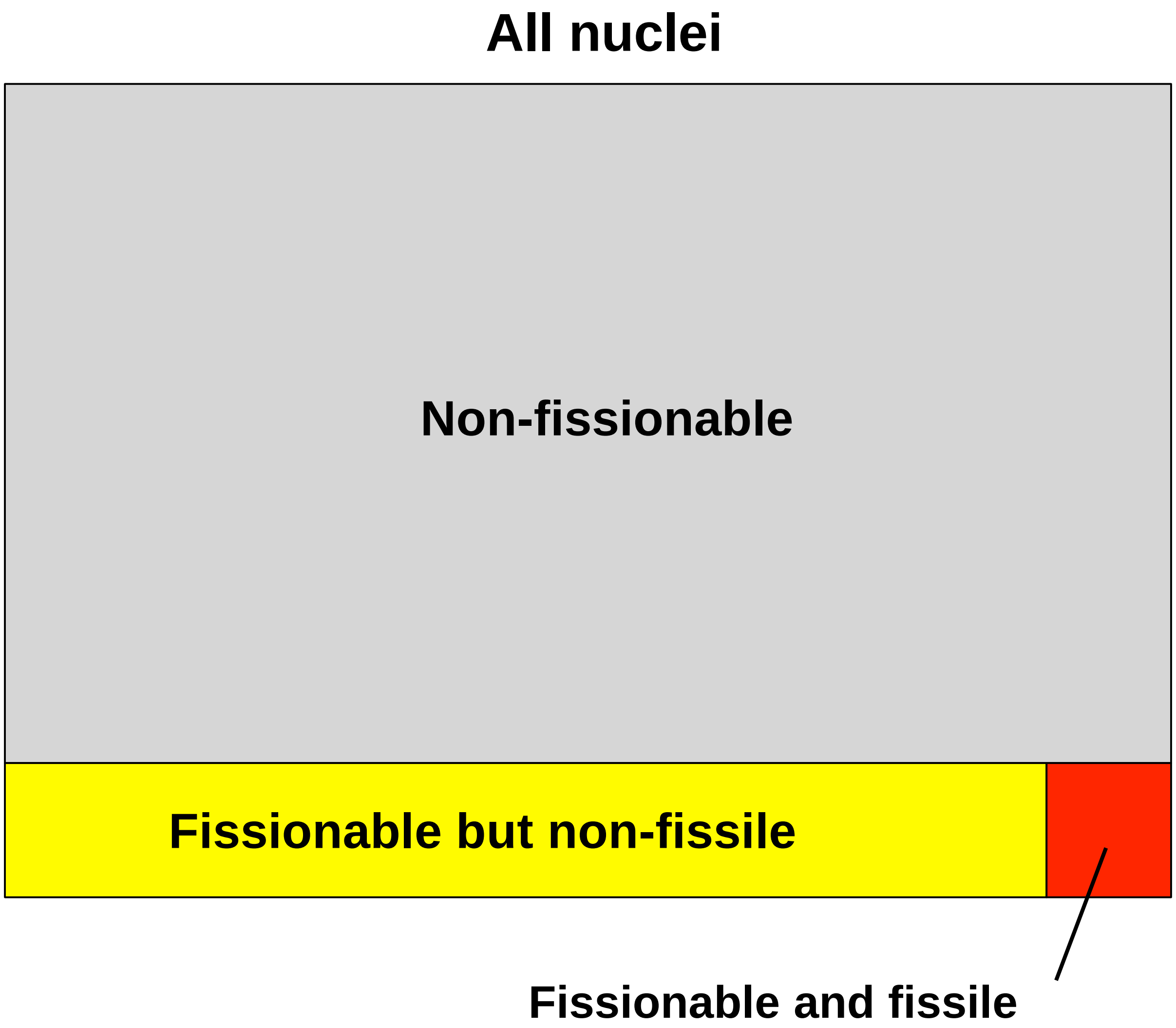
Relationship of Non-fissionable, Fissionable, Fissile, and Non-fissile Nuclides



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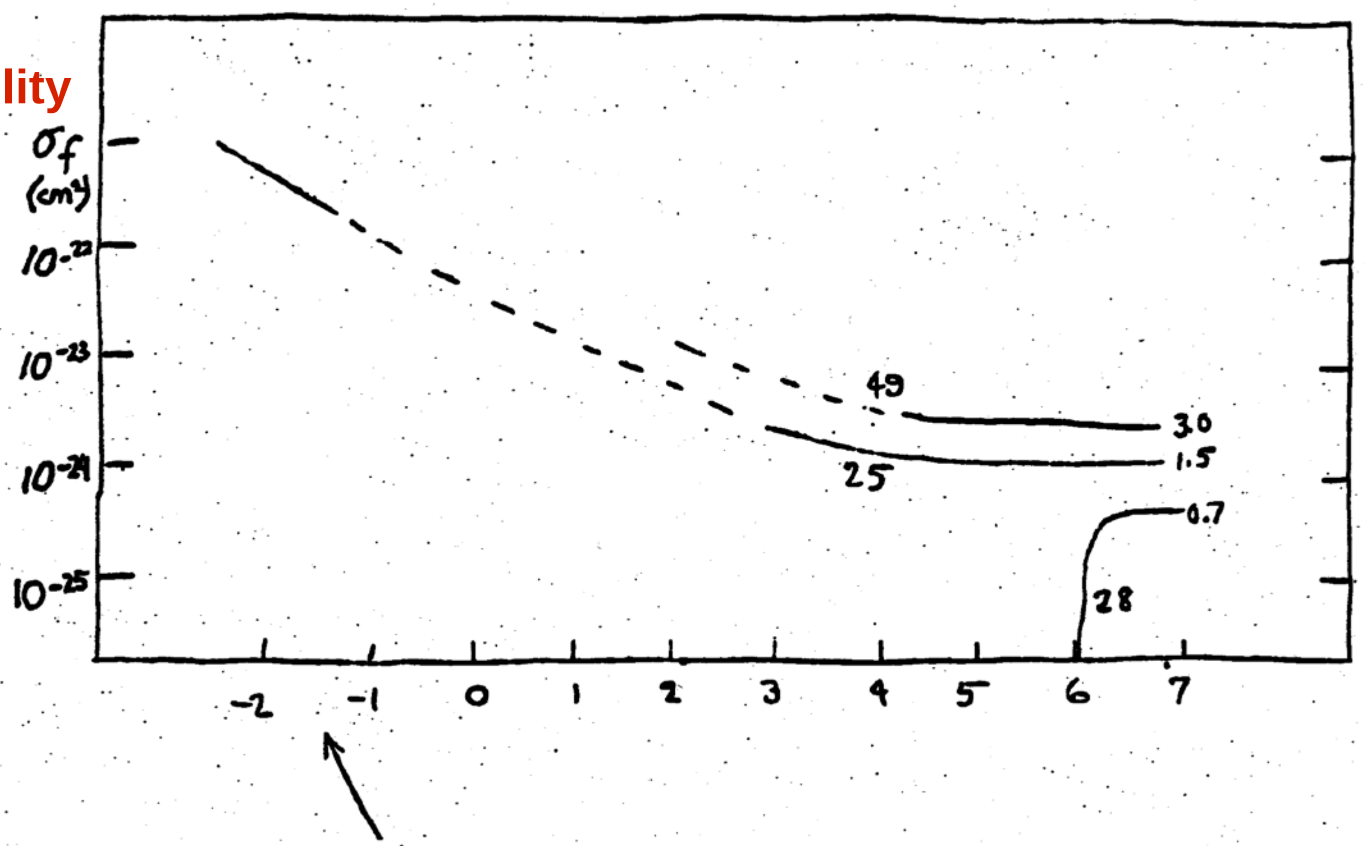
Neutron-Induced Fission Probability As a Function of the Incoming Neutron Energy for Three Important Nuclides

From: Los Alamos Primer, Robert Serber (Manhattan Project, ~1943)

Secret Codes: 25 = U(235), 28 = U(238), 49 =Pu(239)

FISSION CROSS-SECTIONS 15

Fission Probability



(thermal) log neutron energy in EV.
Fig. 1

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What Are Nuclear-Explosive Nuclides?
What Is Nuclear-Explosive Material?

Nuclear-explosive *nuclide* —in a configuration with suitable quantity, purity, and geometry—can support an explosive (exponentially growing) fast-neutron fission chain reaction.

“Fast” neutrons are fission-produced neutrons that have not been slowed by interacting with their environment.

Nuclear-explosive *material (NEM)* is a mixture of various nuclear-explosive nuclides and other nuclides that—in a configuration with suitable quantity, purity, and geometry—can support a fast-neutron fission chain reaction.

Nuclear-explosive material can be used to create a nuclear bomb.

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Some Nuclear-Explosive Nuclides Are Not Fissile

Whether nuclides are capable of supporting a *slow-neutron chain reaction* (i.e., whether they are *fissile*) is not directly relevant to whether they can support a fast-neutron chain reaction.

However, the underlying physics is such that —

- All fissile nuclides are nuclear-explosive
- Some nuclides that are not fissile are nuclear-explosive

Fissionable but non-fissile nuclides cannot be used in a nuclear reactor, but some can be used to create nuclear-explosive material.

For example, the even-numbered isotopes of Plutonium — most importantly Pu-238, Pu-240, and Pu-242 — are *not* fissile but *are* nuclear explosive nuclides.

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Fertile Nuclides

Fertile Nuclides can be used to “breed” Nuclear Explosive Nuclides in Nuclear Reactors

Example: Uranium-238

fertile nuclide

$$ {}^{1}_{0}n + {}^{238}_{92}U \rightarrow {}^{239}_{92}U $$

neutron capture

$$ {}^{239}_{92}U \rightarrow {}^{239}_{93}Np + e^{-} + \overline{\nu}_e $$

Beta-decay

$$ {}^{239}_{93}Np \rightarrow {}^{239}_{94}Pu + e^{-} + \overline{\nu}_e $$

Beta-decay

nuclear explosive nuclide

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How to Produce a Nuclear Explosion

A nuclear explosion can be produced by the rapid assembly of NEM into a configuration that will sustain a fast-neutron chain reaction.

To sustain a fast-neutron chain reaction, on average at least one of the several energetic neutrons released per fission must be “productively” captured, i.e., it must produce another fission following its capture.

To be productive, the neutron must cause a fission before it is unproductively captured or escapes from the configuration.

To produce a nuclear explosion, the fast neutrons from each “generation” of fissions must produce *more* fast neutrons in the next “generation”.

Such a configuration is “prompt supercritical” and will explode.

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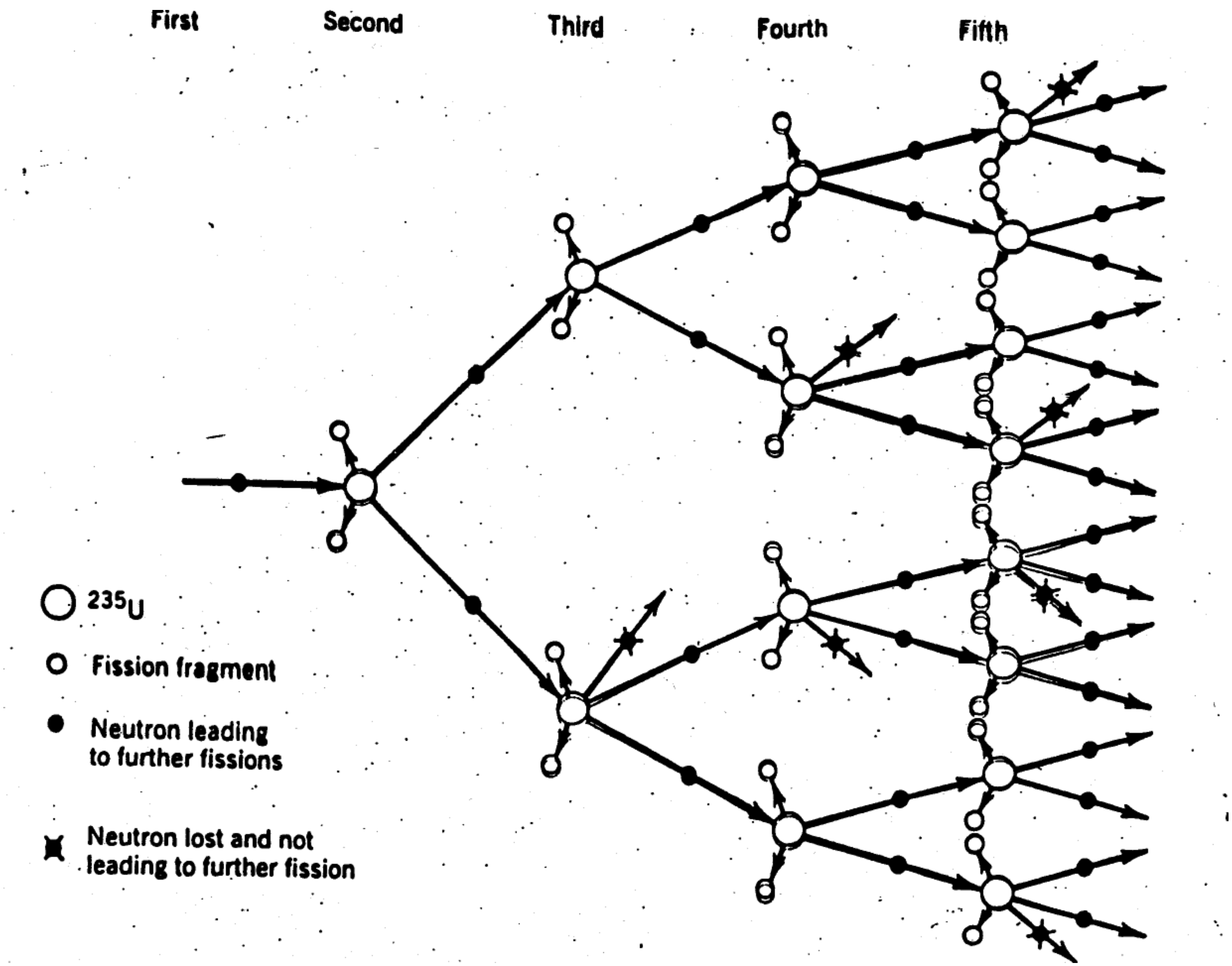
Explosive Chain Reaction: Generations



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Number of Fissions When a Nuclear Weapon is Exploded

Generation	Fissions in the generation	Energy released
1	$2^0 = 1$	
2	$2^1 = 2$	
3	$2^2 = 2 \times 2 = 4$	
4	$2^3 = 2 \times 2 \times 2 = 8$	
5	$2^4 = 2 \times 2 \times 2 \times 2 = 16$	
10	$2^9 = 512$	
30	$2^{29} = 5.3 \times 10^8$	
70	$2^{69} = 5.9 \times 10^{20}$	2.5×10^{-4} Y
79	$2^{78} = 3.0 \times 10^{23}$	0.12 Y
80	$2^{79} = 6.0 \times 10^{23}$	0.25 Y
81	$2^{80} = 1.2 \times 10^{24}$	0.50 Y
82	$2^{81} = 2.4 \times 10^{24}$	1.00 Y

Each generation lasts about 1 “shake” = 10^{-8} sec = 1/100,000,000 sec.

All 82 generations last 82 x 10^{-8} sec = 0.8 x 10^{-6} sec ≈ 1 microsecond.

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Plan for This Session

Questions about the course

Module 2: Nuclear weapons cont'd

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Physics 280: Session 6

Annoucements

Questions About The Course

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Definitions of Fission and Nuclear Materials Summary – Important !

- ***Nuclear fission*** is the breakup of a heavy nucleus, such as uranium, into two medium-weight nuclei. Fission is usually accompanied by emission of a few neutrons and γ-rays.
- A ***fissionable nuclide*** is one that can be fissioned by bombardment with neutrons.
- A ***fissionable but non-fissile nuclide*** is one that can be fissioned only by neutrons with energies above a certain threshold energy.
- A ***fissile nuclide*** is one that can be fissioned by neutrons of any energy; in fact, the lower the neutron's energy, the greater the probability that it will cause the nuclide to fission.
- ***Nuclear-explosive material*** is a mixture of nuclides that can support an explosive fast-neutron chain reaction.
- ***Fertile material*** is a mixture of nuclides that are transformed into fissile nuclides by capturing a neutron.

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Examples of Fissile, Fissionable but Non-fissile, and Fertile Nuclides (Important)

U-235 and Pu-239 are *fissile*

- *Neutrons of any energy can cause fission*
- Hence a slow-neutron chain reaction is possible
- A fast-neutron chain reaction is also possible

U-238 and Th-232 are *fissionable but not fissile;* both are *fertile*

- *Only neutrons with energies above a threshold energy can cause fission*
- For, e.g., U-238, only ~ 25% of the neutrons emitted have energies above the threshold energy for causing fission
- Hence a fast-neutron chain reaction is impossible
- A slow-neutron chain reaction is also impossible, because the energies of slow neutrons are below the threshold energy for inducing fission

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Number of Fissions When a Nuclear Weapon is Exploded

Generation	Fissions in the generation	Energy released
1	$2^0 = 1$	
2	$2^1 = 2$	
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4	$2^3 = 2 \times 2 \times 2 = 8$	
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70	$2^{69} = 5.9 \times 10^{20}$	2.5×10^{-4} Y
79	$2^{78} = 3.0 \times 10^{23}$	0.12 Y
80	$2^{79} = 6.0 \times 10^{23}$	0.25 Y
81	$2^{80} = 1.2 \times 10^{24}$	0.50 Y
82	$2^{81} = 2.4 \times 10^{24}$	1.00 Y

88% of total Yield (explosive energy) are released in the 3 final stages of a chain reaction!

Each generation lasts about 1 “shake” = 10^{-8} sec = 1/100,000,000 sec.

All 82 generations last 82 x 10^{-8} sec = 0.8 x 10^{-6} sec ≈ 1 microsecond.

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Fertile Nuclides → Nuclear Explosive Nuclide

Fertile Nuclides can be used to “breed” Nuclear Explosive Nuclides in Nuclear Reactors:

Example: Uranium-238

fertile nuclide

$$ {}^{1}_{0}n + {}^{238}_{92}U \rightarrow {}^{239}_{92}U $$ neutron capture

$$ {}^{239}_{92}U \rightarrow {}^{239}_{93}Np + e^{-} + \overline{\nu}_e $$ Beta-decay

$$ {}^{239}_{93}Np \rightarrow {}^{239}_{94}Pu + e^{-} + \overline{\nu}_e $$ Beta-decay

nuclear explosive nuclide

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Properties of Nuclear Explosive Nuclides

Reactivity, Critical Mass, and Explosive Yield

TABLE A-1 Properties of Nuclear-Explosive Nuclides

Isotope or Mixture	Critical Mass (kg)	Half Life (years)	Decay Heat (watts/kg)	Neutron Production From Spontaneous Fission (per kg-sec)	Main Gamma Energies (MeV)
U-233	16	160,000	0.28	1.2	2.6 from Tl-208
U-235	48	700,000,000	0.00006	0.36	0.19
Np-237	59	2,100,000	0.021	0.14	0.087
Pu-238	10	88	560	2,700,000	0.100
Pu-239	10	24,000	2.0	22	0.41
Pu-240	37	6,600	7.0	1,000,000	0.10
Pu-241	13	14	6.4	49	0.66 from Am-241
Pu-242	89	380,000	0.12	1,700,000	0.045
Am-241	57	430	110	1,500	0.66

Properties are important for usage of NEN in nucl. weapons:

- heat from rad. Decay
  ➔ requires cooling
- radiation from rad. Decay
  ➔ must control damage to personal and materials
- neutrons from spontaneous fission ➔ early trigger of chain reaction

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Properties of Nuclear Explosive Materials

TABLE A-2 Heat, Radioactivity and Radiation from Various Nuclear Materials

Material	Radioactivity (Ci/g)	Neutron Generation (n/g-sec)	Heat Release (W/kg)	Gamma Dose (rem/hr)
Natural U	0.0000007	0.013	0.000019	0.000012
LEU	0.0000019	0.012	0.000054	0.000057
Weapon-grade HEU	0.0000095	0.0014	0.00026	0.0015
Weapon-Grade Pu	0.22	52	2.5	0.94
Reactor-Grade Pu	6.2	340	14	15

Properties are important for usage of nuclear explosive materials in nuclear weapons:

- heat from rad. Decay ➔ requires cooling
- radiation from rad. Decay ➔ must control damage to personal and materials
- neutrons from spontaneous fission ➔ early trigger of chain reaction

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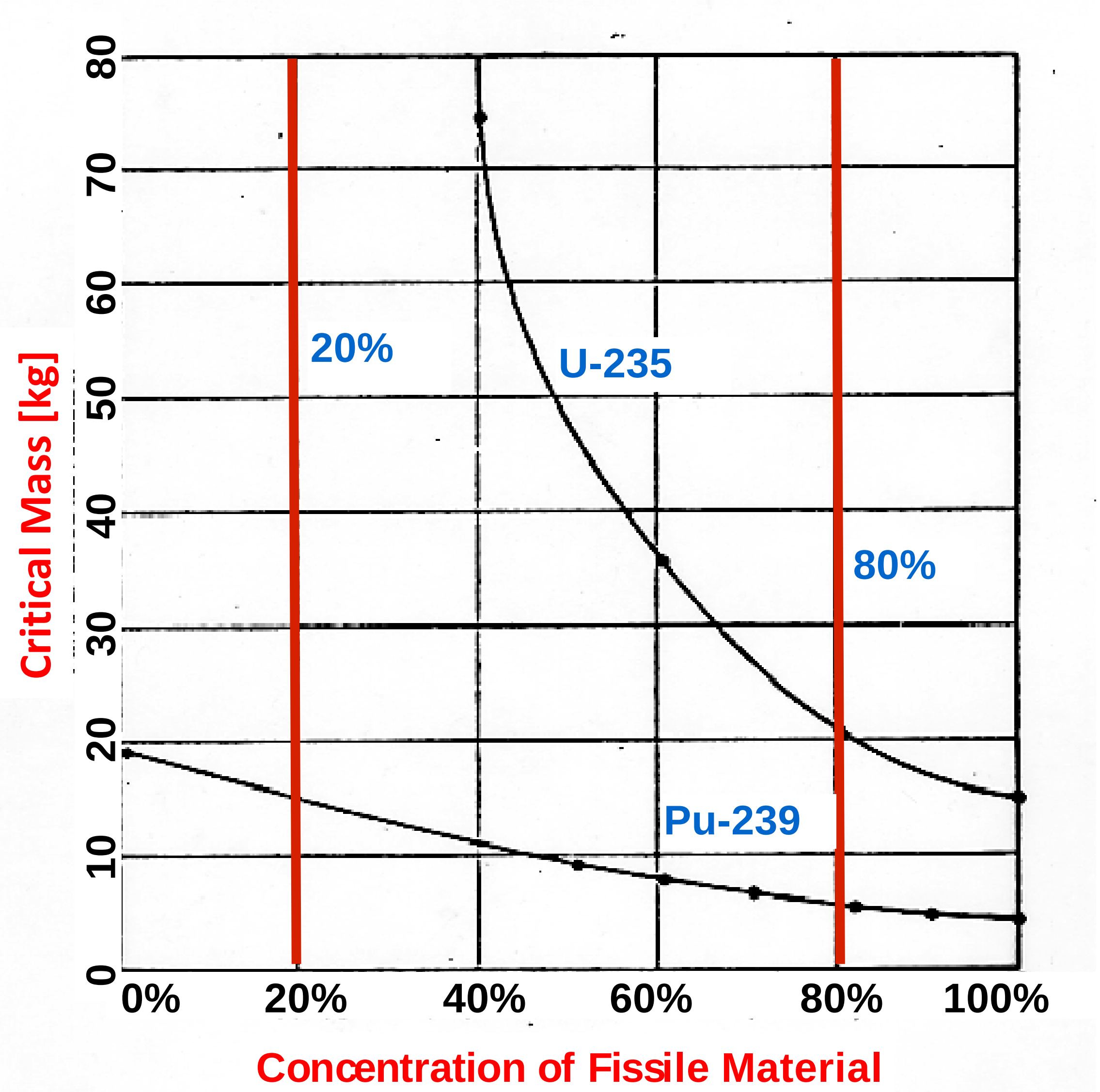
Reducing the Fast-Neutron Critical Mass – 1

Dependence on the Concentration of the Fissile Material



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Reducing the Fast-Neutron Critical Mass – 2

Dependence on the Density ρ of the Fissile Material

Let m_C be the critical mass. Then

$$\frac{m_c(\rho)}{m_c(\rho_0)} = \left(\frac{\rho_0}{\rho}\right)^2$$

where ρ_0 is normal density and ρ is actual density

Example: $\frac{\rho}{\rho_0} = 2, \quad \frac{m_c(\rho)}{m_c(\rho_0)} = \frac{1}{4}$ ⇒ Increasing the density by a factor 2 reduces the critical mass by a factor 4!

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Reducing the Fast-Neutron Critical Mass – 3

- A reflector surrounding a configuration of fissile material will reduce the number of neutrons that escape through its surface
- The best neutron reflectors are light nuclei that have have no propensity to capture neutrons
- The lightest practical material is Beryllium, the lightest strong metal
- Heavy materials (e.g., U-238) sometimes used instead to reflect neutrons and "tamp" explosion

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Mass Required for a Given Technology

kg of Weapon-Grade Pu for Technical Capability				kg of Highly Enriched U for Technical Capability		
Low	Medium	High	Yield (kt)	Low	Medium	High
3	1.5	1.0	1	8	4	2.5
4	2.5	1.5	5	11	6	3.5
5	3.0	2.0	10	13	7	4.0
6	3.5	3.0	20	16	9	5.0

For P280, we assume 6 kg of Pu-239 and 16 kg of HEU are required.

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iClicker Question (Use Channel C-C)

Which one of the following statements is true?

A. A non-fissionable nuclide can sometimes be fissioned

B. A fissile nuclide cannot be fissioned

C. A fissile nuclide can be fissioned, but only by a neutron with sufficient kinetic energy

D. A fissile nuclide can be fissioned by a neutron of any energy

E. None of the above statements are true

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iClicker Answer

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D. A fissile nuclide can be fissioned by a neutron of any energy

E. None of the above statements are true

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iClicker Question (Use Channel C-C)

Which one of the following statements is **false**?

A. A nuclear explosion can be created using any fissionable material
B. A nuclear explosion can be created using any fissile material
C. A nuclear explosion can be created using U(235)
D. A nuclear explosion can be created using Pu(239)
E. A nuclear explosion can be created using reactor fuel

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iClicker Answer

Which one of the following statements is **false**?

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E. A nuclear explosion can be created using reactor fuel

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Fission Weapons ("A-bombs")

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Important Concepts

- Induced vs. spontaneous fission
- Critical vs. supercritical configurations
- Neutron multiplication factor
- Explosive chain reaction
- Nuclear-explosive materials

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First Let's Discuss Chemical Bombs

Simulated road side bomb attack with chemical explosive

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How to Make a Chemical Explosion – 1

Explosive —

- Mixture of fuel and oxidizer (e.g., TNT)
- Close proximity of fuel and oxidizer can make the chemical reaction very rapid

Packaging —

- To make a bomb, fuel and oxidizer must be confined long enough to react rapidly and (almost) completely
- A sturdy bomb case can provide confinement
- Bomb case fragments can also increase damage

Ignition —

- Via flame or spark (e.g., a fuse or blasting cap)
- Started by lighting the fuse or exploding the cap

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How to Make a Chemical Explosion – 2

Stages —

- Explosive is ignited
- Fuel and oxidizer burn (chemically), releasing ~ 5 eV per molecule
- Hot burned gases have high pressure, break bomb case and expand

Energy released goes into —

- Light
- Blast wave (strong sound wave and air motion)
- Flying shrapnel
- Heat

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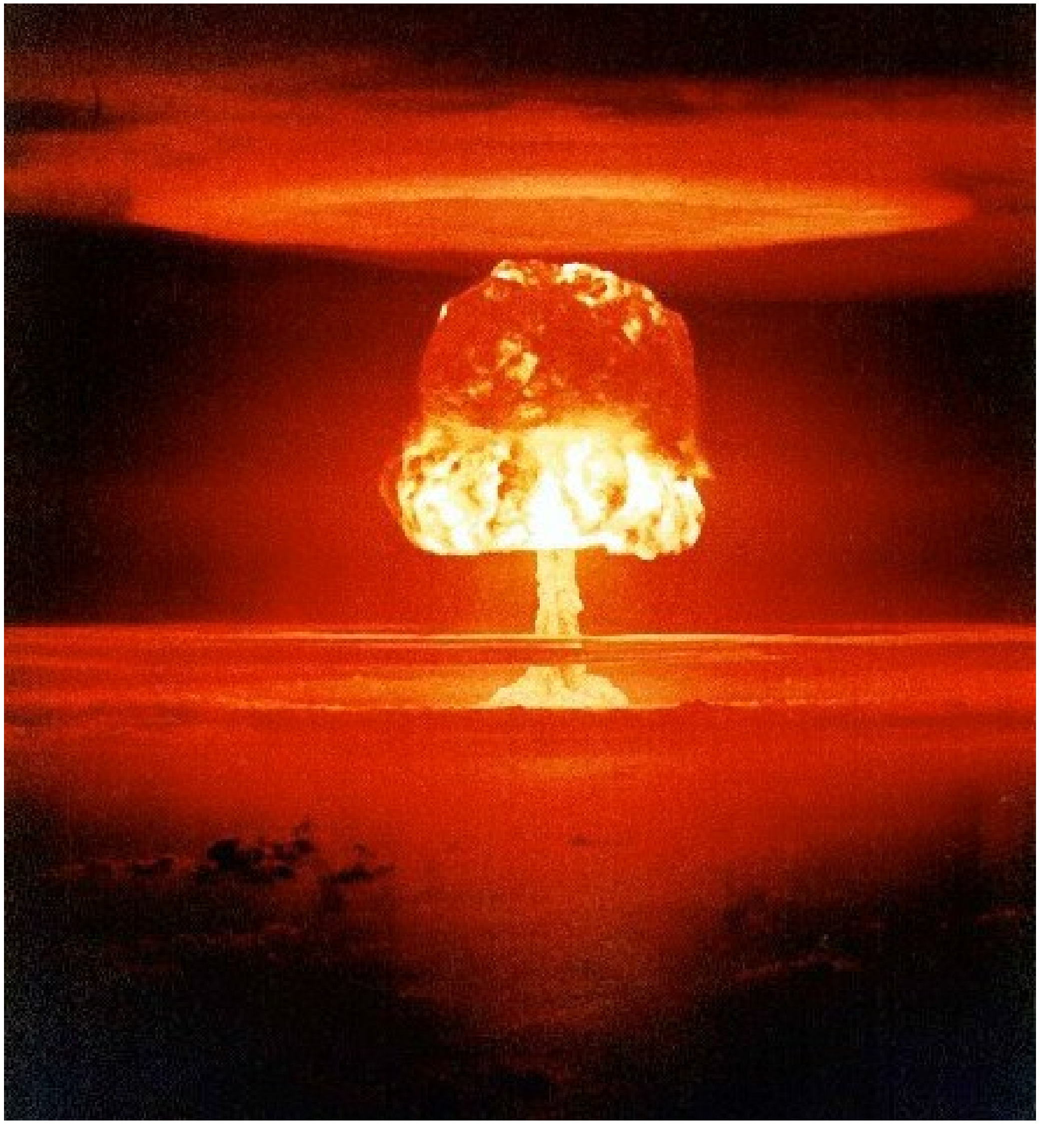
Now Let's Discuss Nuclear Bombs



Thermonuclear explosion in the Pacific (Castle-Romeo, 11 Mt)

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How to Make a Nuclear Explosion

Key steps required to create a fission explosion —

- Collect at least a critical mass of NEM (*be sure to keep the material in pieces, each with a subcritical mass!*)
- Quickly assemble the pieces into a single supercritical mass
- Initiate a fast-neutron chain reaction in the assembled mass
- Hold the assembly together until enough of it has fissioned

Additional steps required to create a thermonuclear (two-stage) explosion —

- Assemble as much fusion fuel as desired
- Arrange the fusion fuel near the fission bomb in such a way that the X-rays produced by the exploding NEM compress and heat the fusion fuel until it reacts

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Energy Released By a Single Fission (Details)

n + (fissile nucleus) $\rightarrow$ (fission frags) + (2 or 3 n's)

Energy Distribution (MeV)

Kinetic energy (KE) of fission fragments	~ 165*
Energy of prompt gamma-rays	7*
KE of prompt neutrons	5
KE of beta-rays from fragments	7
E of gamma-rays from fragments	6
E of neutrinos from fragments	10
Total	~ 200

*Only this 172 MeV is counted in the explosive "yield" of nuclear weapons

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Energy Yields of Nuclear Weapons – 1

- The *yield* of a nuclear weapon is defined (roughly) as *the total energy it releases when it explodes*

- The energy release is quoted in units of the energy released by a ton of TNT

  —1 kiloton (kt) = 1 thousand tons of TNT

  —1 Megaton (Mt) = 1 million tons of TNT

- For this purpose the energy of 1 kt of TNT is defined as 10^{12} Calories = 4.2×10^{12} Joules

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Energy Yields of Nuclear Weapons – 2

Fission weapons (“A-bombs”) —

- Theoretical maximum yield-to-weight ratio: 8,000 tons TNT = 8 kt TNT from 1 lb. of NEM (~ 10,000,000 times as much per lb. as TNT)
- Difficult to make weapons larger than few 100 kt (Yields of tested weapons: 1–500 kt)

Thermonuclear weapons (“H-bombs”) —

- Theoretical maximum yield-to-weight ratio: 25 kt TNT from 1 lb. of fusion material (~ 3 times as much per lb. as fission weapons)
- There is no fundamental limit to the size of a thermonuclear weapon

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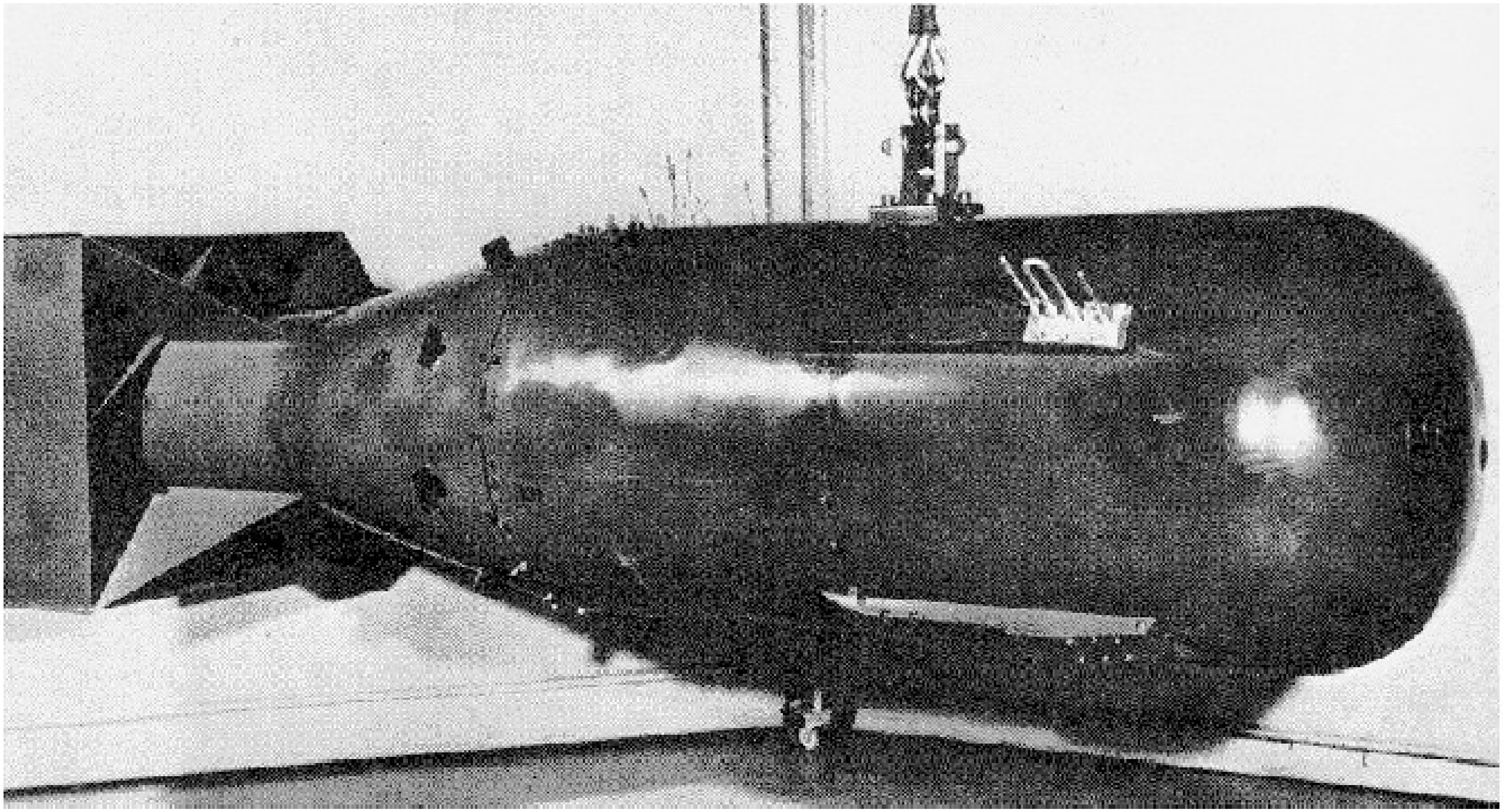
Fission Weapons – Gun Type

Little Boy



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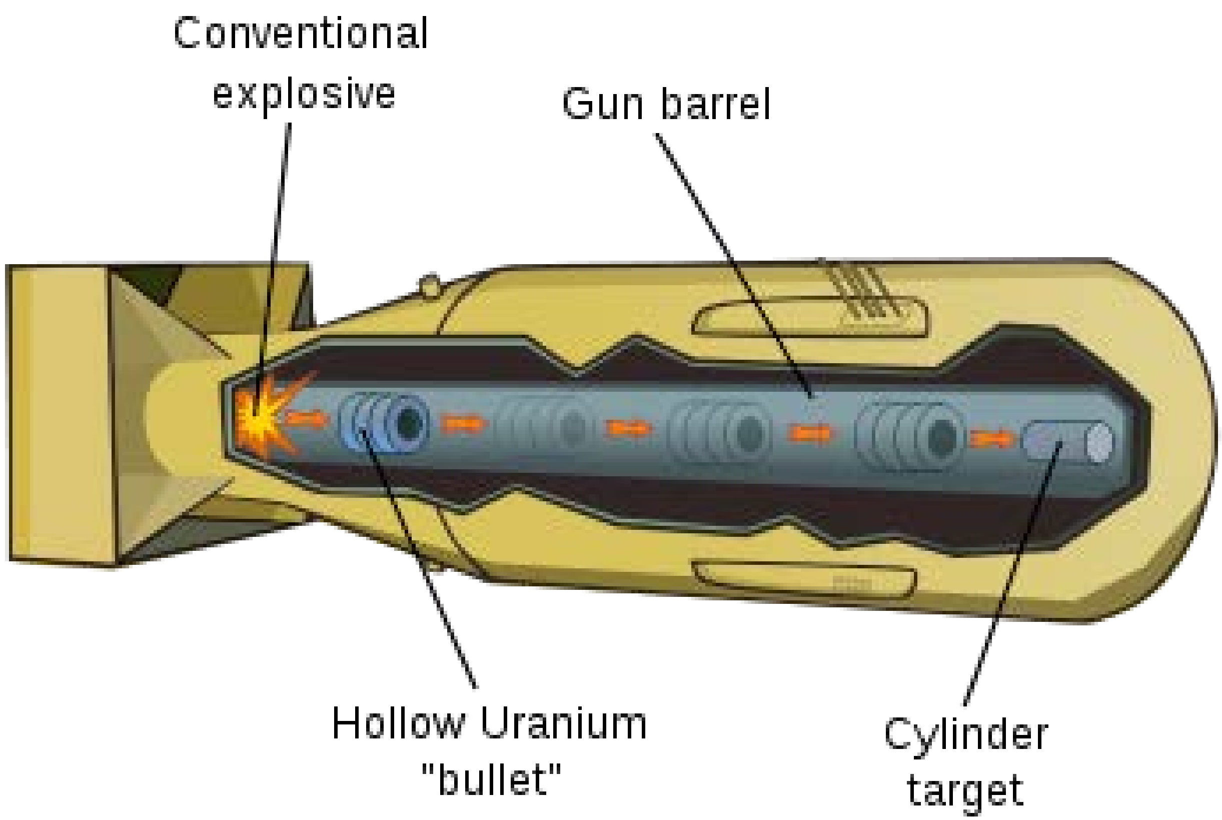
Fission Weapons – Gun Type



Works only with HEU

(relevant today mostly for terrorists or non-state groups)

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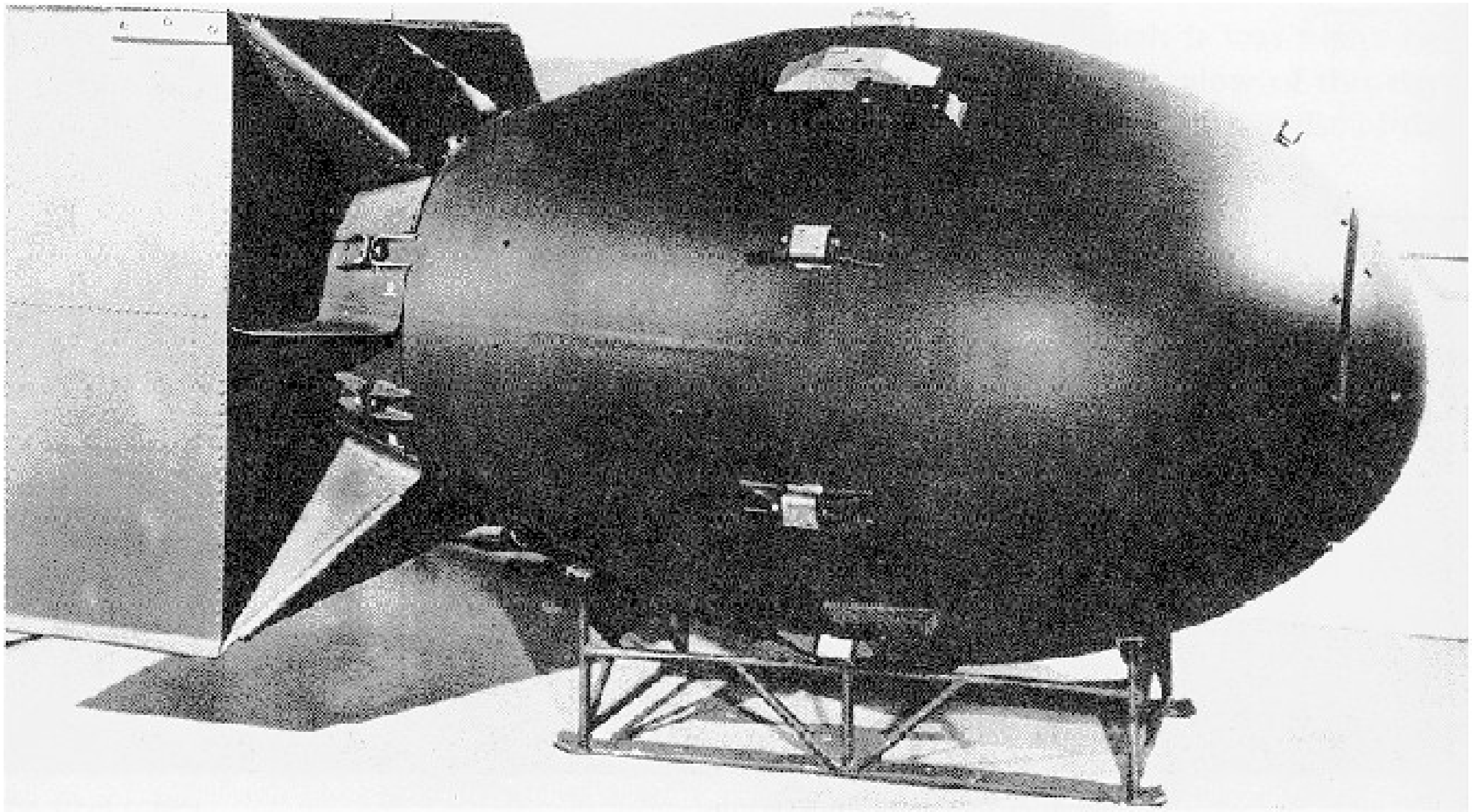
Fission Weapons – Implosion Type

Fat Man



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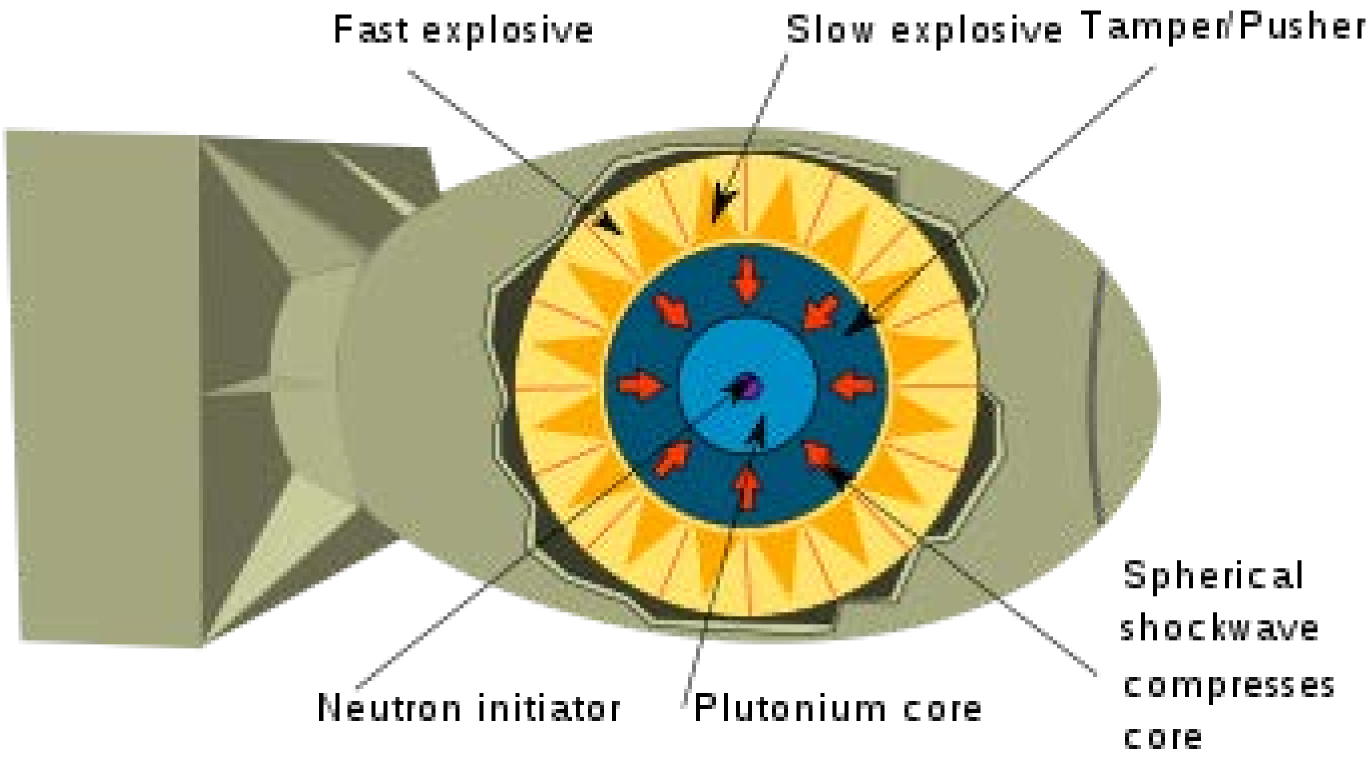
Fission Weapons – Implosion Type



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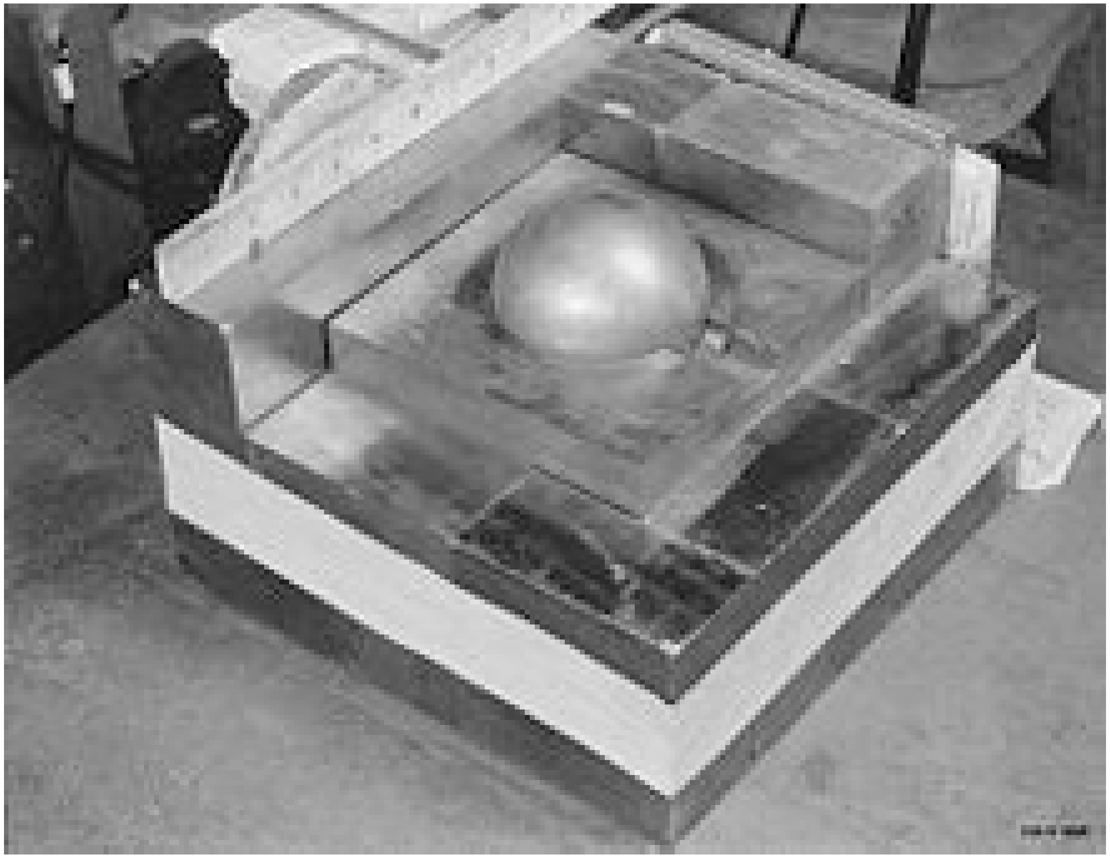
Fission Weapons – Implosion Type

Plutonium Sphere ("Pit")



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Initiating a Fission Explosion – 1

- Quickly assemble a *prompt supercritical configuration* of nuclear-explosive material and, at the instant of maximum compression (maximum density)…
- Introduce *millions* of neutrons to initiate millions of chain reactions
- Chain reactions will continue until the increasingly hot nuclear-explosive material expands sufficiently to become *subcritical*

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Initiating a Fission Explosion – 2

Timing is everything —

- If initiation occurs too early (*before* the moment of maximum supercriticality), the yield will be low (a “fizzle”)
- If initiation occurs too late (*after* the moment of maximum supercriticality), the configuration will have re-expanded and the yield will be less than the maximum yield
- Even if the initiator fails, there are always stray neutrons around that will trigger a chain reaction and produce an explosion—but the yield will be unpredictable
- In a nuclear war, neutrons from a nearby nuclear explosion may cause pre-initiation in a nuclear weapon—this is referred to as “over-initiation” (weapon designers seek to design weapons that will not suffer from this effect)

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iClicker Question (Use Channel C-C)

Which one of the following nuclear processes is essential for creating a nuclear explosion?

A. Radioactivity

B. Spontaneous fission

C. Induced fission

D. Neutron activation

E. All of the above

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iClicker Answer

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iClicker Question (Use Channel C-C)

The minimum amount of *highly enriched Plutonium* needed to make a nuclear bomb has about the same volume as:

A = a marble

B = a softball

C = a basketball

D = a large beach ball

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iClicker Answer

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iClicker Question (Use Channel C-C)

China first tested a nuclear device in what year?

A. 1960
B. 1964
C. 1968
D. 1972
E. 1974

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iClicker Answer

China first tested a nuclear device in what year?

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B. 1964
C. 1968
D. 1972
E. 1974

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Thermonuclear Weapons (“H-Bombs”)

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Fusion Nuclear Reactions (Basics)

Fusion: a nuclear reaction in which two nuclides combine to form a single nuclide, with emission of energetic particles or electromagnetic radiation —

- gamma rays (EM radiation from the nucleus)
- neutrons
- occasionally other nuclear particles

Particles involved:

- deuteron (D)
- triton (T)
- He-4 (alpha)
- neutron (n)

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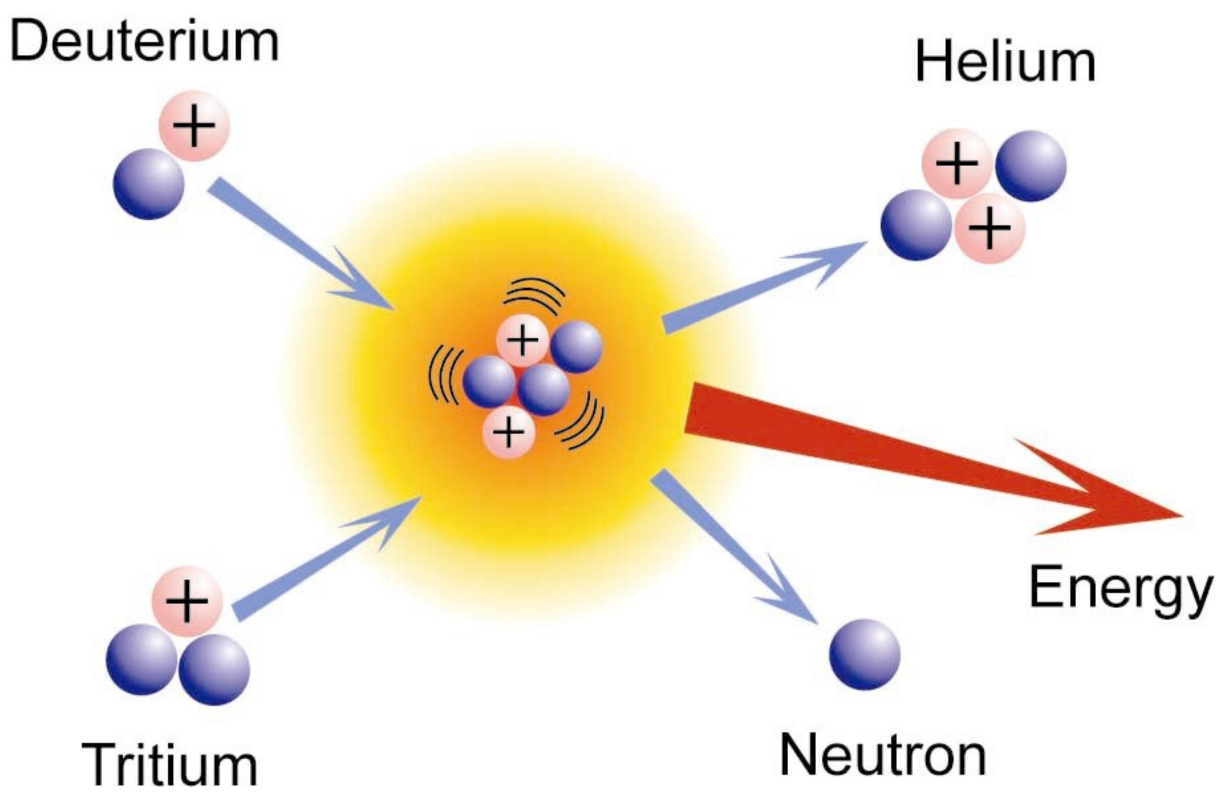
Example Fusion Nuclear Reaction



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Two-Stage (Thermonuclear) Weapons – 1

- Theoretical analysis showed that the original design proposed by Edward Teller was unworkable
- Andrei Sakarov proposed a workable “boosted fission” design, the so-called “layer-cake” design (it was not a true thermonuclear weapon but was deliverable by an aircraft)
- Stanislaw Ulam came up with a new idea that Teller improved, the so-called “Ulam-Teller design”
- In this design, X-rays from the primary interact with the secondary, compressing and heating the secondary
- Several designs are possible, but we will assume a simple “P280 design” for essays and exams

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Physics 280: Session 7

Plan for This Session

Announcements about the course

➔ RE2v2 due Thursday 2-13 at beginning of class

Questions about the course

Module 2: Nuclear weapons (conclusion)

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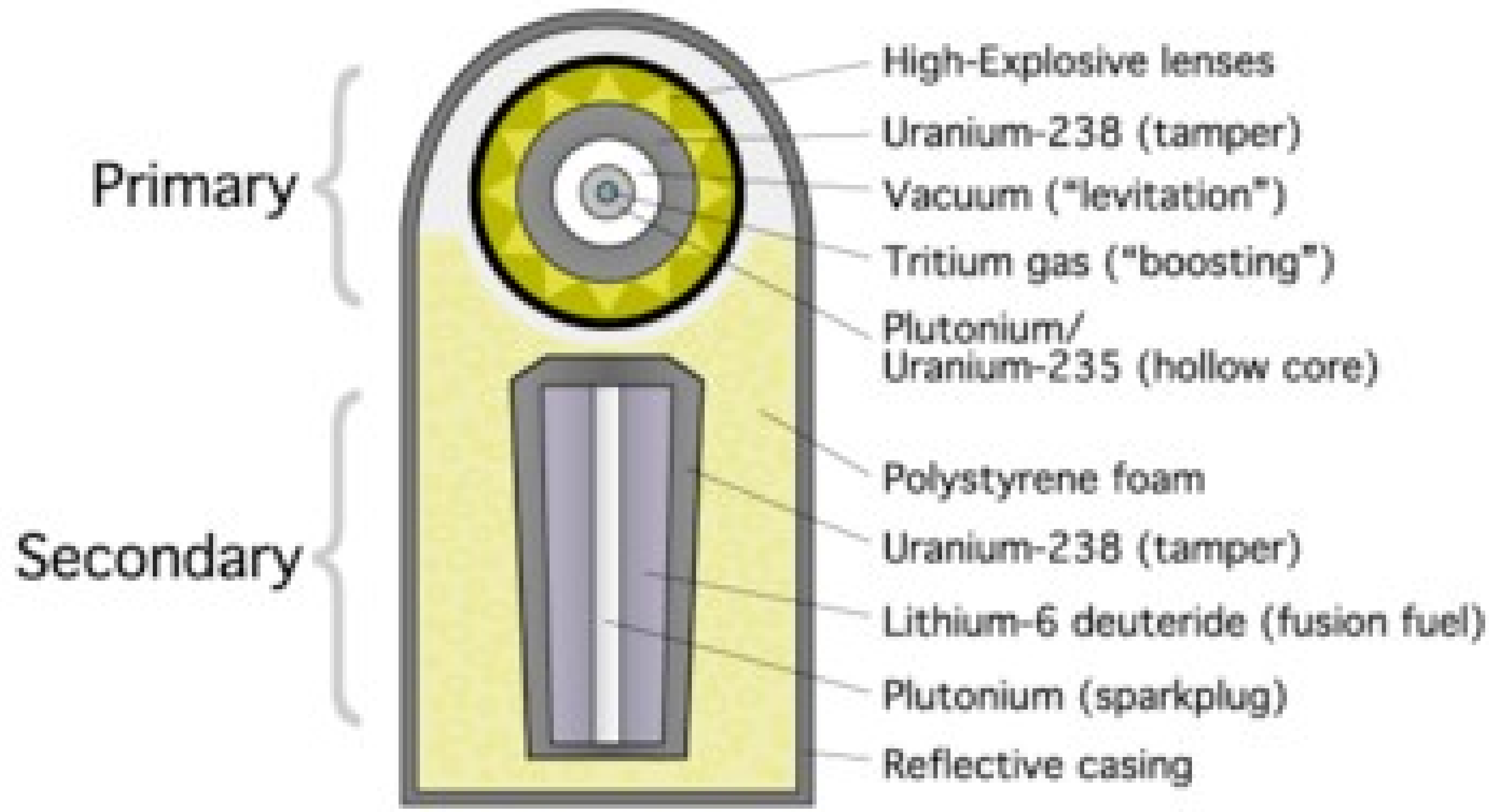
Two-Stage (Thermonuclear) Weapons – 2



From "The Secret that Exploded"
by Howard Morland, Random House, 1981

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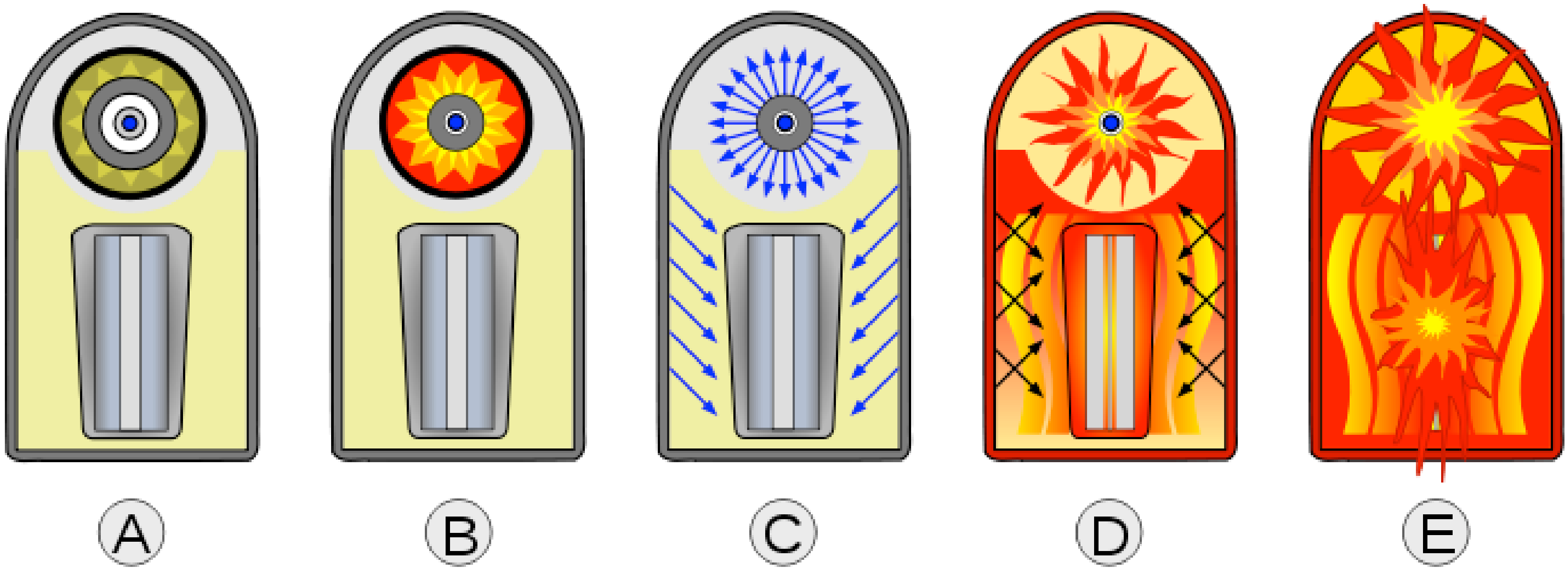
Two-Stage (Thermonuclear) Weapons – 3

Sequence of events —



From "The Secret that Exploded"
by Howard Morland, Random House, 1981

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Two-Stage (Thermonuclear) Weapons – 4

- Modern thermonuclear weapons have two stages:

  - the primary (mostly fission)

  - the secondary (fusion+fission)

  Fissions during the second stage are produced by high-energy neutrons from the fusion reactions and greatly increase the yield ("fission-boosted fusion")

- The secondaries of deliverable bombs use ^{6}Li-D to make T+D

- Burning grows quickly, but not geometrically (exponentially): the fusion burn is not a chain reaction

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Two-Stage (Thermonuclear) Weapons – 5

- X-rays from the 'primary' compress and heat the 'secondary', causing thermonuclear fusion of T + D
  - Radiation pressure is not important
  - Ablation (blow off) of surface material is the dominant heating and compressive effect
- There in no fundamental limit to the yield that is possible from a fusion secondary
  - The Soviets conducted an atmospheric test with a yield of 50 Mt (Sakarov rebelled)
  - The U.S. concluded that this particular design was capable of releasing 100 Mt

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Two-Stage (Thermonuclear) Weapons – 6

- Making a 50 Mt device makes no sense except (maybe) as a propaganda exercise, no matter how evil the intent
- U.S. developed and fielded H-bombs with yields up to 9 Mt
- As ballistic missile accuracies improved, the maximum yield of deployed US weapons dropped to 1 Mt or less, allowing an increase in the area of death and destruction (explained later)
- All the States that developed fission bombs and sought to develop true thermonuclear bombs succeeded in doing so

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Two-Stage (Thermonuclear) Weapons – 7

HEU, DU, natural U, or Pu are used to increase the yield —

- During the thermonuclear burn, vast numbers of energetic neutrons are present in the secondary
- These neutrons will fission HEU, DU, or natural U (or Pu) in the fusion packet or the bomb case
- These fissions release additional energy, increasing the yield
- They also make the bomb much "dirtier", i.e., it will produce much more radioactive fallout

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Balance of Energy Release from Two-Stage Nuclear Weapons - 8

- There is fission and a small amount of fusion in a (boosted) primary
- There is lots of fusion and fission in the secondary (which is understood to include the DU shell)
- The yield Y_p of the primary may be 10 kiloton (kt)
- The yield Y_s of the secondary can range from a few100 kt to a few Mt
- Overall, approximately
  - 50% of the energy released comes from fission
  - 50% of the energy released comes from fusion

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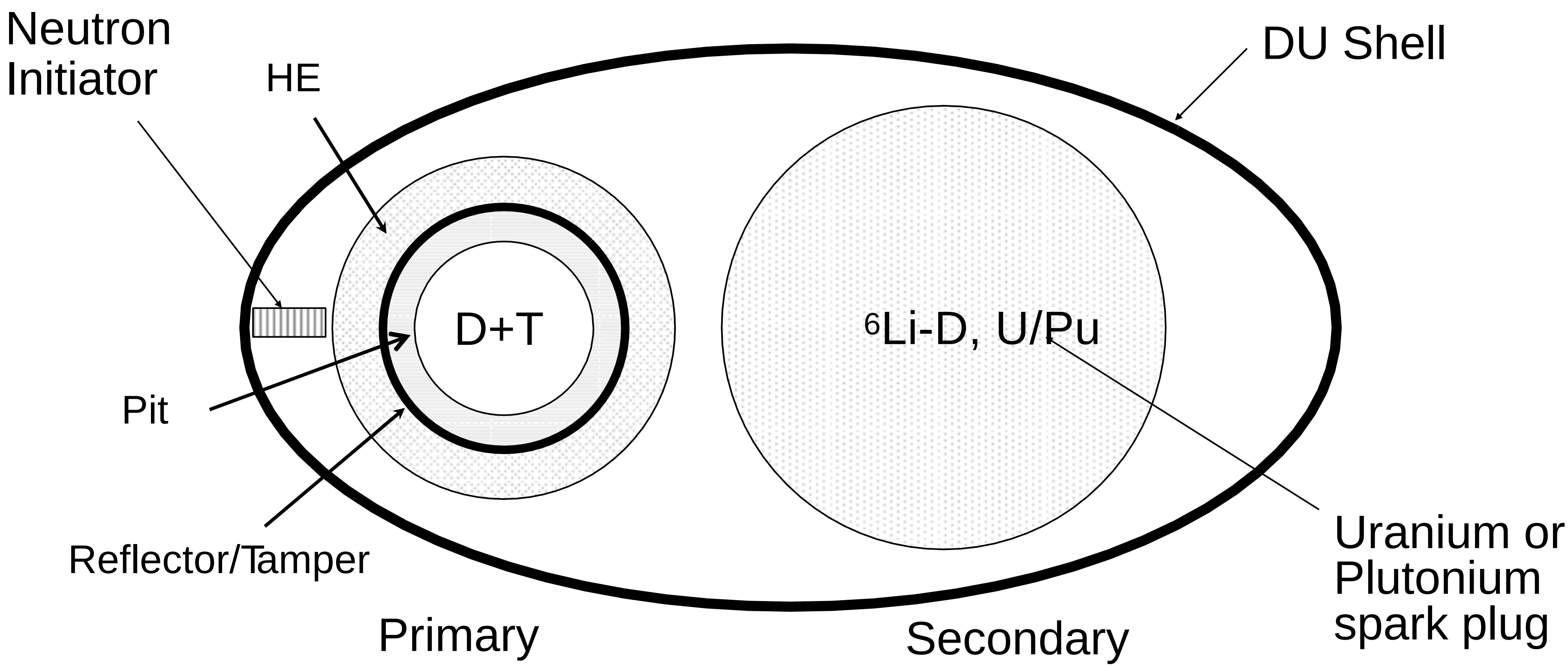
Two-Stage Nuclear Weapon ("P280 Design") Important



Y_P = primary yield, Y_S = secondary yield, $Y = Y_P + Y_S$ = total yield

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Components of a Two-Stage (Thermonuclear) Weapon and Their Functions - Important

Fission trigger —

- HE lenses + tamper + fissile core

Fusion fuel packet —

- X-rays heat and implode the fusion packet
- At high enough temp. and density the fusion packet burns
- Contributes ~ 50% of the yield of a high-yield weapon
- The fusion reaction produces many fast neutrons (~ 10–20 times as many as fission reactions)

Uranium components —

- Inside and surrounding the fusion fuel
- Fissions when irradiated by fast neutrons
- Contributes ~ 50% of the yield of a high-yield weapon
- Numerous fission products makes such weapons “dirty”

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iClicker Question

How is ^{6}LiD used as fusion fuel in a two stage thermo nuclear weapon?

A) **Under pressure and heat the Li nucleus fuses with the nucleus of the Deuterium, a Deuteron**

B) **^{6}Li captures a neutron and splits into a Triton and a He nucleus. The Triton is the Tritium nucleus and fuses with a Deuteron.**

C) **Under pressure and heat the Deuteron captures a neutron forming a Triton. The Triton fuses with a Deuteron.**

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iClicker Answer

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C) **Under pressure and heat the Deuteron captures a neutron forming a Triton. The Triton fuses with a Deuteron.**

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Another Example for Important Reactions with Light Nuclides : Initiators

Example of a simple initiator —

- Mixture of Polonium (Po) and Lithium (Li)
  - —Polonium has several radioactive isotopes

    Po-218 $\rightarrow$ Pb-214 + α
    Po-216 $\rightarrow$ Pb-212 + α
    Po-210 $\rightarrow$ Pb-206 + α
  - —High probability nuclear reaction

    α + Li-7 $\rightarrow$ B-10 + n
- Essential to keep Po and Li separate until desired time of initiation

  Aluminum foil is perfect

  Pure Li-7 is not required

  Be-9 can be used instead of Li-7

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Technologies Needed for "Weaponizing" a Nuclear Device

Technologies needed to make a nuclear *weapon* —

- Technology to produce nuclear-explosive material (NEM)

- Casing and electronics technology
- Detonator technology
- High-explosive (HE) technology
- Initiator technology
- Nuclear assembly technology

- Secure transport, storage, and control
- A delivery system

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Additional Materials and Knowledge Needed to Make a Two-Stage Nuclear Weapon

- The basic materials required for the 'secondary' (Li-6 and D) are widely available
- The geometry of the 'secondary' is not critical
- Compression and ignition of the 'secondary' is described by *radiation-hydrodynamics* —
  - Electromagnetic radiation moves at the speed of light
  - A uniform distribution of radiant energy is quickly achieved
  - All the matter behaves as a fluid at the high temperatures and pressures involved and hence is described by hydrodynamics
  - Large, fast computers are required to simulate the explosion accurately

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B-61 Bomb

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Making a Nuclear Warhead That Can Be Delivered By a Missile – 1

Physics and Engineering Requirements

The physics package, fusing, and re-entry shroud must be —

- Small enough to fit inside the missile's diameter
- Light enough for the missile to be able to deliver it
- Able to survive the intense vibrations at lift-off
- Able to survive through maximum dynamic stress
- Able to survive accelerations and vibration during staging
- Able to survive buffeting, deceleration, and very high temperatures as the warhead re-enters the atmosphere at hypersonic speeds

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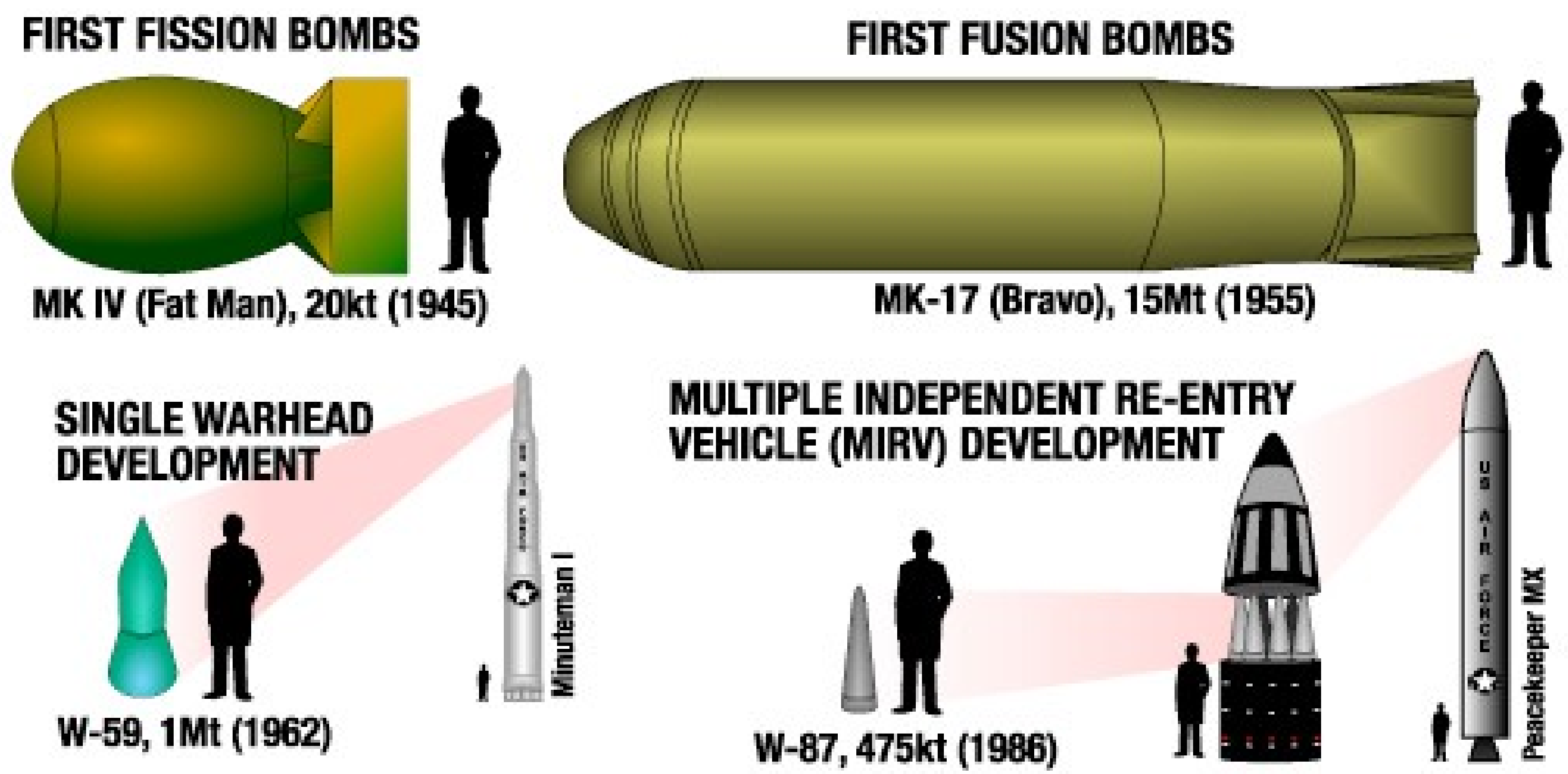
Making a Nuclear Warhead That Can Be Delivered By a Missile – 2

Miniaturizing Massive Death and Destruction



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iClicker Question

Which Statement is correct for most modern two stage weapons (prior to detonation)?

- **A)** **Deuterium and Tritium are present as fusion fuel both in the primary and secondary stage**
- **B)** **LiD is present as fusion fuel in both stages**
- **C)** **There is only fission in the primary stage and LiD is present as fusion fuel in the secondary stage**
- **D)** **There is only fission in the primary stage and Deuterium and Tritium are present as fusion fuel in the secondary stage**
- **E)** **Deuterium and Tritium are present as fusion fuel in the primary stage and LiD in the secondary stage**

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iClicker Question

Which Statement is correct for most modern two stage weapons (prior to detonation)?

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D) There is only fission in the primary stage and Deuterium and Tritium are present as fusion fuel in the secondary stage

E) Deuterium and Tritium are present as fusion fuel in the primary stage and LiD in the secondary stage

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iClicker Question

What is the biggest technology challenge in making nuclear weapons?

- **A) Critical assembly and related technologies (eg. high speed explosives)**
- **B) Ballistic missile technology**
- **C) Production of NEM**
- **D) Super computer technology for simulations of nuclear explosions and ballistic missile flight**
- **E) Production of fusion fuel**

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Production of Nuclear Explosive Material

Enrichment of U-235

Creation and ***Separation*** of Pu-239

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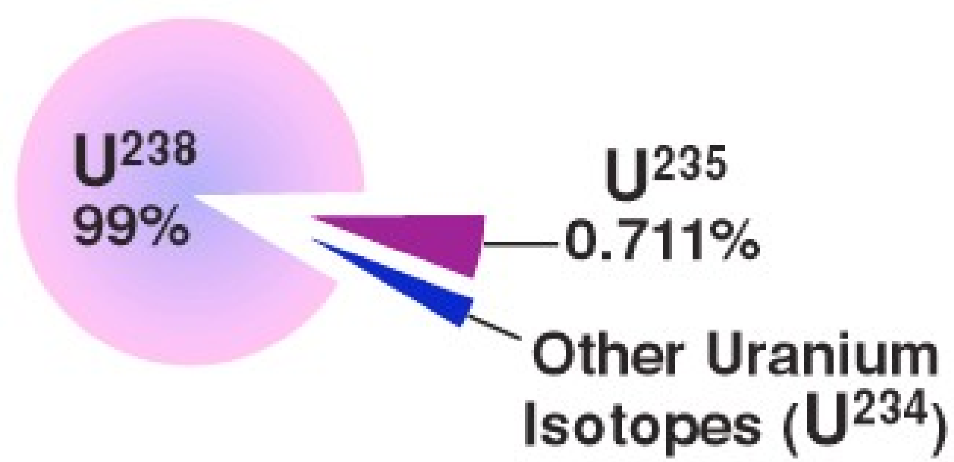
Enrichment of Uranium Is Required to Make a Nuclear Bomb

- Natural uranium is
  - 99.3% U-238 (which is fissionable but not fissile)
  - 0.7% U-235 (which is fissile)



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Enrichment of Uranium Is Required to Make a Nuclear Bomb

- Natural uranium must be *enriched* in U-235 to make a nuclear explosion (but not for use in some nuclear reactors).
- A nuclear explosion can be produced by uranium enriched to 20% or more U-235. Such uranium is called “weapons-usable”.
- Uranium enriched to more than 80% U-235 is called “weapons-grade”.
- Uranium enriched to more than 90% U-235 is preferred for nuclear weapons.

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Enriching Uranium – Overview

There are 4 main uranium enrichment techniques:

- Gaseous diffusion isotope separation
- Electromagnetic isotope separation
- Gas centrifuge isotope separation (currently preferred)
- Molecular laser isotope separation (now being perfected, a serious proliferation threat)

All four depend in one way or another on the different masses of U-238 and U-235.

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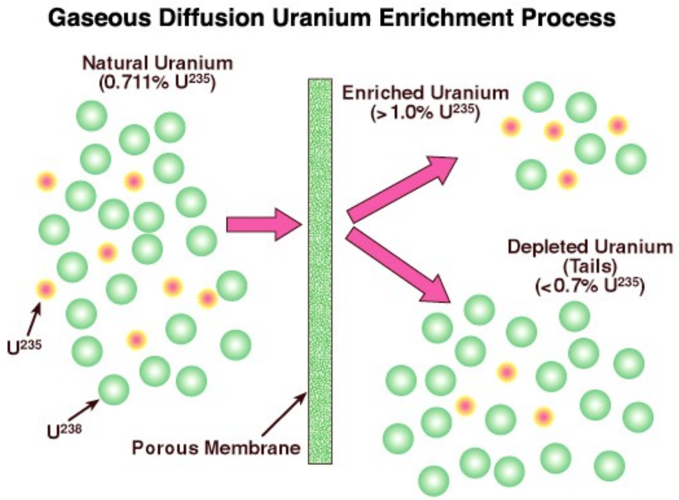
Enriching Uranium – Details 1

- Gaseous diffusion isotope separation
  - —Developed at Oak Ridge National Laboratory, TN during WW II Manhattan Project
  - —Uses high pressures to drive diffusion of uranium hexaflouride (UF_6) gas through semi-permeable membranes
  - —Thousands of stages are required: the enrichment factor in a single stage is typically ~1.004



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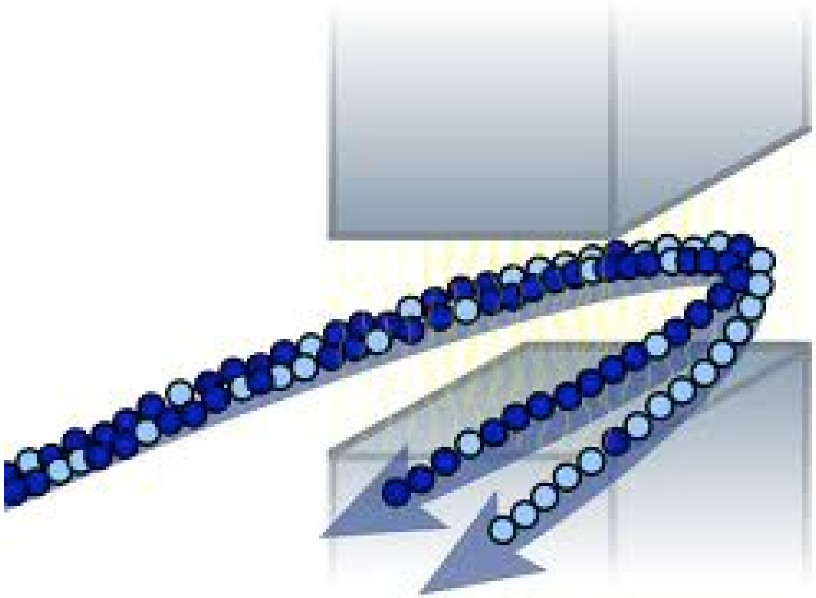
Enriching Uranium – Details 2

- Electromagnetic isotope separation
  - —Calutrons (California cyclotrons)
  - — Manhattan Project
  - —Basically a high-throughput mass spectrometer that sorts atoms by their charge to mass ratios (q/m); 2–3 stages are adequate



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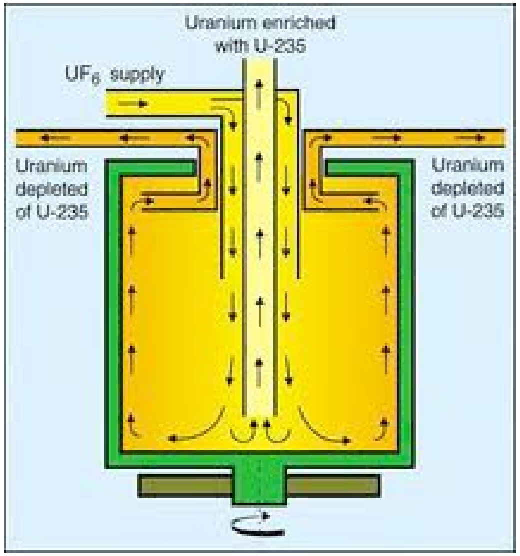
Enriching Uranium – Details 3

- Gas centrifuge isotope separation
  - — Massive version of centrifuges used in science and medicine
  - — Feed stock is uranium hexaflouride (UF_6) gas
  - — Compact, easy to hide, and energy efficient; 40-90 stages
  - — Requires high strength materials (Al, Fe)
  - — Has become bomb proliferators' technology of choice



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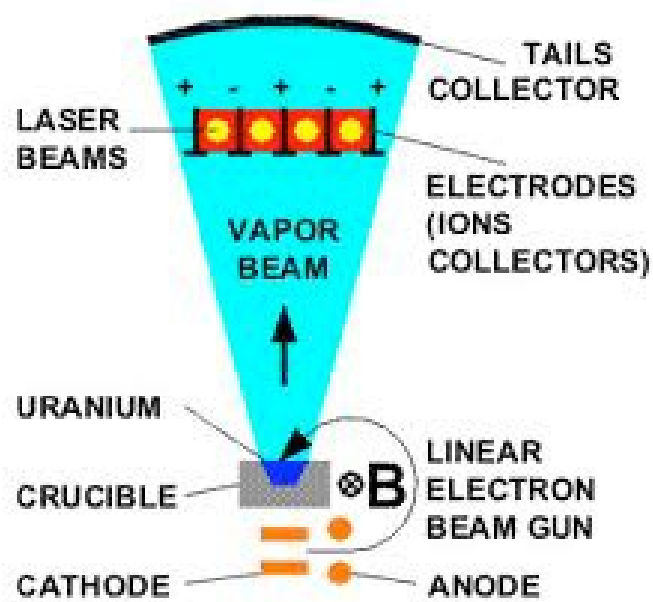
Enriching Uranium – Details 4

- Molecular laser isotope separation
  - — High-tech and compact (only 1 to 3 stages required)
  - — Based on small differences of molecular energy levels of UF_6 for U-238 vs. U-235
  - — End of Cold War and nuclear reactor industry initially killed the market for this technology but it is now being revived
  - — Even more of a proliferation danger than gas centrifuges



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Plutonium Is Created in Nuclear Reactors

The fissile nuclide Pu-239 can be created by bombarding U-238 with neutrons in a nuclear reactor —

- U-238 + n → Pu-239 (via a two-step process)

  (non-fissile) (fissile)

N Reactor, Hanford, WA

Reactor, Yongbyon, NK

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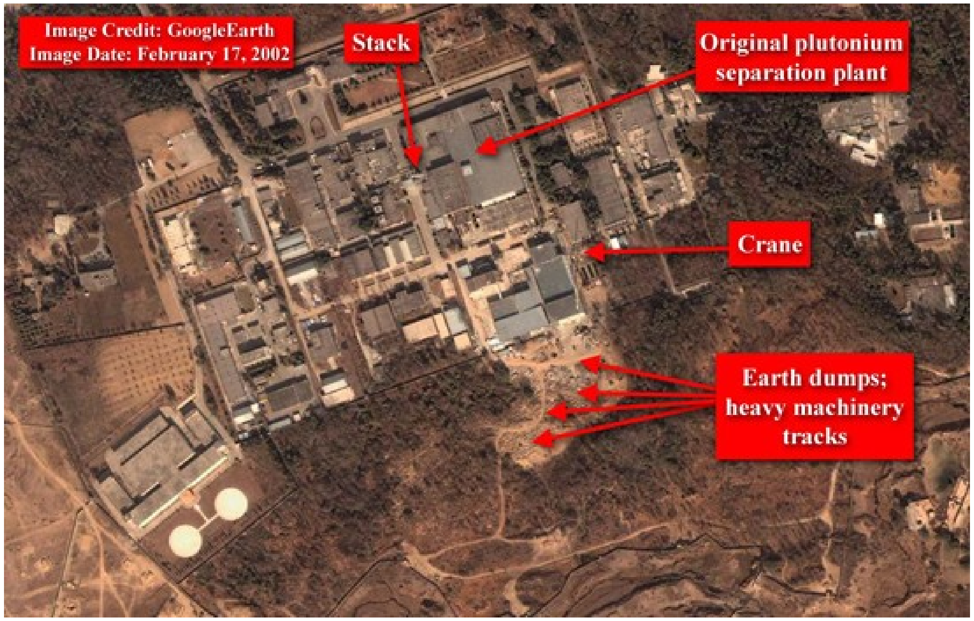
Plutonium Must Then Be Chemically Separated from Uranium and Other Elements

224-B Plutonium Separation Plant, Hanford, WA, 1985



Plutonium Separation Plant Rawalpindi, Pakistan, Feb 2002

Plutonium is extracted from the uranium fuel rods by first dissolving the rods to form a slurry and then extracting the trace amounts of plutonium in the slurry by chemically processing the slurry.

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Producing a Nuclear Explosion Using Plutonium – 1

- **Virtually any combination of plutonium isotopes can be used to make a nuclear weapon.**
- Not all combinations, however, are equally convenient or efficient.
- Pu-239 is produced when the most common isotope of uranium, U-238, absorbs a neutron and then quickly decays to plutonium.
- Pu-239 is the most useful isotope for making nuclear bombs. It is produced in varying quantities in virtually all operating nuclear reactors.

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Producing a Nuclear Explosion Using Plutonium – 2

- As fuel in a nuclear reactor is exposed to longer and longer periods of neutron irradiation, heavier isotopes of plutonium build up, as some of the plutonium absorbs additional neutrons, creating Pu-240, Pu-241, and so on.
- Pu-238 also builds up from a chain of neutron absorptions and radioactive decays starting from U-235.
- Plutonium with substantial quantities of Pu-238, Pu-240, Pu-241, Pu-242 is called “high burn-up” or “reactor-grade” plutonium.
- High burn-up plutonium can approach ~ 40% Pu-239, ~ 30% Pu-240, ~ 15% Pu-241, and ~ 15% Pu-242.

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Producing a Nuclear Explosion Using Plutonium – 3

Producing a nuclear explosion is much easier if the plutonium is "weapon-grade" (defined as more than 93% Pu-239).

Producing a nuclear explosion is more difficult using reactor-grade plutonium —

- It is impractical to separate Pu-239 from Pu-240 (it has never been done on a large scale)
- Pu-240 and heavier Pu isotopes are highly radioactive ("hot") and hence difficult to handle
- This radioactivity is likely to cause pre-initiation, producing a "fizzle" rather than a full-yield explosion

Even so, a bomb *can* be made using reactor-grade Pu. The U.S. tested such a bomb in 1962 to demonstrate this.

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Producing a Nuclear Explosion Using Plutonium – 4

- Because of the preference for relatively pure Pu-239 for making bombs, **when a reactor is used specifically for creating weapons plutonium, the fuel rods are removed and the plutonium is separated from them after a relatively brief period of irradiation**. The resulting “low burn-up” plutonium has a higher concentration of Pu-239.

- However, brief irradiation is very inefficient for power production. Hence, **in power reactors the fuel is left in the reactor much longer, producing “high burn-up” ("reactor grade") plutonium, which is less suitable for bombs**.

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A Nuclear Explosion Can Be Produced Using Reactor-Grade Plutonium – 1

Use of reactor-grade plutonium complicates bomb design for several reasons. One of the most important is that Pu-240 has a high rate of spontaneous fission and therefore will continually produce many background neutrons.

- In a well-designed nuclear explosive using weapons-grade plutonium, a pulse of neutrons is released to start the chain reaction at the optimal moment, but there is some chance that a background neutron from spontaneous fission of Pu-240 will set off the reaction prematurely. This is called "pre-initiation”.

- With reactor-grade plutonium, the probability of pre-initiation is very large. Pre-initiation can substantially reduce the explosive yield, since the weapon may blow itself apart earlier, cutting short the chain reaction that releases energy.

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A Nuclear Explosion Can Be Produced Using Reactor-Grade Plutonium – 2

- However, calculations demonstrate that ***even if pre-initiation occurs at the worst possible moment*** (when the material first becomes compressed enough to sustain a chain reaction), ***the explosive yield of even a relatively simple device similar to the Nagasaki bomb would likely be about 1—3 kilotons*****.**

- While this yield is referred to as the "fizzle yield", a 1-kiloton bomb would still have a radius of destruction roughly one-third that of the Hiroshima weapon, making it a horrendous weapon.

- Regardless of how high the concentration of troublesome isotopes is, the yield would not be less than this. With a more sophisticated design, weapons could be built with reactor-grade plutonium that would be assured of having higher yields.

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A Nuclear Explosion Can Be Produced Using Reactor-Grade Plutonium – 3

In short, *it would be quite possible for a potential proliferator to make a nuclear explosive from reactor-grade plutonium using a simple design that would be assured of having a yield in the range of one to a few kilotons, or more if a more advanced design were used*.

Hence theft of separated plutonium, whether weapons-grade or reactor-grade, poses a grave security risk.

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Categories of Nuclear Explosive Materials (Very Important)

- Uranium —
  - –LEU: < 20% U-235
  - –Weapons-usable HEU: > 20% U-235
  - –Weapons-grade HEU: > 80% U-235
- Plutonium —
  - –Reactor-grade: < 80% Pu-239 (e.g., light-water)
  - –Fuel-grade: 80% to 93% Pu-239
  - –Weapons-grade: > 93% Pu-239

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Nuclear Weapon Design

- Is a solved problem (technology is mature)
- No significant design changes for ~ 25 years
- Little more can be learned from additional testing
- Purposes of testing —
  - Proof of design ("proof testing")
  - System optimization
  - Weapon effects tests

    [Testing is not useful for establishing reliability]
- Weapons can be tested using non-nuclear tests
- Uncertainties are introduced by "improvements" and replacement of old parts with new parts

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Supplementary Material

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Nuclear Physics Terminology

- Nucleus: the positively charged central core of an atom, which contains most of its mass
- Nuclide: a distinct kind of atomic nucleus characterized by a specific number of protons and neutrons
- *Critical configuration* (we don't use "critical mass")

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Key Forces Inside the Nucleus

The pattern (Z, N) for stable nuclides reflects the competition between the attractive and repulsive terms in the binding energy

- Stable low-Z nuclei have N approximately equal to Z
- Stable high-Z nuclei have N much larger than Z
- Eventually, as Z gets large enough, no number of neutrons results in a stable nucleus
  - —Binding energy for each added neutron slowly decreases
  - —Weakly bound neutrons beta decay to protons
  - —This why naturally occurring elements stop at some Z value (for us, it's $Z = 92$, Uranium)

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Review of Important Definitions

Fissionable but non-fissile material —

Material composed of nuclides that can be fissioned by neutrons only if their energy is above a certain threshold energy.

Examples: U-238, Pu-240, Pu-242

Fertile material —

Material composed of nuclides that are transformed into fissile nuclides when they capture a neutron

Examples: U-238 and Th-232

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Importance of Delayed Neutrons for Controlling Nuclear Reactors

Some neutrons are emitted from fission products only after a few seconds (0.7% in the fission of U-235, a much smaller fraction in the fission of Pu-239).

These “delayed neutrons” are irrelevant for nuclear *weapons*, which explode in a microsecond, but they make control of nuclear *reactors* much easier.

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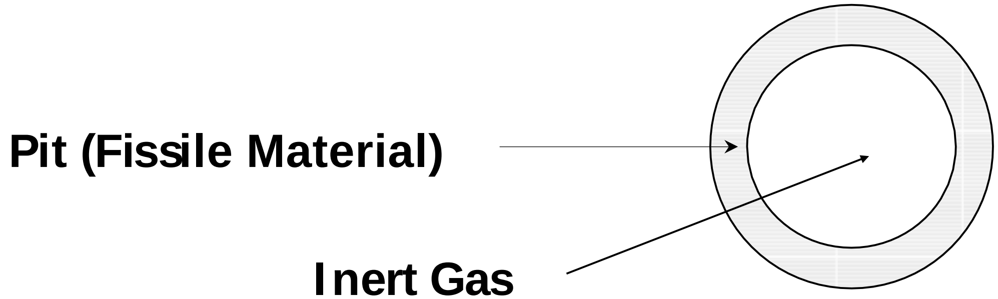
Hollow "Pit" Implosion Design – Step 1

Arrange the fissile material in a hollow spherical shell (called the "pit") —



Advantage:

—Can implode an initially hollow spherical shell to a higher density than an initially solid sphere

—Explain using an analogy

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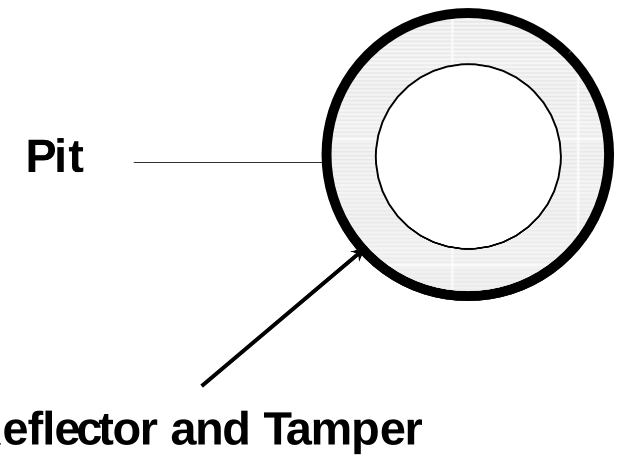
Hollow "Pit" Implosion Design – Step 2

Add a reflector and tamper —



Advantages:

- The reflector (e.g., Be) greatly reduces the number of fission neutrons that escape from the pit during the nuclear reaction
- The tamper (e.g., U-238) slows the expansion of the pit when it begins to heat up, allowing more fissions to occur

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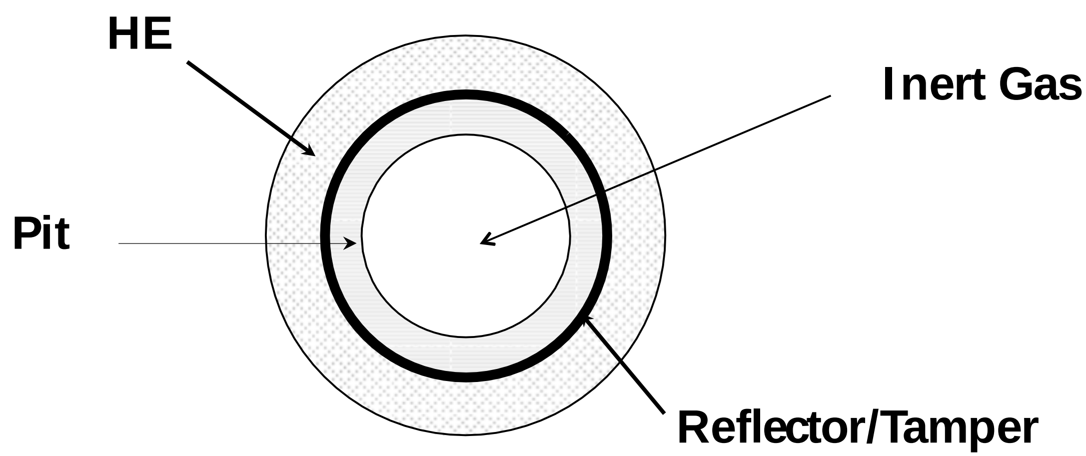
Hollow "Pit" Implosion Design – Step 3

Add the HE lenses, initiator, and fusing and firings circuits (latter two parts not shown) —



Advantages:

- Greater fraction of the fissile material undergoes fission, which means greater *efficiency* in the use of fissile material
- A hollow shell is further from criticality than the earlier "fat boy" design and handling the weapon is therefore safer
- A hollow geometry allows "boosting" (explained later)

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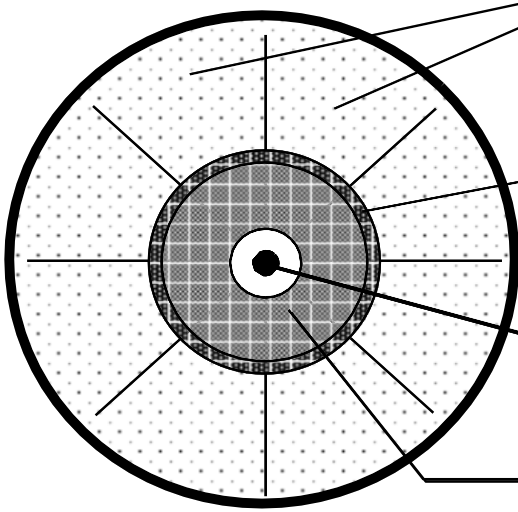
Fission Weapons – Implosion Type



- Imploding parts have higher velocities and travel shorter distances so assembly is quicker
- Initiator must initiate chain reaction at the moment of maximum compression

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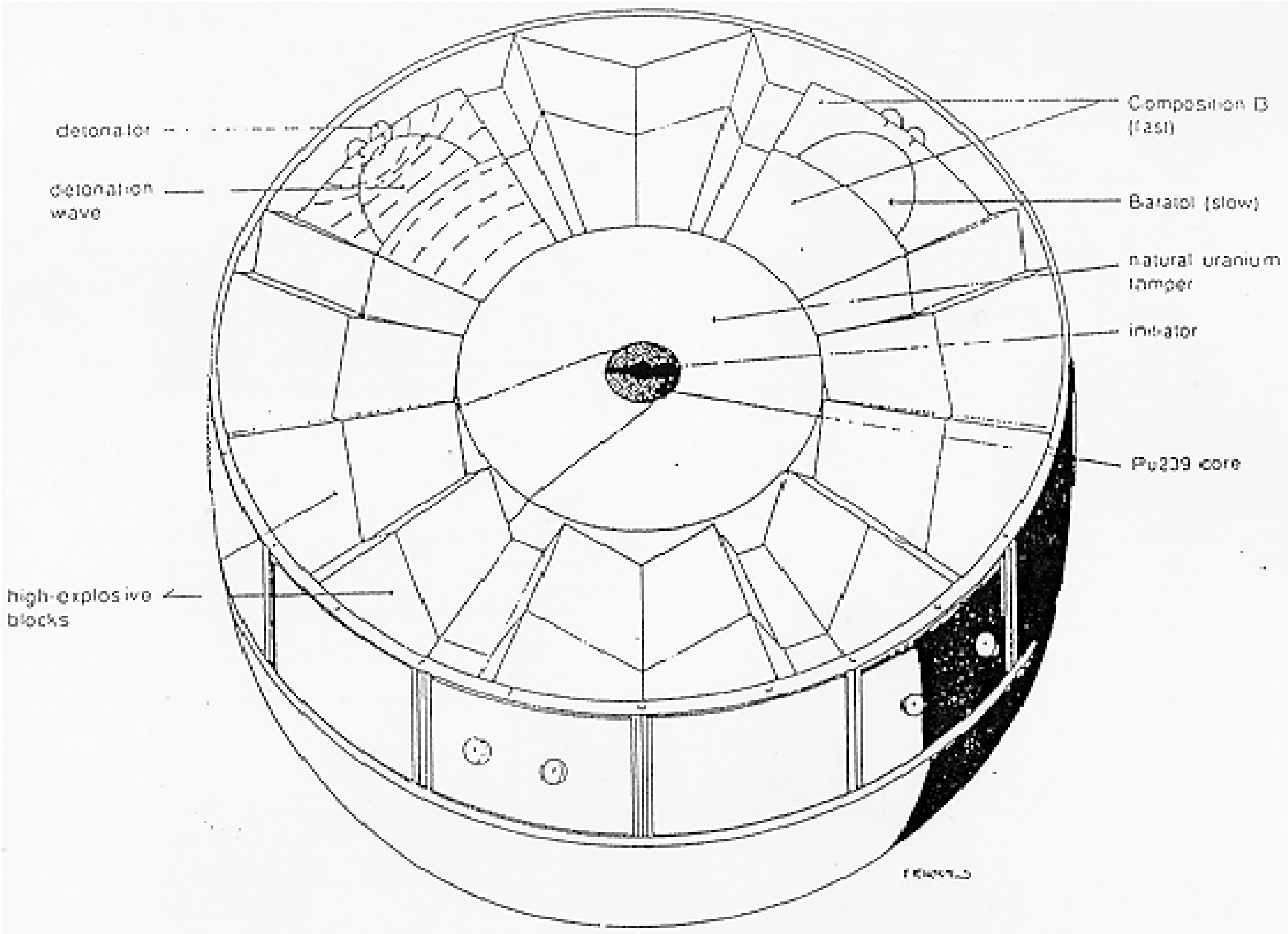
Fission Weapons – Implosion Type

View of the interior of an implosion weapon



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Initiators – 1

Example of a simple initiator —

- Mixture of Polonium (Po) and Lithium (Li)

  —Polonium has several radioactive isotopes

  Po-218 $\rightarrow$ Pb-214 + α
  Po-216 $\rightarrow$ Pb-212 + α
  Po-210 $\rightarrow$ Pb-206 + α

  —High probability nuclear reaction
  α + Li-7 $\rightarrow$ B-10 + n

- Essential to keep Po and Li separate until desired time of initiation

  Aluminum foil is perfect

  Pure Li-7 is not required

  Be-9 can be used instead of Li-7

Initiators – 2

Example of a sophisticated initiator —

- Mini-accelerator
  - —Use a small linear accelerator that produces 1-2 MeV energy protons (p)
  - —Hydrogen gas bottle provides source of protons
  - —Use a battery to charge a capacitor, which can be quickly discharged to produce the necessary accelerating electric fields
  - —Use a (p, n) nuclear reaction (have many choices)

$$p + X \longrightarrow Y + n$$

  - —A mini-accelerator initiator can give more neutrons than is possible with a Po-Li initiator
- Can locate the mini-accelerator *outside* the pit of NEM
  - —Neutrons will get into fissile material readily

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Boosted Fission Weapons – 1 (Details)

T. fusion can be used to increase (“boost”) the yield of a *fission* weapon —

- Insert an equal mixture of D and T gas into the hollow cavity at the center of the pit made of NEM
- At the maximum compression of the pit, the temperature and density conditions in the interior can exceed the threshold for D+T fusion (design goal)

$$\mathrm{D} + \mathrm{T} \rightarrow \alpha + \mathrm{n} + 17.6\ \mathrm{MeV}$$

- The D+T reaction releases only a very small amount of energy, but the resulting burst of 14 MeV neutrons initiates a new burst of fission reactions, greatly “boosting” the total fission yield of the weapon
- The timing is automatic!

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Boosted Fission Weapons – 2 (Details)

Advantages —

- Increases the maximum possible fission yield
- Less hard-to-produce Pu or HEU is required for a given yield — the “efficiency” is higher
- Warheads of a given yield can be smaller and lighter

Tritium (T) decays, but it can be produced in a nuclear reactor.

Fresh D-T boost gas can then be inserted just prior to firing.

This also increases the safety of the weapon.

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Fusion Nuclear Reactions (Details)

- Four key reactions (most important = ***):

$$D + T \rightarrow {}^4He + n + 17.6 \text{ MeV (D-T fusion)}$$
$$n + {}^6Li \rightarrow {}^4He + T + 4.8 \text{ MeV (catalytic)}$$
$$D + D \rightarrow {}^3He + n + 3.2 \text{ MeV (catalytic)}$$
$$D + D \rightarrow {}^1H + T + 4.0 \text{ MeV (catalytic)}$$

- At standard temperatures and pressures (STP), D and T are gasses whereas Li-D is a solid (it's a salt)
- To make the fusion reactions go, need extremely high temperatures, densities, and pressures
- D-T fusion has lowest energy threshold
- Once D-T fusion (burning) has started, D-D fusion also contributes, but we will focus only on the former for simplicity

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True Thermonuclear Weapons

- Modern thermonuclear weapons have two stages: Primary (fission) and Secondary (fusion)
- The Mike device, the first US thermonuclear device, used liquefied D and T in the secondary
- All practical secondary designs use ^{6}Li-D
- Extra neutrons from the primary generate the initial T in the secondary via the catalytic process.
- Each D+T fusion generates another n, which can generate yet another T, allowing the process to continue until the necessary temperature conditions are lost
- Burning grows quickly, but not exponentially (geometrically): fusion does not proceed by a chain reaction

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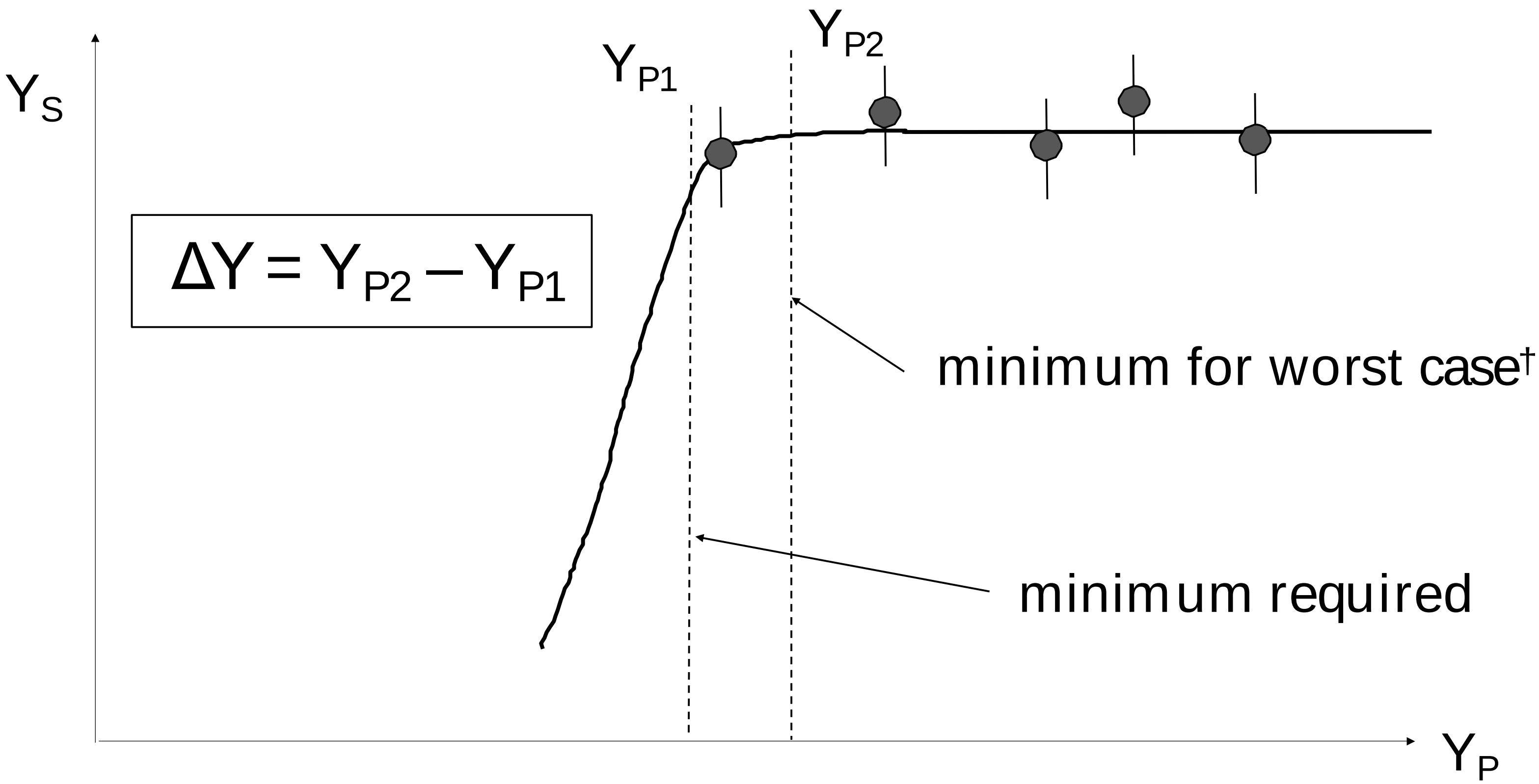
Primary Margin ΔY



†Worst case: T supply at end of life, over-initiated, cold HE

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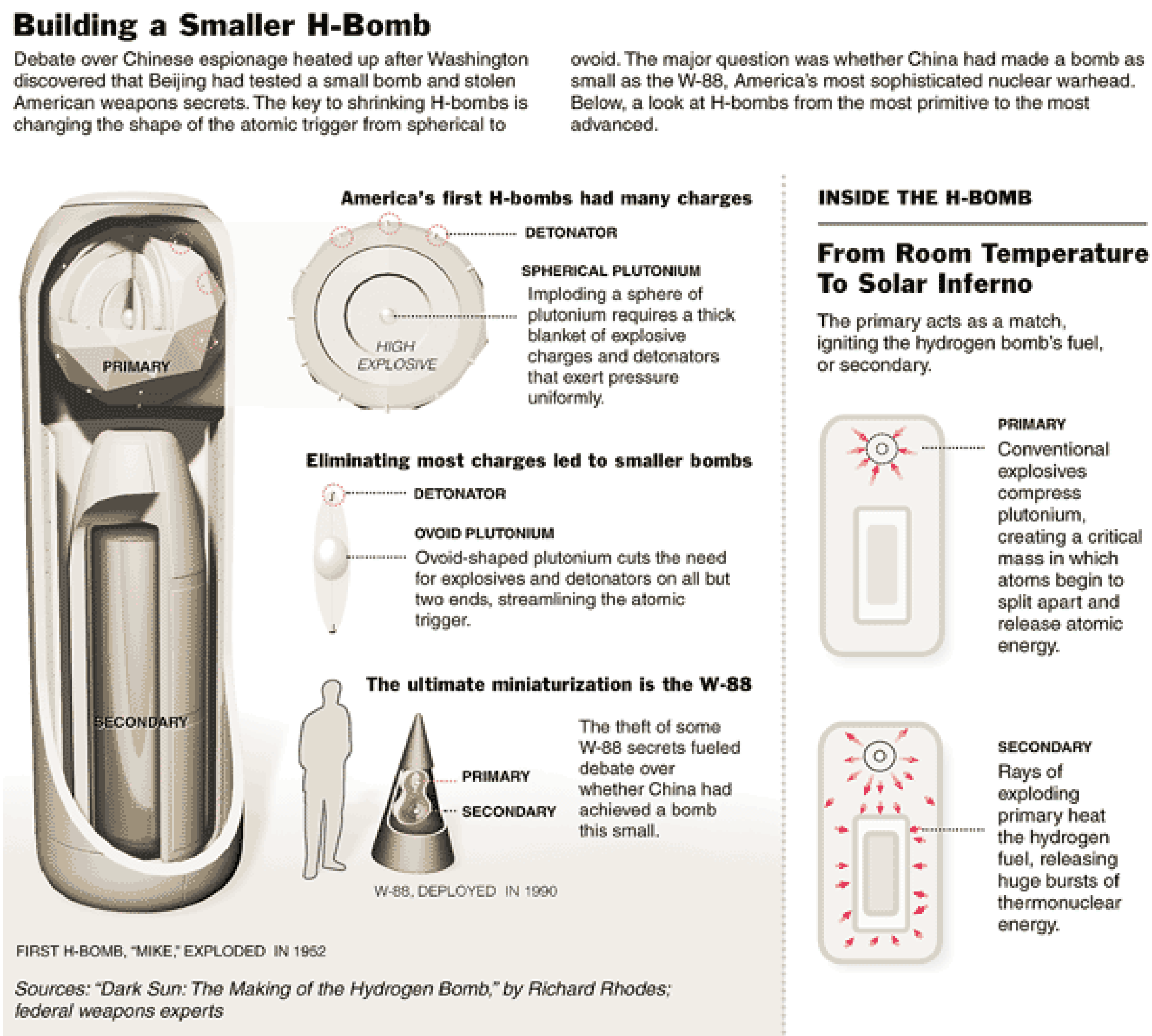
Publicly Reported Design of the U.S. W-88 Warhead



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Review of Modern Thermonuclear Weapons

- The radioactivity from fallout comes entirely from fission fragments
  - The “additional design features” greatly increase fallout
  - In the early days of thermonuclear weapon development there was much talk about “clean” nuclear weapons, but it was never credible and soon stopped
  - There was also much talk about *pure fusion* weapons (no primary) with very low fallout— never demonstrated and probably infeasible
- The most important requirement is that the primary produce enough yield to “drive” (ignite) the secondary
- Hence *the main way to prevent development of thermonuclear weapons is to prevent development of fission weapons*

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Designing Nuclear Weapons To Use Reactor-Grade Plutonium

The isotope Pu-238 decays relatively rapidly, thereby significantly increasing the rate of heat generation in the material.

- The heat generated by Pu-238 and Pu-240 requires careful management of the heat in the device. Means to address this problem include providing channels to conduct the heat from the plutonium through the insulating explosive surrounding the core, or delaying assembly of the device until a few minutes before it is to be used.

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Designing Nuclear Weapons To Use Reactor-Grade Plutonium

The isotope Americium-241 (which results from the 14-year half-life decay of Pu-241 and hence builds up in reactor grade plutonium over time) emits highly penetrating gamma rays, increasing the radioactive exposure of any personnel handling the material.

- The radiation from Americium-241 means that more shielding and greater precautions to protect personnel might be necessary when building and handling nuclear explosives made from reactor-grade plutonium. But these difficulties are not prohibitive.

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Enhanced Radiation Weapons – 1

Purpose —

- To kill people without destroying or contaminating structures or areas

Design principles —

- Minimize the fission yield
- Maximize the fusion yield

Methodology —

- Use smallest possible fission trigger
- Eliminate fissionable material from fusion packet
- Eliminate fission blanket
- Eliminate any material that will become radioactive when exposed to nuclear radiation

These are technically challenging requirements

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Enhanced Radiation Weapons – 2

Enhance the fraction of the total energy that comes out in fast neutrons by —

- Using DT rather than ^{6}LiD in the fusion packet
  - — The theoretical limit is 6 times more neutrons per kt of energy release than in pure fission
  - — T has a half-life of ~ 11 years, so the T in ERWs must be replaced periodically
- Eliminating any material that would absorb neutrons (such as a weapon casing)

An ERW ("neutron bomb") is more costly to manufacture than a "conventional" fission weapon that would produce the same neutron flux.

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Four Types of Radioactive Decay (Details)

1. Alpha decay: α

$$ {}^{A}_{Z}P_{N} \rightarrow {}^{A-4}_{Z-2}D_{N-2} + \alpha + \text{Energy} $$

2. Beta decay: $\beta^{\pm}$

$$ {}^{A}_{Z}\mathrm{P}_{N} \rightarrow {}^{A}_{Z+1}\mathrm{D}_{N-1} + e^{-} + \bar{\upsilon} + \text{energy} $$

$$ {}^{A}_{Z}\mathrm{P}_{N} \rightarrow {}^{A}_{Z-1}\mathrm{D}_{N+1} + e^{+} + \upsilon + \text{energy} $$

3. Gamma decay: γ

$$ {}^{A}_{Z}\mathrm{P}^{*}_{N} \rightarrow {}^{A}_{Z}\mathrm{P}_{N} + \gamma + \text{energy} $$

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Four Types of Radioactive Decay (cont'd)

4. Spontaneous fission: fission products

$$^{A}_{Z}P_{N} \rightarrow {}^{A_1}_{Z_1}X_{N_1} + {}^{A_2}_{Z2}Y_{N2} + \eta\,\mathrm{n} \; + \text{energy}$$

$$\eta \; = \; 1 - 3, \text{ typically}$$

$$Z \; = \; Z_1 + Z_2$$

$$N \; = \; N_1 + N_2 + \eta$$

$$A \; = \; A_1 + A_2 + \eta$$

The parent nucleus *P* is a nuclide of high Z (uranium or beyond) whereas the fission fragments *X* and *Y* are medium-*Z* nuclei

Bombardment by n, γ, or β particles can make the target nuclide radioactive. *This process is called activation* (e.g., *neutron activation*), *not "induced radioactivity".*

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Induced Fission

- Induced fission (*not a form of radioactivity*)

$$n + {}^{A}_{Z}T_{N} \rightarrow {}^{A_1}_{Z_1}\mathrm{X}_{\mathrm{N}_1} + {}^{A_2}_{Z2}\mathrm{Y}_{\mathrm{N2}} + \eta\,\mathrm{n} + \text{energy}$$

$$\eta = 1\text{-}3, \text{ typically}$$

$$Z = Z_1 + Z_2,$$

$$N = N_1 + N_2 + \eta$$

$$A = A_1 + A_2 + \eta$$

- *X* and *Y* (the fission fragments) are neutron-rich medium-*sized* nuclei and are highly radioactive

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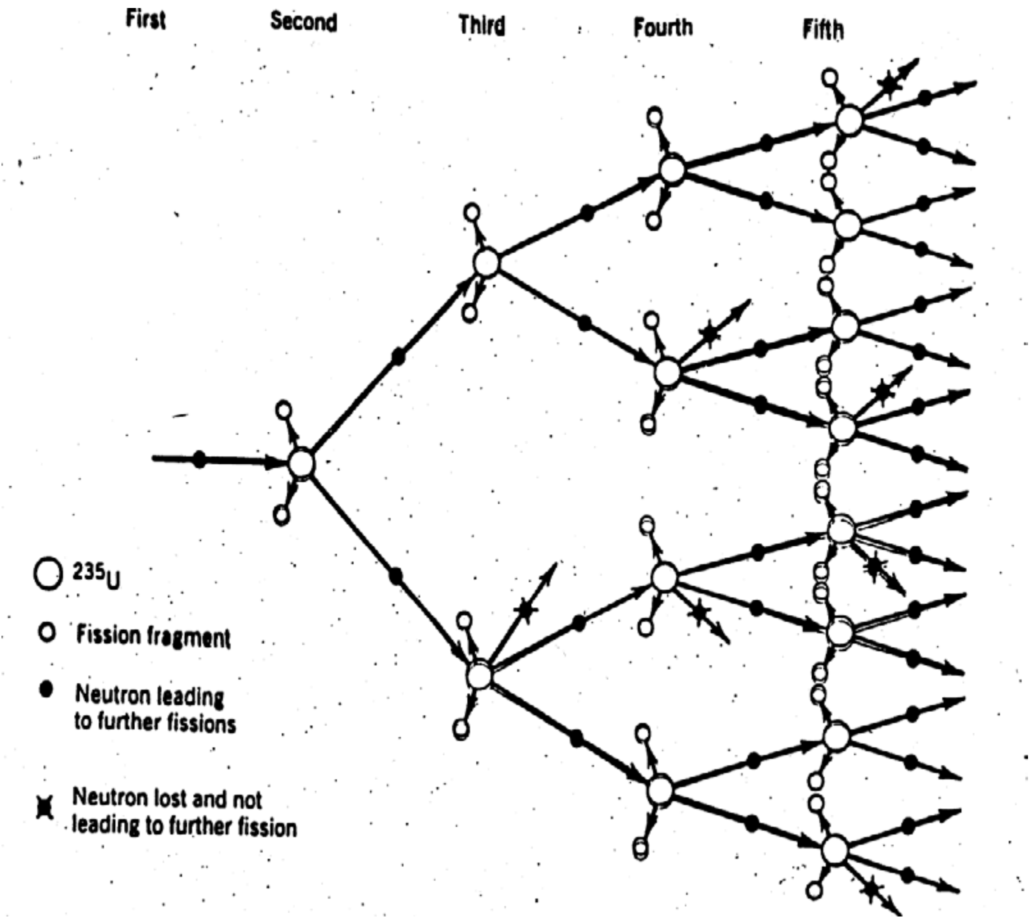
The Principle of a Nuclear Weapon

A nuclear explosion is achieved by the rapid assembly, in a suitable geometry, of NEM with sufficient nuclear reactivity to initiate and sustain a chain reaction driven by fast neutrons.



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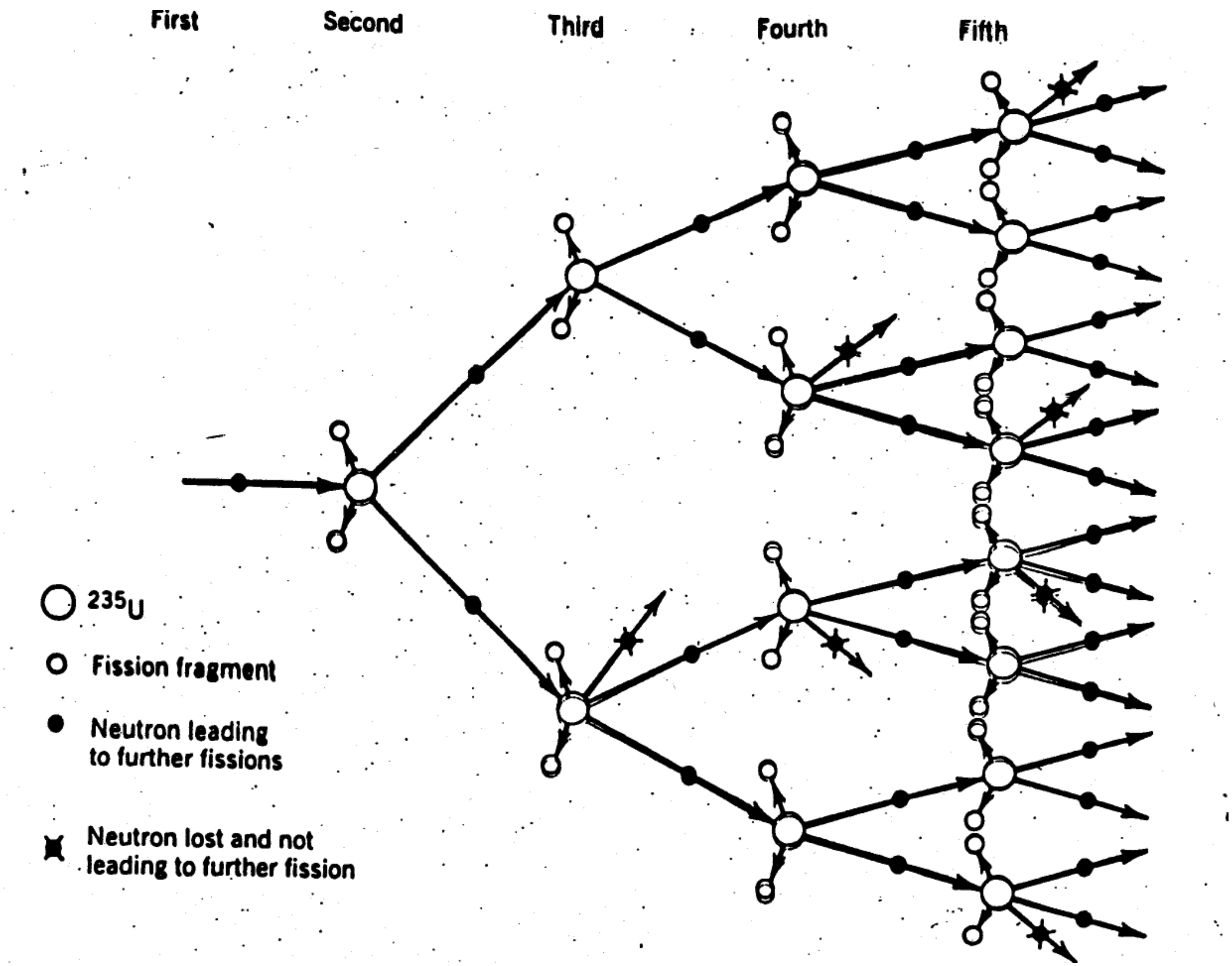
Explosive Chain Reaction



[Mousetrap Demonstration]

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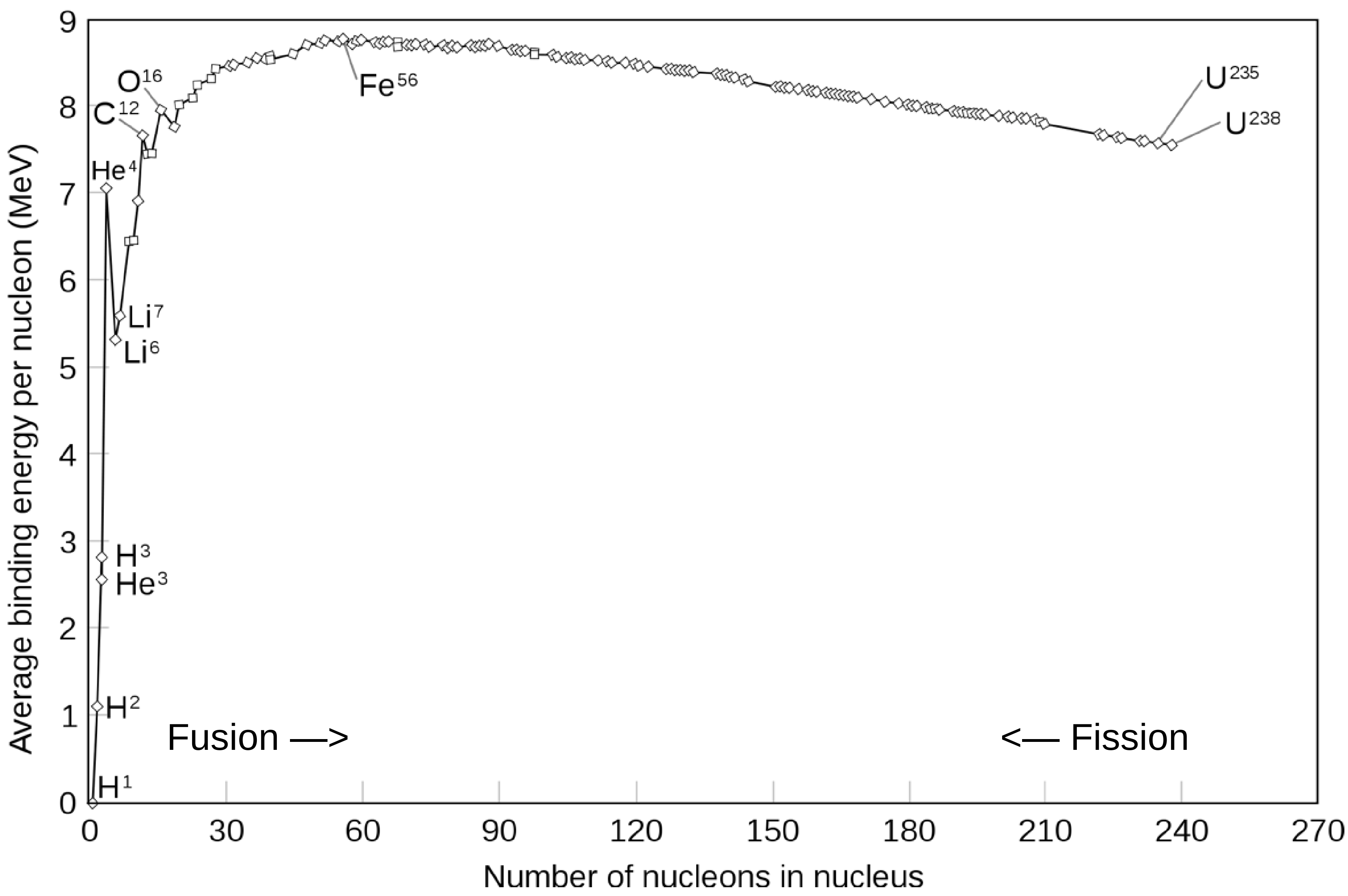
Binding Energy/Nucleon for Selected Isotopes



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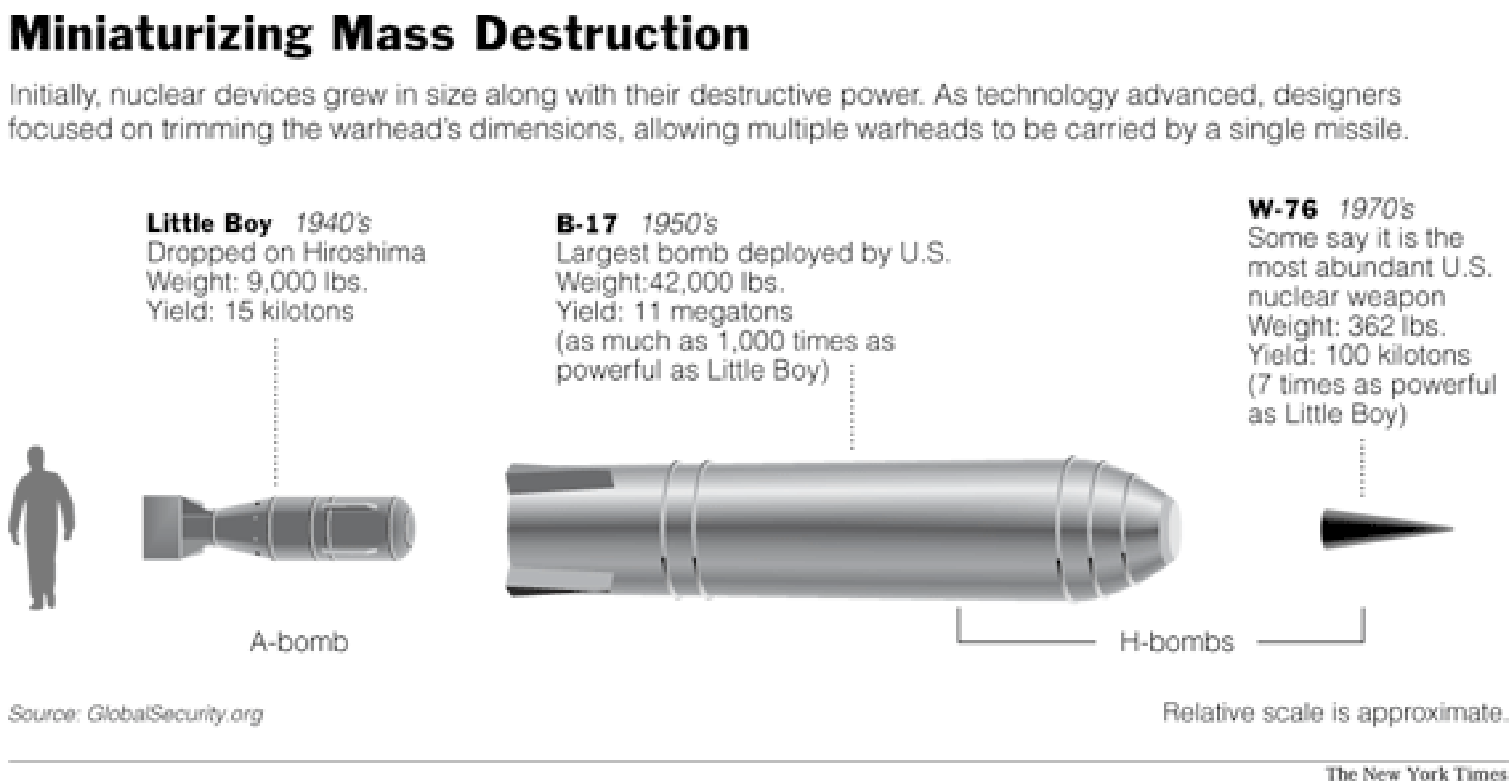
Making a Nuclear Warhead That Can Be Delivered By a Missile – 2



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Requirements for Making a Fission Bomb

1. Know the nuclear physics of fission

2. Have needed data on the physical and chemical properties of weapon materials

3. Build technical facilities to fabricate and test devices and components of the chosen design

All these requirements are now met in any significantly industrialized country

4. **Obtain the needed nuclear-explosive material**

5. Allocate the necessary resources

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In Making a Nuclear Explosion It's Not Just the Mass, It's the ***Configuration***

Some ***mixtures*** of various **nuclear-explosive nuclides with other nuclides** in a suitable quantity, purity, and geometry, can support a ***fast-neutron chain reaction***.

*Such material is called **nuclear-explosive material (NEM)** and can be used to create a nuclear explosion.*

F**or there to be an explosion, on average more than one of the several fast neutrons released per fission in the NEM must be "productively captured"** (i.e., it must be captured and then produce another fission event).

A configuration in which this is true is said to be a "nuclear-explosive" or "prompt supercritical" configuration. It will produce an explosive chain reaction.

To be "productively captured", a neutron must not be unproductively captured or escape from the NEM.

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Nuclear Weapon Secrets

Nuclear weapon design information is special in being “born secret”.

There were 3 important secrets —

- It’s possible to make a nuclear weapon
- How to make implosion designs work
- How to initiate fusion

Many details about the first two “secrets” are now public and the basic idea of the third “secret” is public.

The basic idea of how to make very compact fusion weapons is also now public.

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