Physics 280: Session 4

Plan for This Session

Announcements about the course

Questions about the course

News and Discussion

Module 2: Nuclear weapons

Physics 280: Session 4

Announcements About The Course

Be sure to read

- **the previous session's slides**
- **the reading assignments**

before **coming to the lecture-discussion and Writing Lab!**

Questions About The Course

News and Discussion: North Korea

New York Times
January 22, 2013

Security Council Condemns North Korea Rocket Launching
By NEIL MacFARQUHAR
UNITED NATIONS — **The Security Council on Tuesday unanimously condemned North Korea for launching a rocket last month, with Pyongyang's main ally, China taking the uncommon step by joining the criticism.**

The resolution ratcheted up existing sanctions on North Korea after it used ballistic missile technology to launch a multistage rocket, which carried a 200-pound surveillance satellite into orbit on Dec. 12.

The United States and China said they had worked closely on drafting the resolution, with Security Council diplomats saying they wanted to get it passed before South Korea takes over the monthly rotating presidency of the Security Council in February.

…

The measures included in the resolution will most likely have little day-to-day effect, experts said, but **the 15-to-0 vote was significant because it included China, a longtime economic benefactor and protector of North Korea.**

January 22nd,
UN security council condemns North Korea for rocket launch on Dec. 12.

Unha-3 launch site, Sohae, North Korea
April 2012

News and Discussion: North Korea

New York Times
January 24, 2013

North Korea Vows Nuclear Test and Threatens U.S.
By CHOE SANG-HUN
SEOUL, South Korea — **North Korea vowed on Thursday to launch more long-range rockets and conduct its third nuclear test, saying that it would build up its capability of striking the United States after the United Nations's expansion of sanctions against North Korea.**

. . .

…, **the North expressed bitterness at China and Russia's endorsement of the United Nations resolution**, denouncing "those big countries" as "failing to come to their senses." **It said that North Korea's drive to rebuild its moribund economy and its rocket program, until now billed as a peaceful space project, will now "all orientate toward the purpose of winning in the all-out action for foiling the U.S. and all other hostile forces' maneuvers."**

January 24th, North Korea threatens new nuclear weapons and additional rocket tests.

News and Discussion: North Korea

January 24th, North Korea threatens new nuclear weapons and additional rocket tests.

Possible Motivation:

(1) Intended to strengthen Kim Jung un 's position internally ?
(2) Create deterrent to secure North Korea's interest?
(3) Create "strong base" to negotiate with United States ?

News and Discussion: re-call February 2012

The New York Times

North Koreans Agree to Freeze Nuclear Work; U.S. to Give Aid

=> 240,000 metric tons of food aid

By STEVEN LEE MYERS and CHOE SANG-HUN

WASHINGTON — North Korea announced on Wednesday that it would suspend its nuclear weapons tests and uranium enrichment and allow international inspectors to monitor activities at its main nuclear complex. The surprise announcement raised the possibility of ending a diplomatic impasse that has allowed the country's nuclear program to continue for years without international oversight.

The Obama administration called the steps "important, if limited." But the announcement seemed to signal that North Korea's new leader, Kim Jong-un, is at least willing to consider a return to negotiations and to engage with the United States, which pledged in exchange to ship tons of food aid to the isolated, impoverished nation.

News and Discussion: re-call February 2012

Los Angeles Times

North Korea: What does 240,000 metric tons of food mean?

February 29, 2012 | 1:20 pm

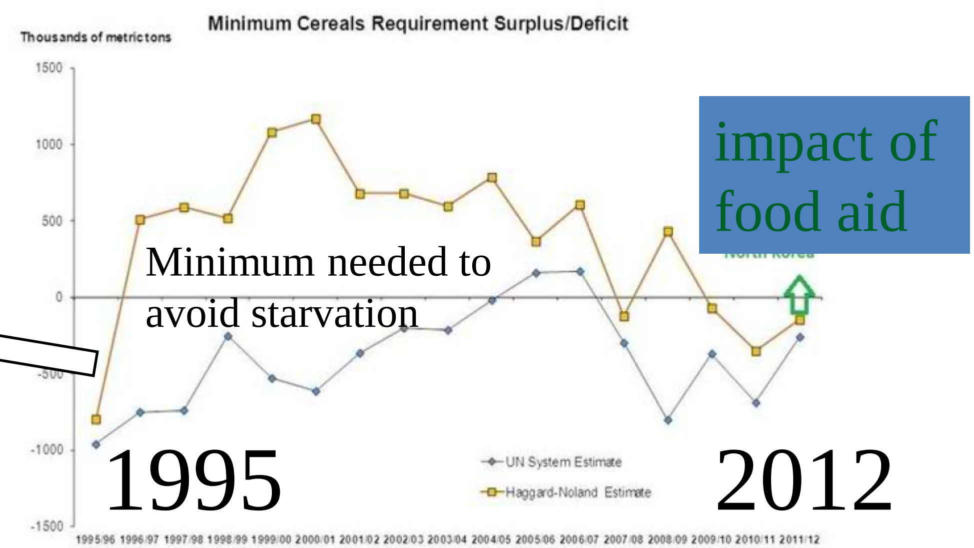
Hunger is a known menace in North Korea: In most of the country, even a bowl of rice is a rare treat. North Korea and the U.S. are poised to stri
would bring 240,000 metric tons of food aid to the impoverished country if it suspends nuclear weapons tests and enrichment.

What would all that food really mean for North Korea? Here's a quick look.

Experts Stephan Haggard and Marcus Noland have estimated that North Korea has been falling below the minimum grain supplies needed for ea
have enough food, as the graph below shows.

The yellow line represents their estimates; the blue line is U.N. estimates, which are somewhat lower. The Times added a green arrow to show h
metric tons of U.S. aid could change that.

Famine in North Korea 1995 – 1998
unknown number of victims
estimates 600,000 – 3,000,000
in a population of 23 million



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iClicker Question

What year did Russia first test a nuclear bomb?

A = 1945

B = 1946

C = 1947

D = 1948

E = 1949

Physics 280: Session 4

iClicker Answer

What year did Russia first test a nuclear bomb?

A = 1945

B = 1946

C = 1947

D = 1948

E = 1949

iClicker Question

What year did the United States first test a nuclear bomb?

A = 1943

B = 1944

C = 1945

D = 1946

E = 1947

Physics 280: Session 4

iClicker Answer

What year did the United States first test a nuclear bomb?

A = 1943

B = 1944

C = 1945

D = 1946

E = 1947

Physics 280: Session 4

iClicker Question

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

A = 12,000

B = 30,000

C = 50,000

D = 70,000

E = 100,000

Physics 280: Session 4

iClicker Answer

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Module 2: Nuclear Weapons

Physics of Nuclear Weapons

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

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?

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.

Physics of Nuclear Weapons

Introduction

Physics of Nuclear Weapons

Atoms and Nuclei

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)
- All protons (and all neutrons, and all electrons) are *identical* and *indistinguishable*

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")

2. Electromagnetic force (structure of atoms and molecules)

- Can be attractive or repulsive
- Classical electrical force decreases as $1/r^2$ ("long-range")
- Magnetic force between bar magnets decreases as $1/r^3$
- 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

Fundamental Forces of Nature – 2

3. Weak nuclear force (radioactivity)

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

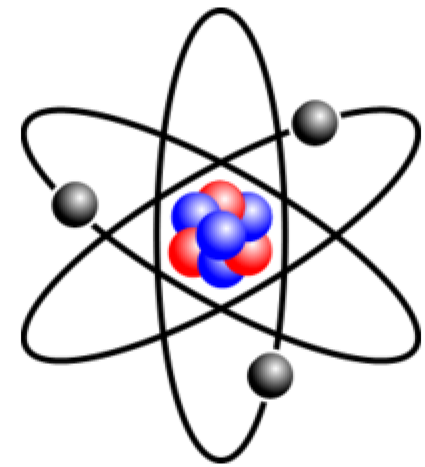
4. Strong nuclear force ("strong force") (structure of nuclei)

- 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

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!



Atoms and Nuclei

Sizes of atoms and nuclei —

- The size of an *atom* is defined by the extent of its electron cloud (size increases slowly as Z increases from 1 to 92)
- The size of a *nucleus* is defined by the size of a nucleon ($\sim 10^{-13}$ cm = 10^{-15} m) and the number of nucleons it contains (the size of a nucleus increases with the number of nucleons as $A^{1/3}$).

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

Masses of subatomic particles —

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

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 ($A = Z + N$).

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.

- To a good approximation, **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.

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: ${}^{238}_{92}U = {}^{238}U = U(238)$, ${}^{235}_{92}U = {}^{235}U = U(235)$

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

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
- 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

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 $\tau_{1/2}$

There are Four Types of Radioactive Decay

1. Alpha decay

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

2. Beta decay

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

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

3. Gamma decay

Parent —> Daughter + gamma-ray

4. Spontaneous fission

Illustration of Alpha Decay

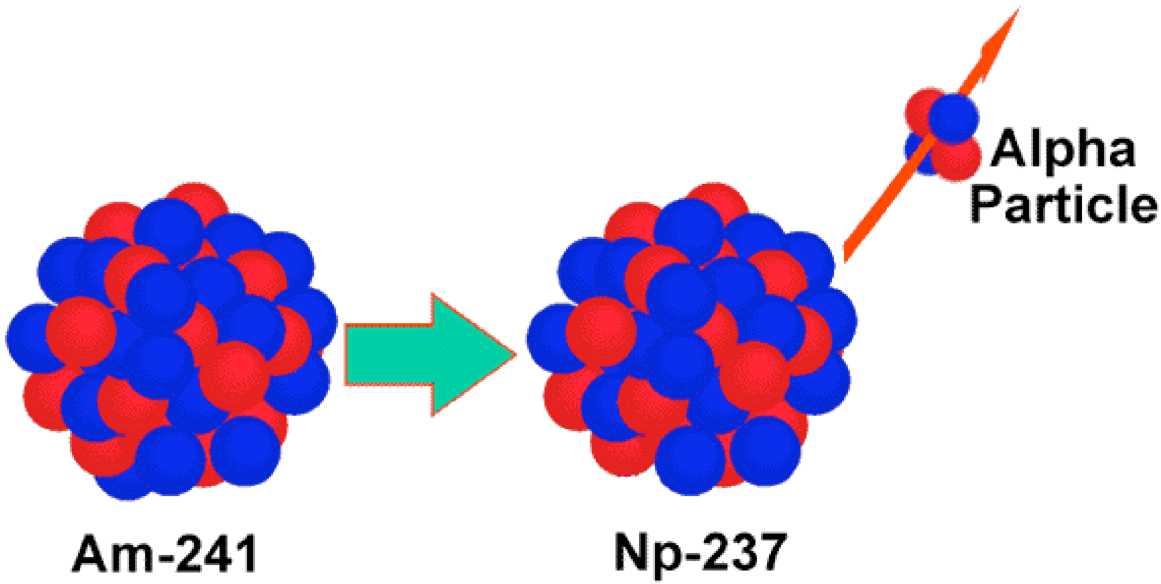


Illustration of Beta Decay (Electron Emission)

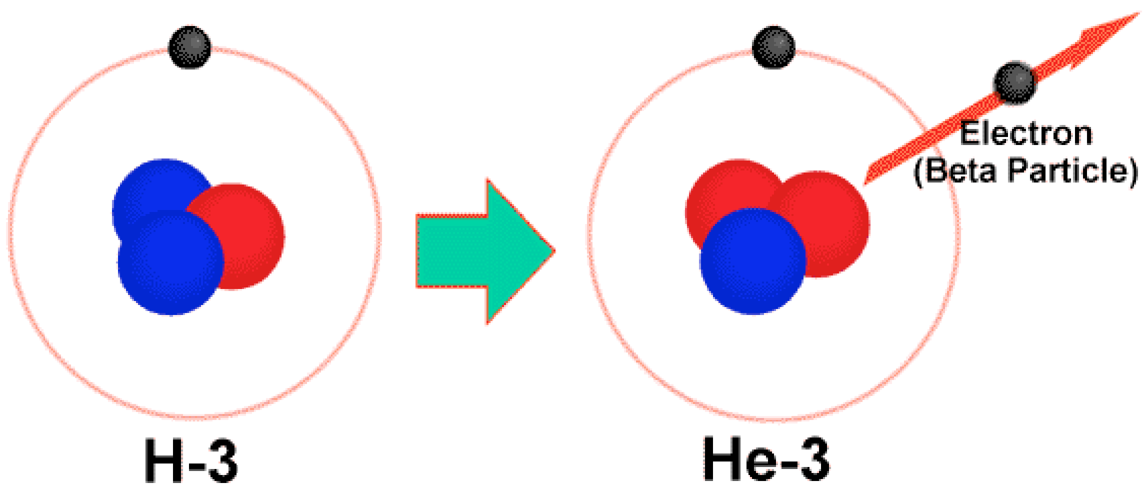


Illustration of Beta Decay (Positron Emission)

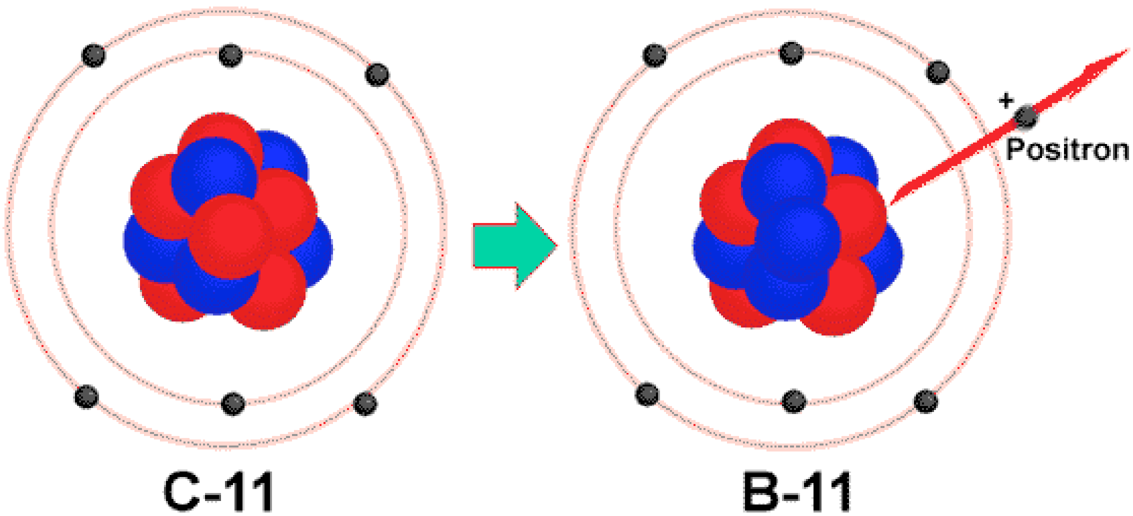


Illustration of Gamma-Ray Emission

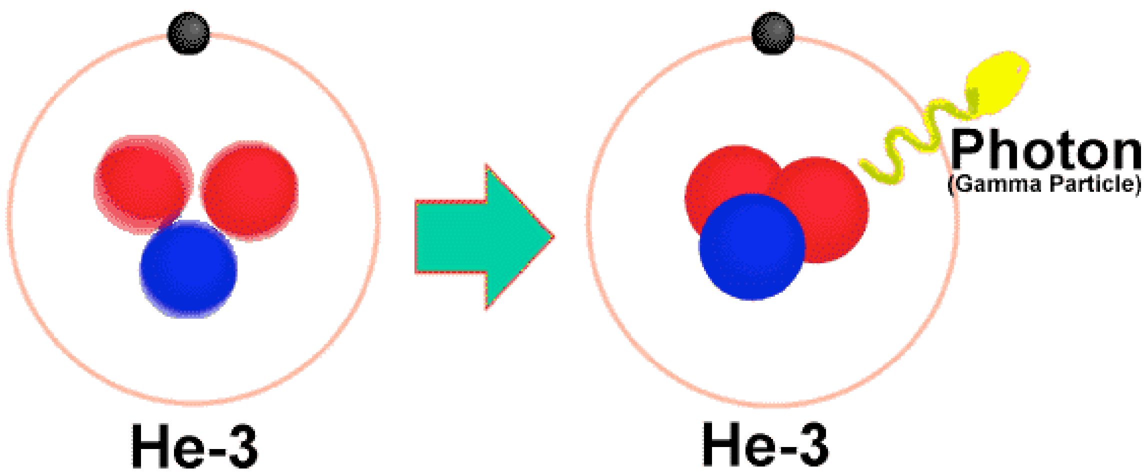
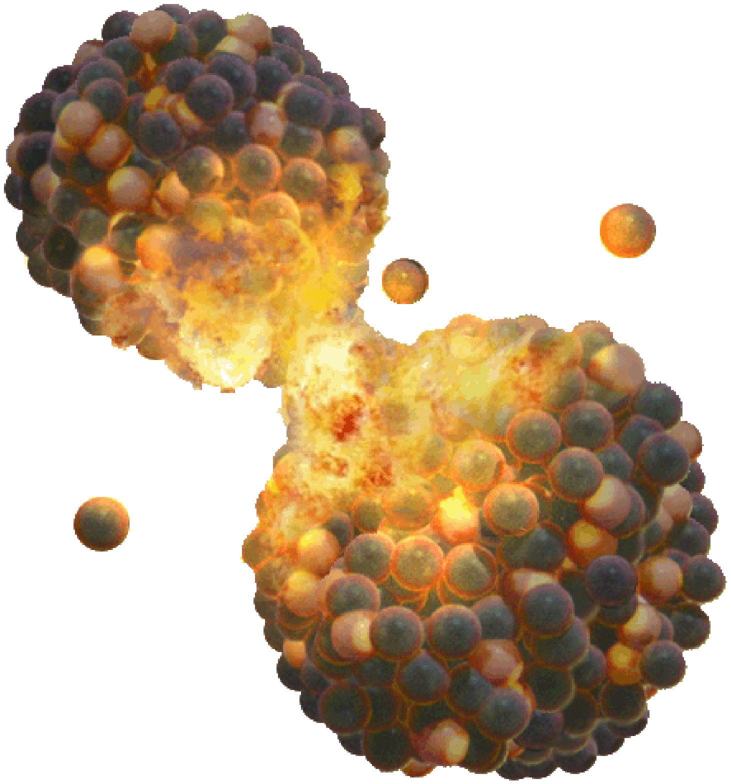


Illustration of Spontaneous Fission



iClicker Question

President Truman started the U.S. H-bomb program in what year?

A. 1948
B. 1949
C. 1950
D. 1951
E. 1952

iClicker Answer

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A. 1948
B. 1949
C. **1950**
D. 1951
E. 1952

iClicker Question

The United Kingdom first tested a nuclear device in what year?

A. 1948
B. 1952
C. 1955
D. 1957
E. 1960

iClicker Answer

The United Kingdom first tested a nuclear device in what year?

A. 1948
B. **1952**
C. 1955
D. 1957
E. 1960

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

iClicker Answer

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

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D. 1,000 times more

E. 1,000,000 times more

Fission and Fusion

The Two Types of Fission

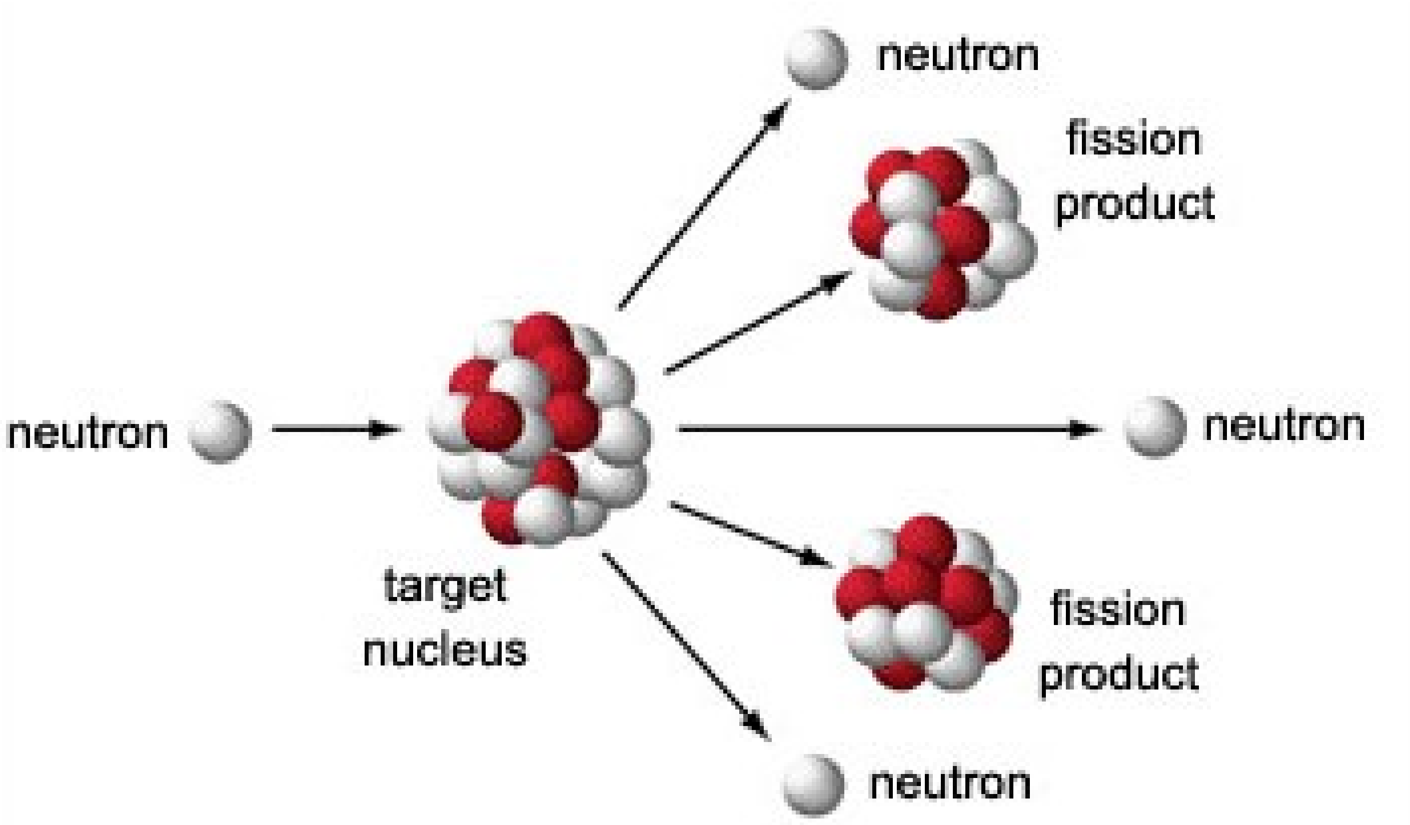
Spontaneous fission —

- 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

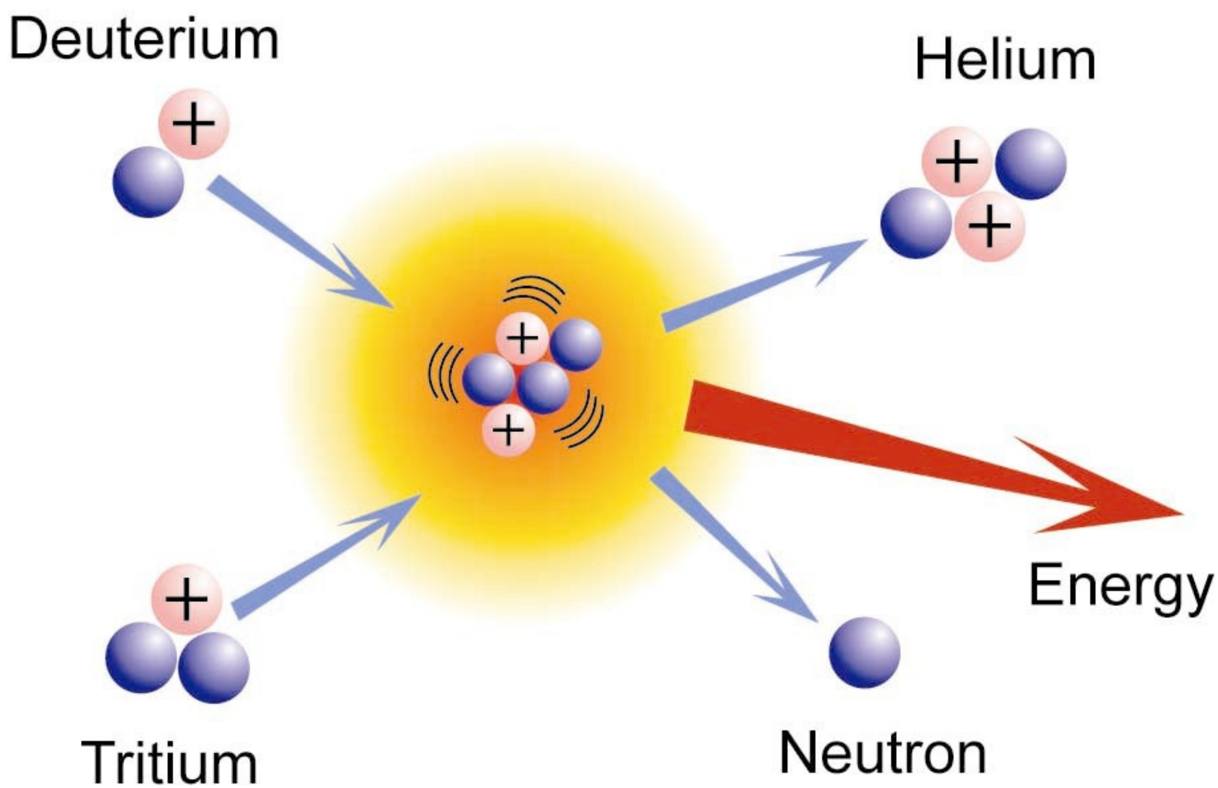
Induced fission —

- 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

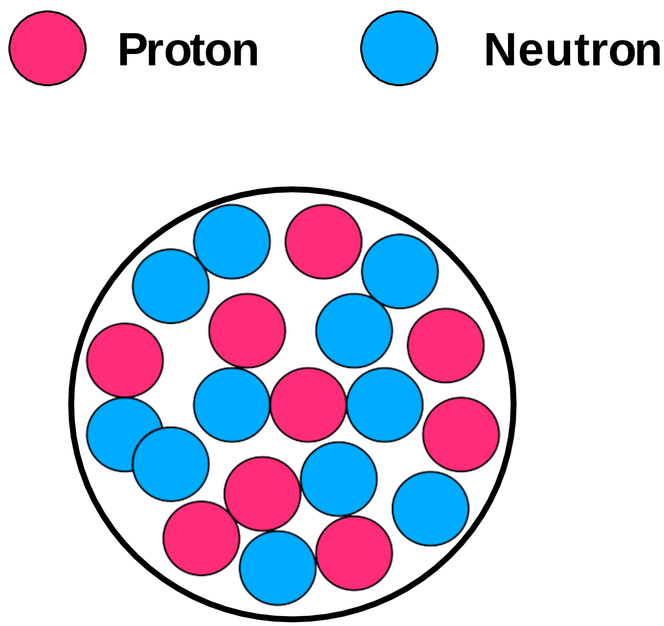
Induced Fission



Fusion



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 !

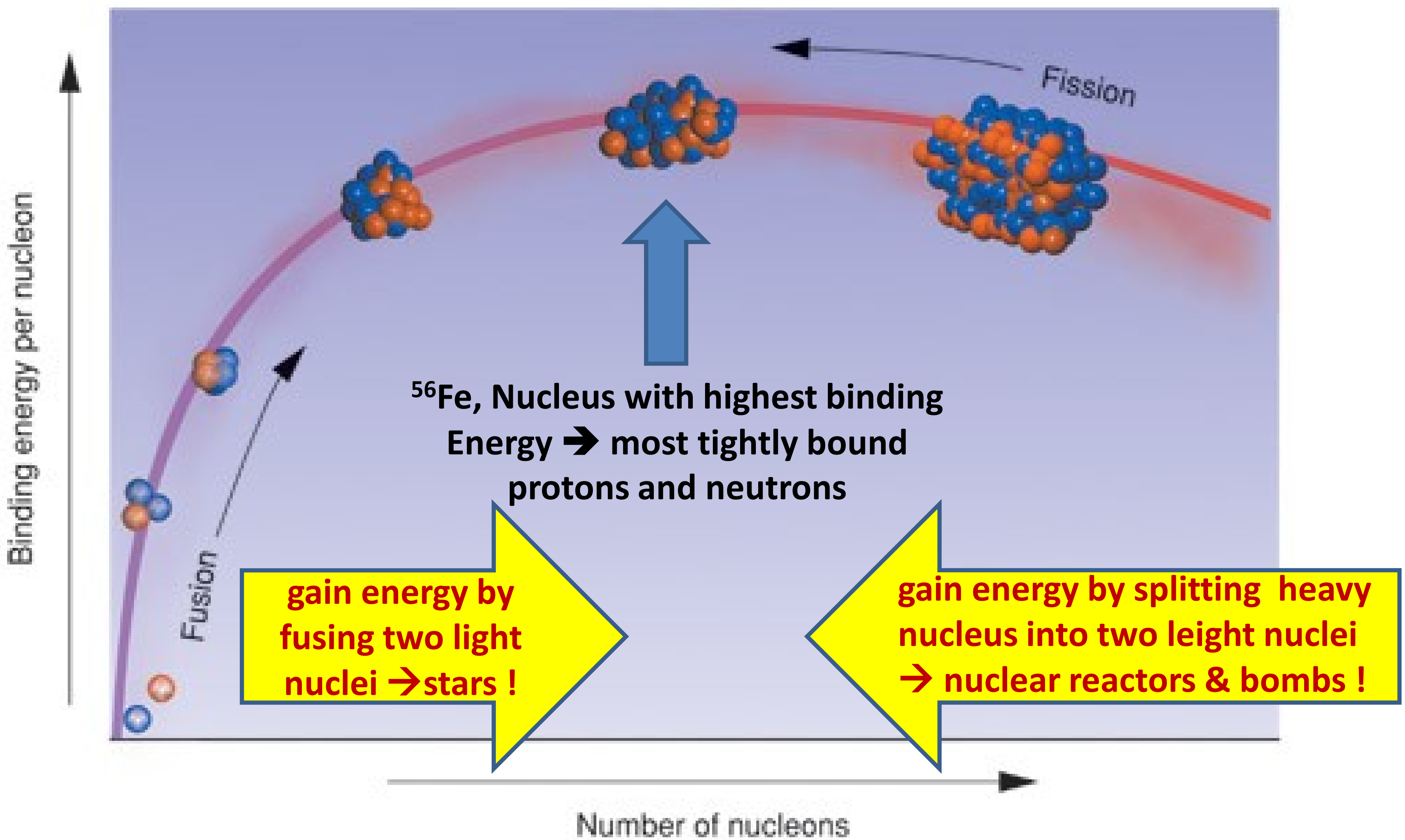
The Binding Energy Per Nucleon

- 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"

The Curve of Binding Energy (Important)

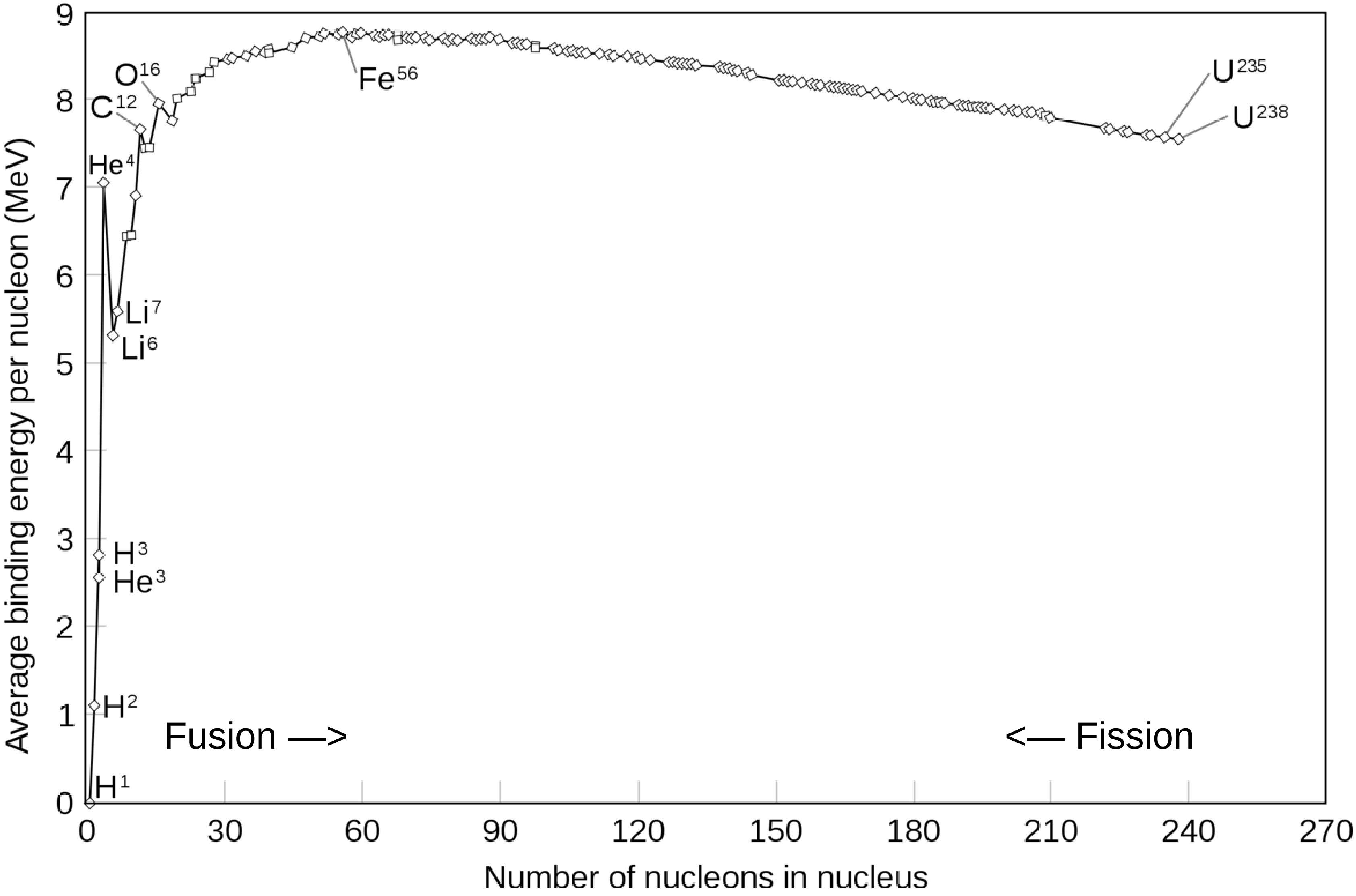


^{56}Fe, Nucleus with highest binding Energy → most tightly bound protons and neutrons

gain energy by fusing two light nuclei →stars !

gain energy by splitting heavy nucleus into two leight nuclei → nuclear reactors & bombs !

Re-call Binding Energy/Nucleon



Plan for This Session

Announcements about the course

Questions about the course

Module 2: Nuclear weapons cont'd

Physics 280: Session 5

Announcements About The Course

RE2v1 will be due Thursday, 1-31, at 1.55pm

- o printed copy + electronic submission
  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/sp2013/assignments/re2v1.html

- o follow all instructions stated in the student handbook

Questions About The Course

Global Zero

Check us out on FB!
Global Zero at the University of Illinois at Urbana- Champaign

Help us fight for a world without nuclear weapons

GLOBAL ZERO

Movie Night:

The World is Not Enough

Meet in the Union North Lounge (by the fish tanks) at 6:15

Come learn about the club, our upcoming campaigns, and what you can do to help.

Free Popcorn!

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

Nuclides Important for Fusion Bombs

Light elements (low Z) —

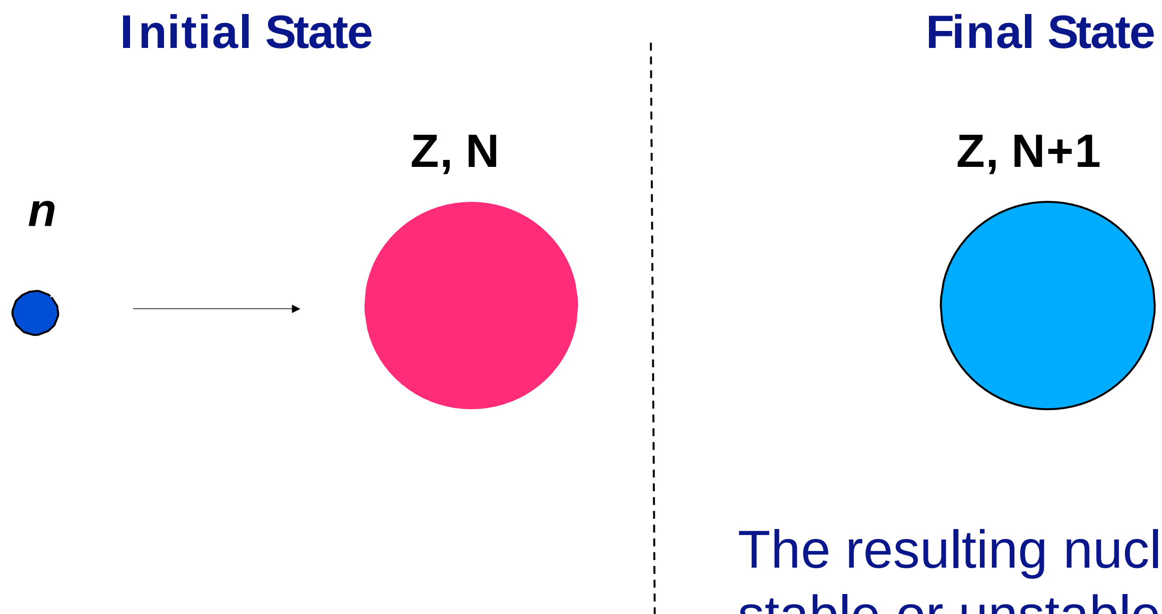
- $^{1}_{1}H$ = P (proton)
- $^{2}_{1}H$ = D (deuteron), stable * * *
- $^{3}_{1}H$ = T (triton), unstable * * *
- $^{4}_{2}He$ = He(4) = α (alpha particle), very stable
- $^{3}_{2}He$ = He(3) , stable (indirectly relevant to NWs) *
- $^{6}_{3}Li$ = Li(6) , stable * *
- $^{7}_{3}Li$ = Li(7), stable (no relevance to NWs)
- $^{9}_{4}Be$ = Be(9) stable (lighest metal) *

*, **, *** denotes increasing importance

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.

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.

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

iClicker Question (Use Channel C-C)

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

iClicker Answer

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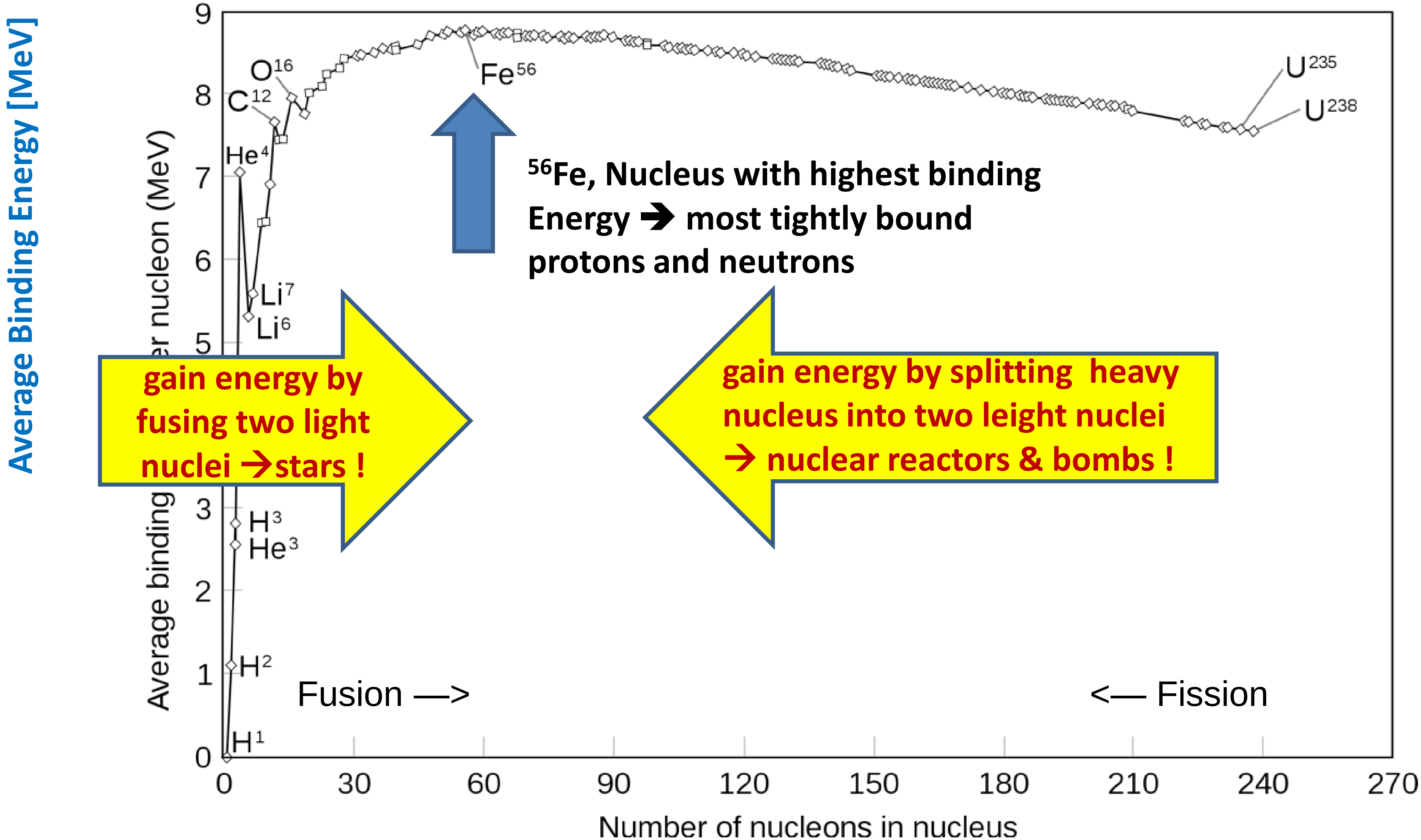
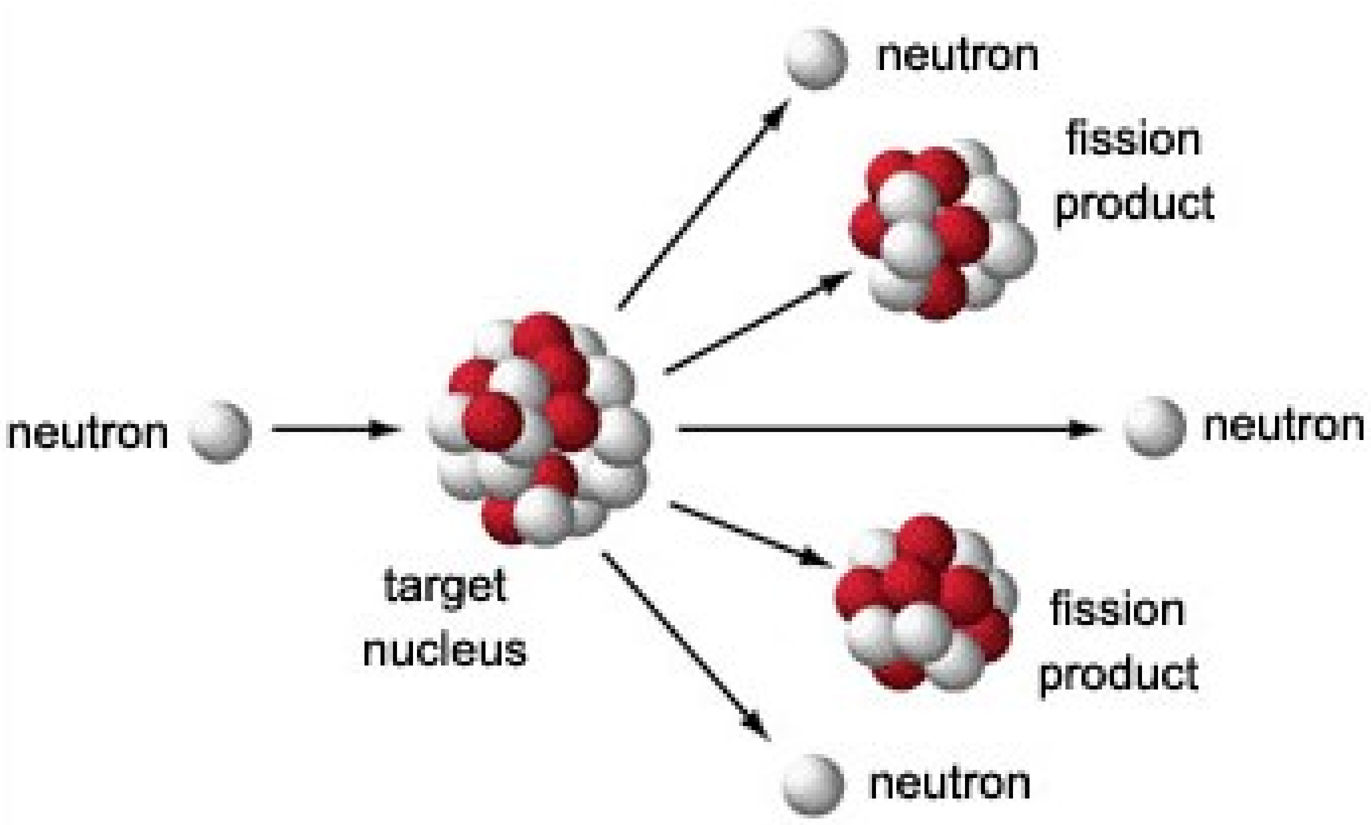
D. None of the above

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



Induced Fission – 1



Induced Fission – 2

The discovery of induced fission was a great surprise!

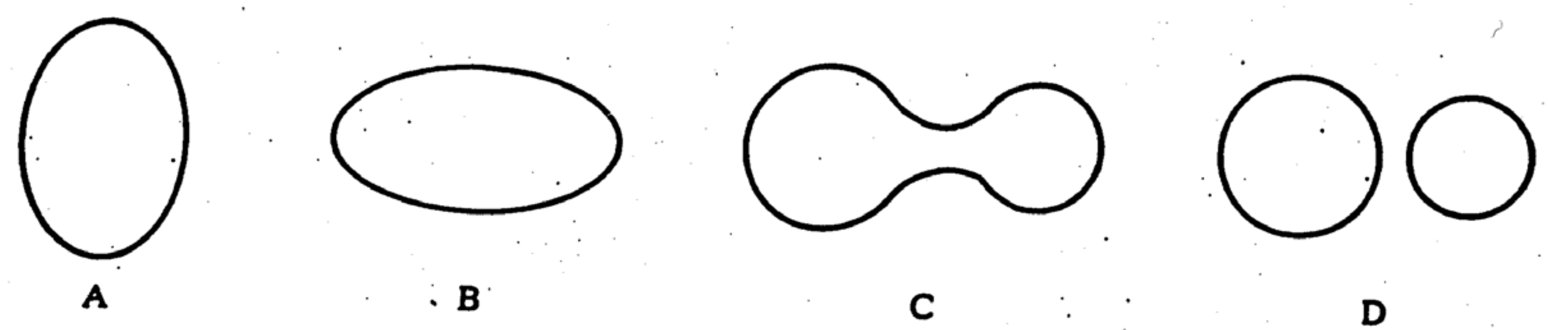
Many groups studying neutron capture by Uranium had induced fission without realizing what was happening.

Lise Meitner, a brilliant Jewish scientist who had fled from Germany to Copenhagen in 1933, was the first person to understand what was happening in the experiments.

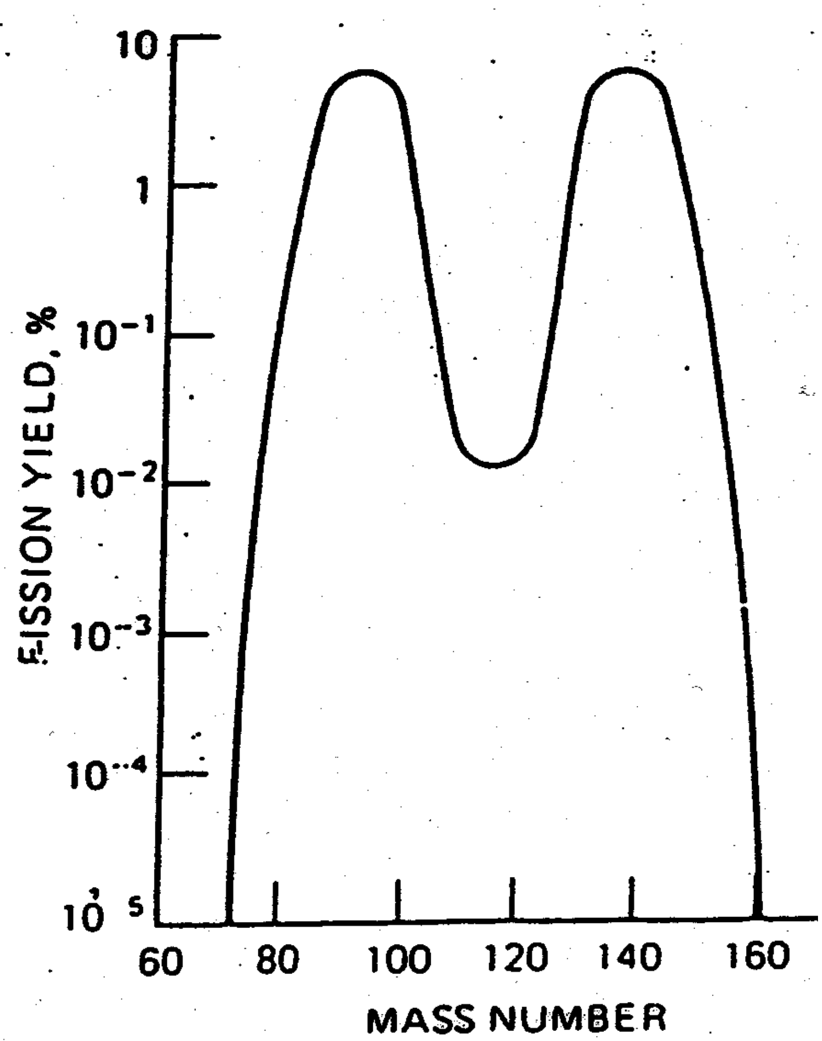
Unfortunately, *she was not included* in the Nobel Prize awarded for the discovery! A shameful omission.

Element 109, Meitnerium, is named in her honor.

Lisa Meitner’s Concept of Fission



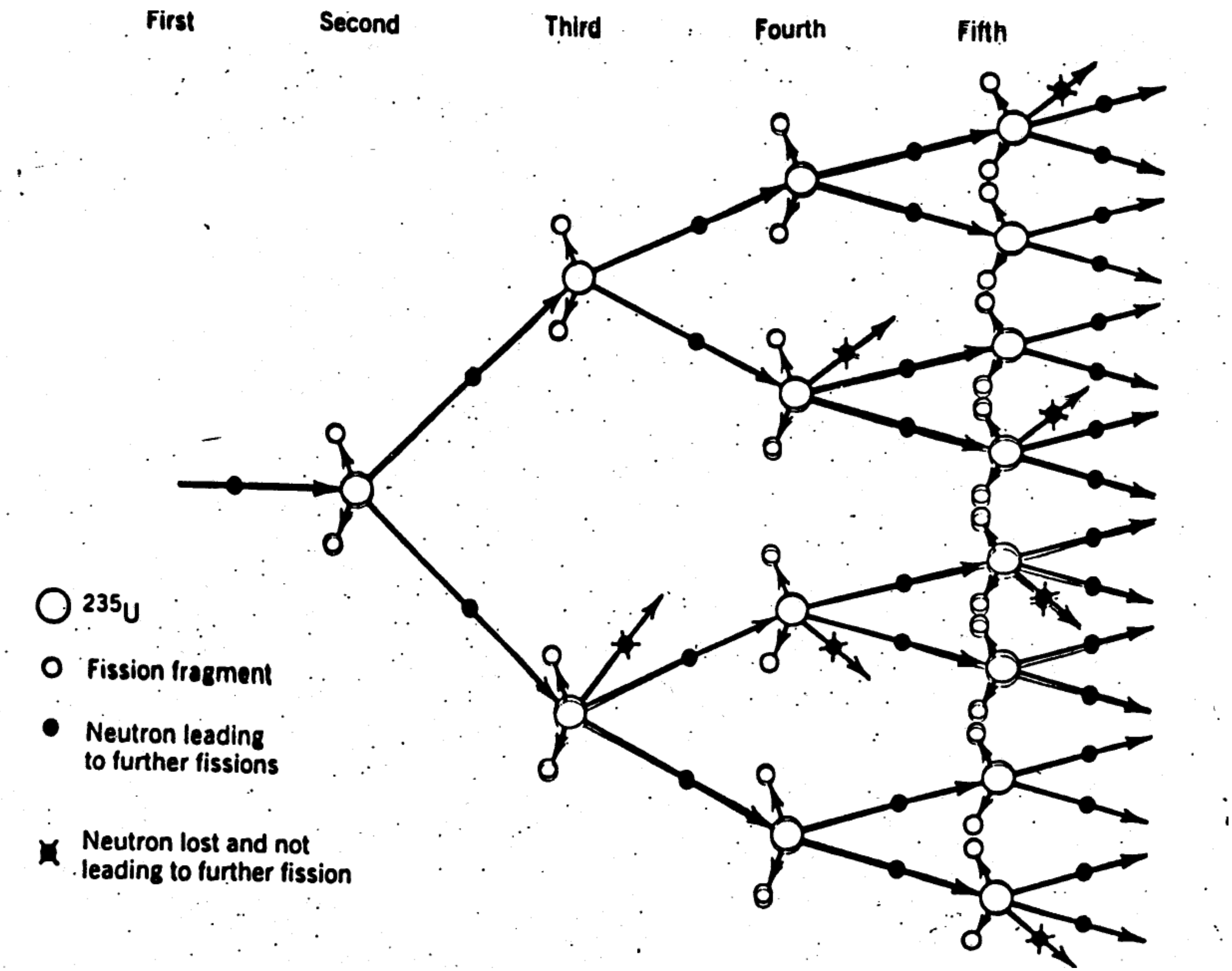
Distribution of Fission Fragment Masses



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)

Chain Reaction



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

iClicker Answer

Which of the following is an example of radioactive decay?

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D. Spontaneous fission

E. All of the above

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

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

Nuclear Reactors and Nuclear Bombs

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.).

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.

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".

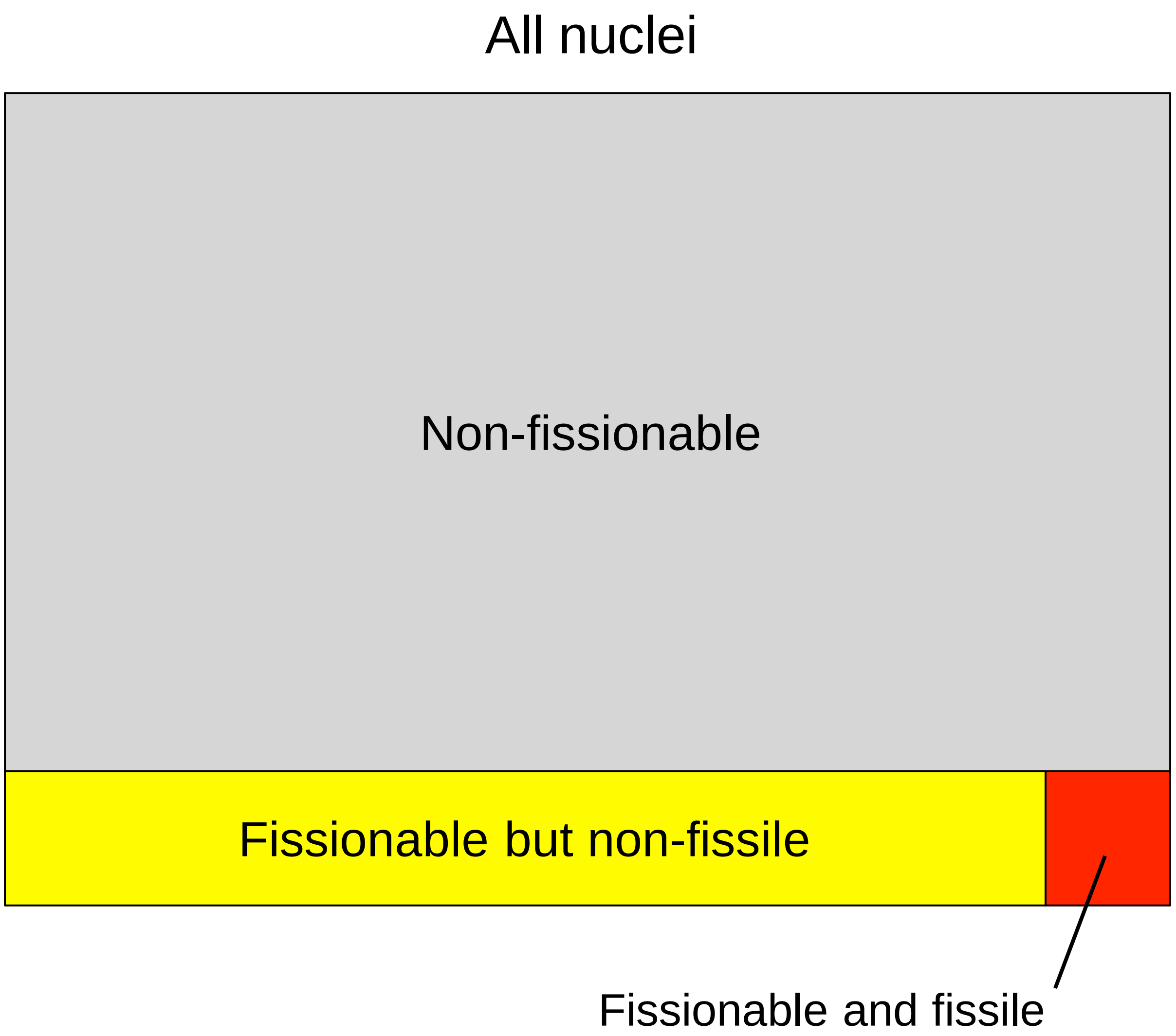
Fissionable but not fissile nuclides cannot be used in a nuclear reactor but some can be used in nuclear bombs.

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)

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



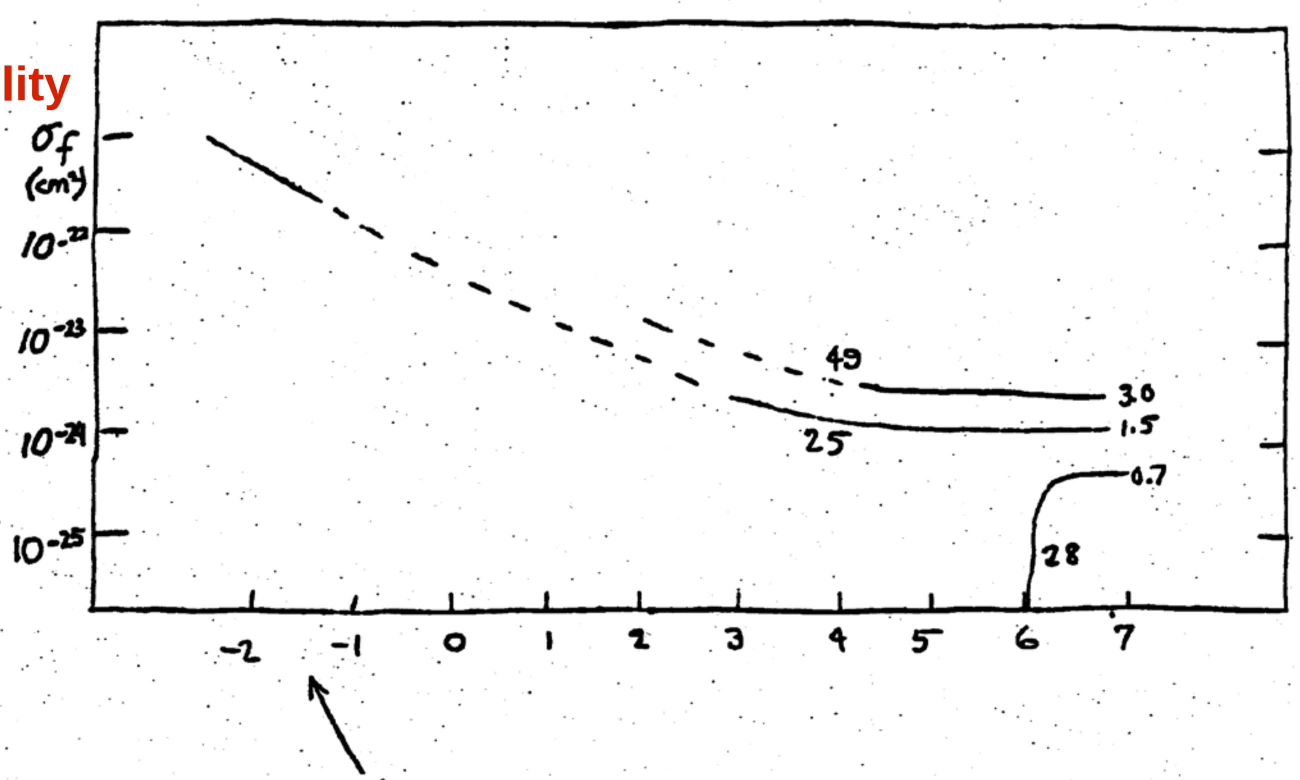
Neutron-Induced Fission Probability As a Function of the Incoming Neutron Energy for Three Important Nuclides

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

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

Nuclear-explosive *nuclides*—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.

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.

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 exploisve nuclide

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.

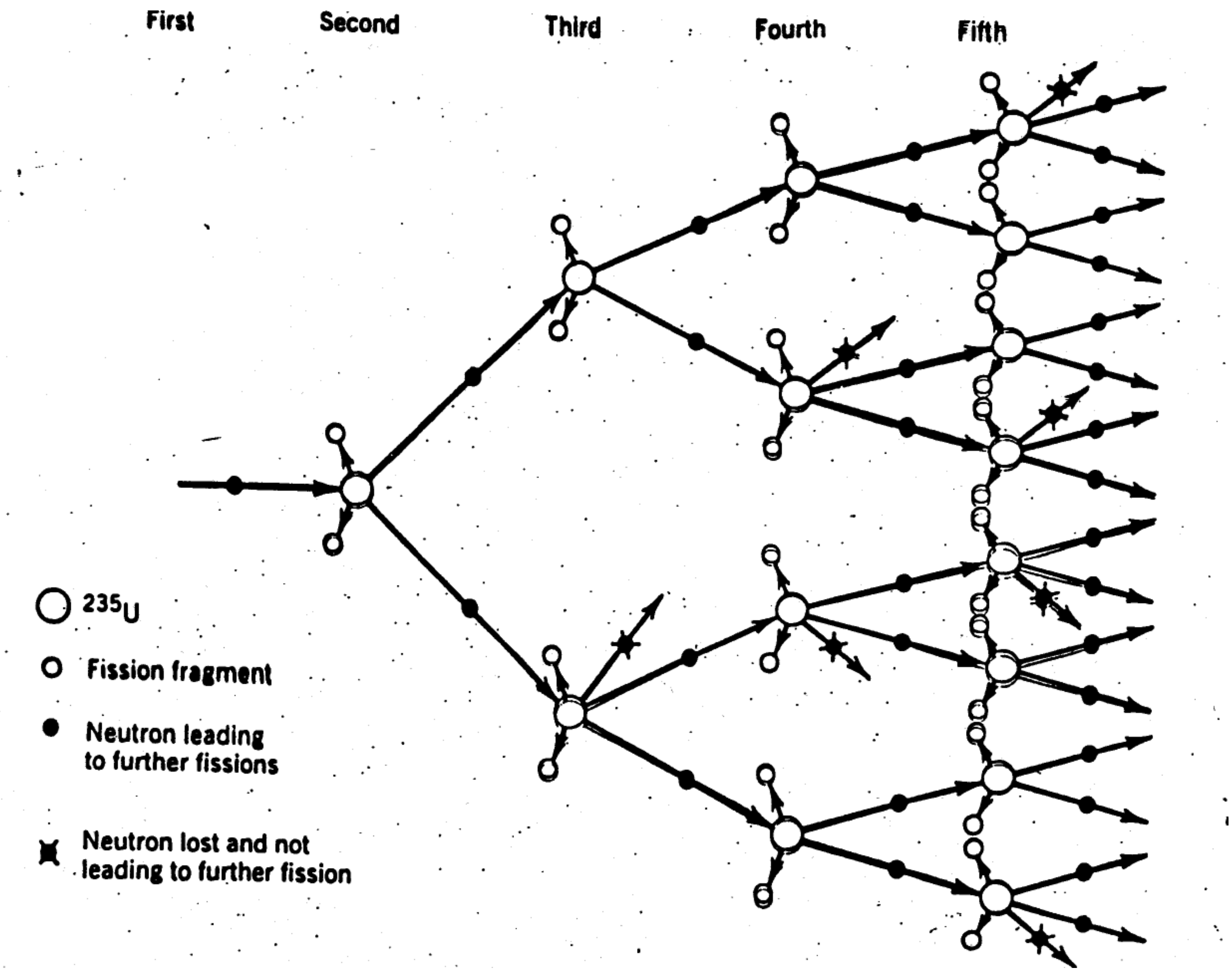
To sustain a fast-neutron chain reaction, on average at least one of the several energetic neutrons released per fission must be “productively” captured, i.e., it must produce another fission following its capture.

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.

Explosive Chain Reaction: Generations



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.

Plan for This Session

Questions about the course

Module 2: Nuclear weapons cont'd

Physics 280: Session 6

Questions About The Course

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	$2^3 = 2 \times 2 \times 2 = 8$	
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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.

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.

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

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

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

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

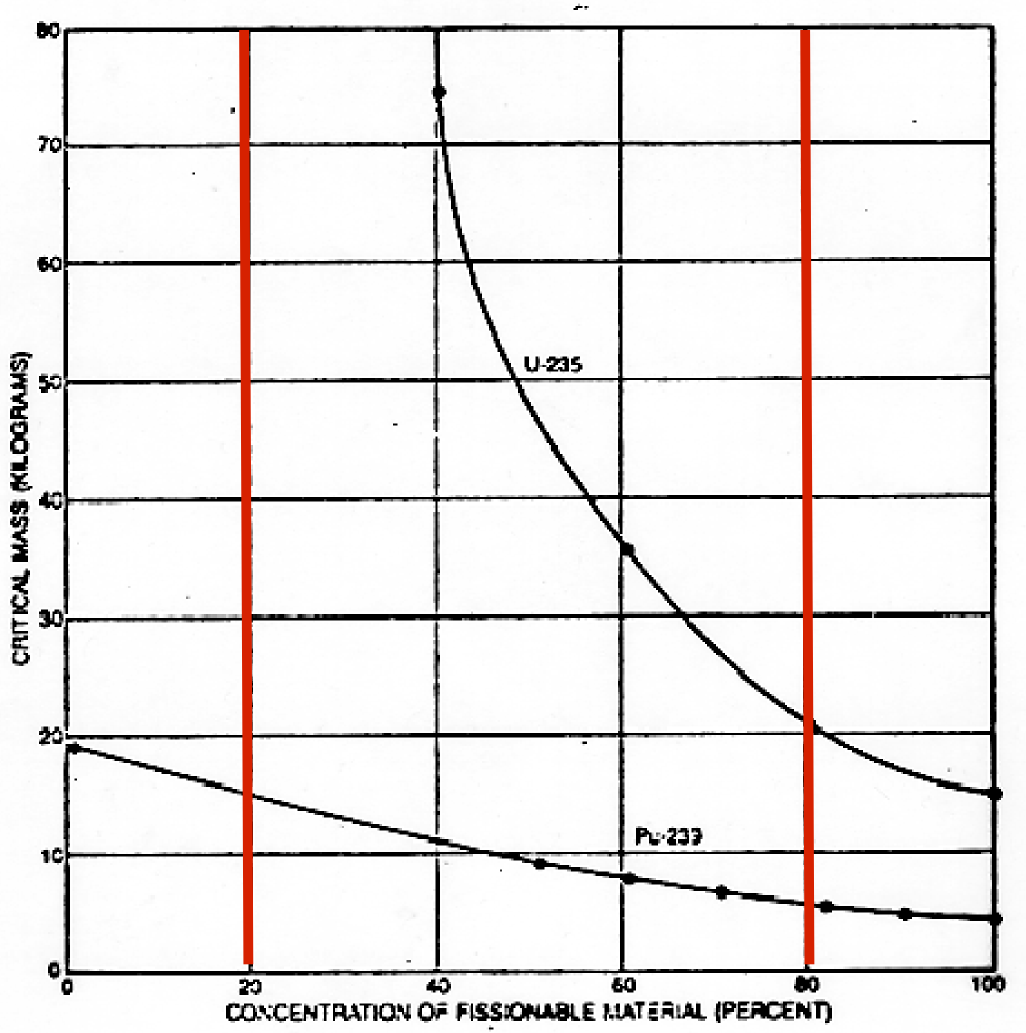
Properties of Nuclear Explosive Materials

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

Reducing the Fast-Neutron Critical Mass – 1

Dependence on the Concentration of the Fissile Material



Concentration of Fissile Material

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: $$\frac{\rho}{\rho_0} = 2, \quad \frac{m_c(\rho)}{m_c(\rho_0)} = \frac{1}{4}$$

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

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

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

iClicker Answer

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

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

iClicker Answer

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

Fission Weapons (“A-bombs”)

Important Concepts

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

First Let's Discuss Chemical Bombs

Simulated road side bomb attack with chemical explosive

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

How to Make a Chemical Explosion – 2

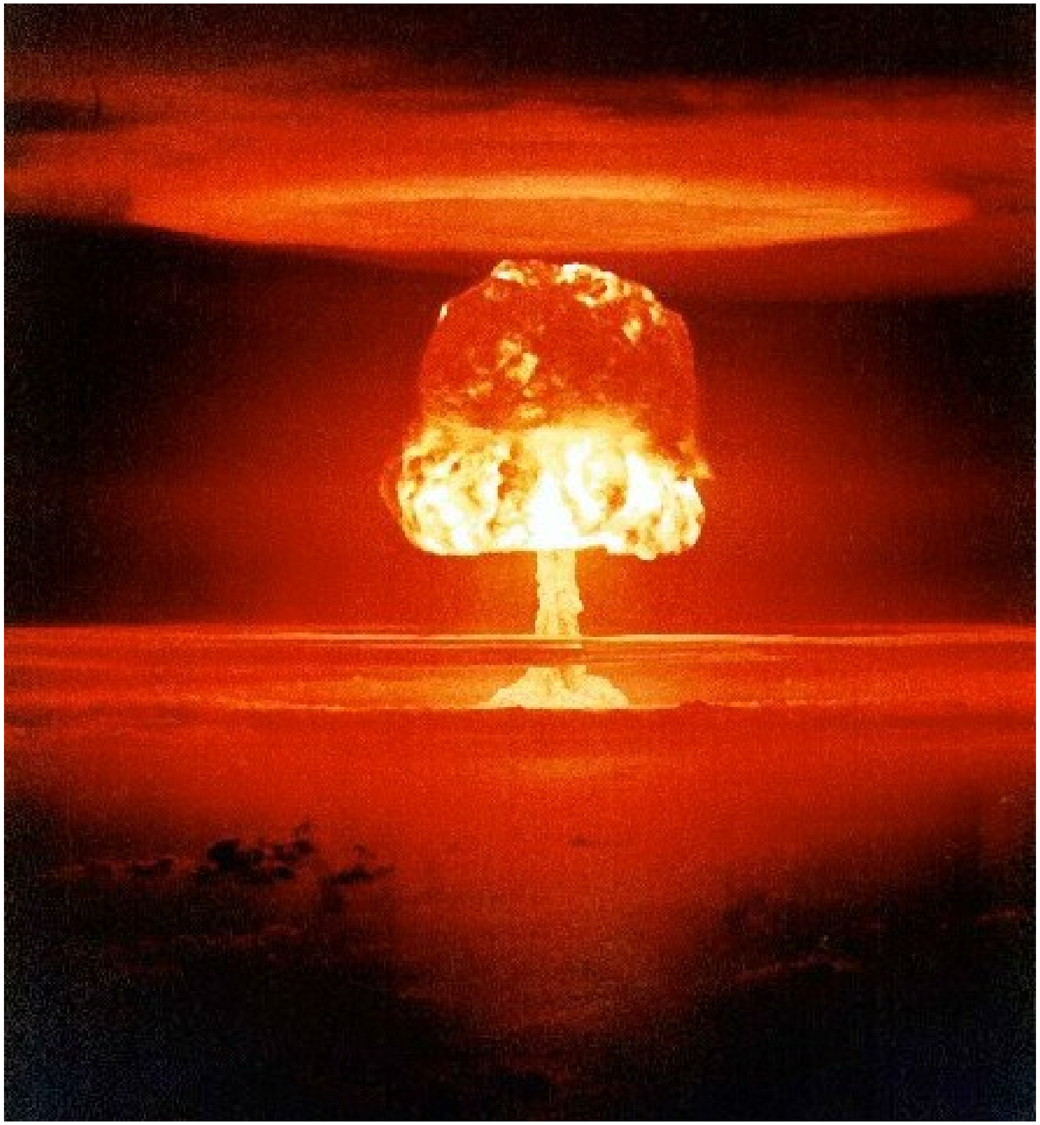
Stages —

- Explosive is ignited
- Fuel and oxidizer burn (chemically), releasing ~ 10 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

Now Let's Discuss Nuclear Bombs



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

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

Energy Released By a Single Fission (Details)

n + (fissile nucleus) → (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 E of	7
gamma-rays from fragments E of	6
neutrinos from fragments	10
Total	~ 200

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

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 x 10^{12} Joules

Energy Yields of Nuclear Weapons – 2

Fission weapons (“A-bombs”) —

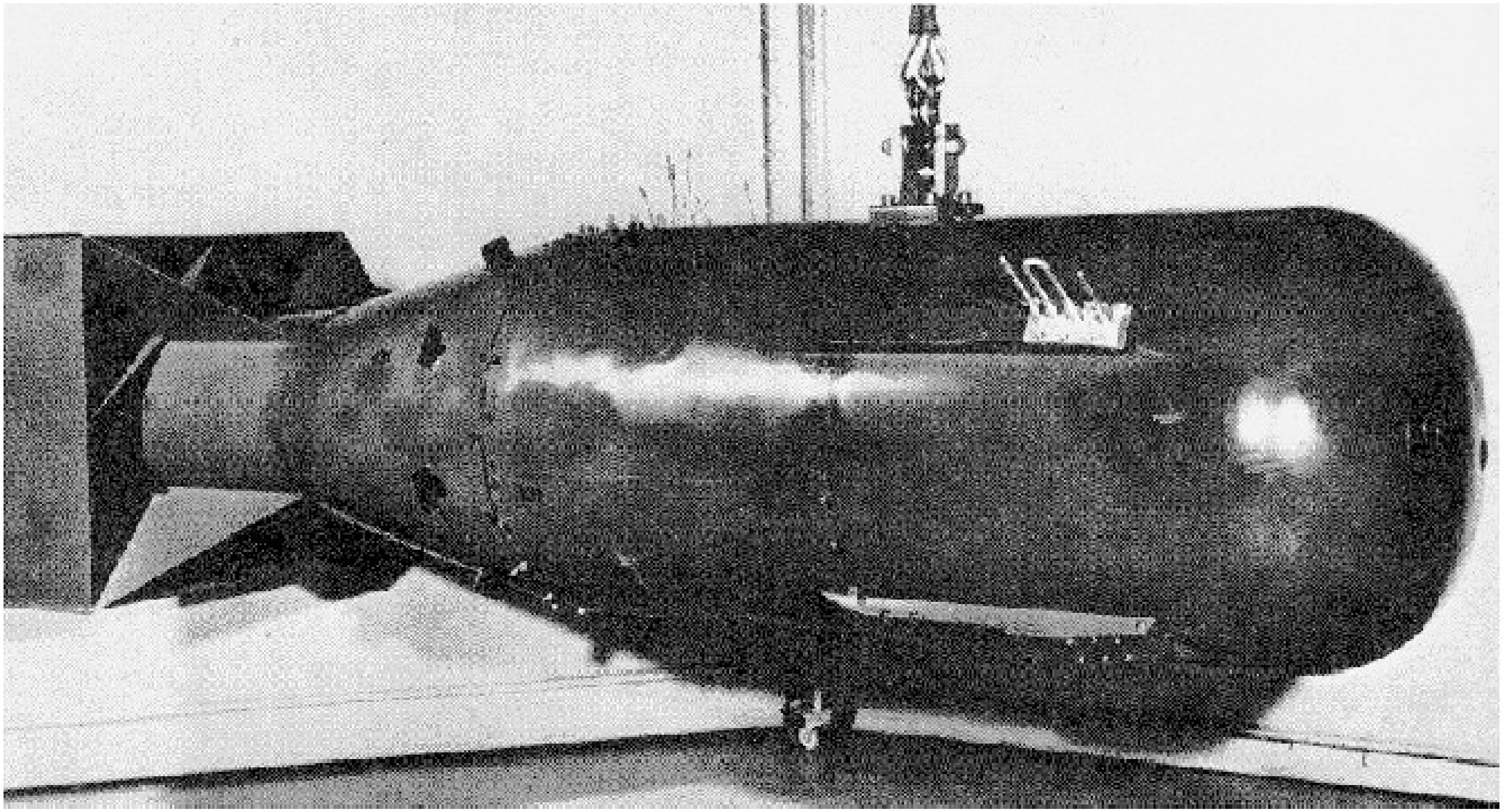
- Theoretical maximum yield-to-weight ratio: 8,000 tons TNT = 8 kt TNT from 1 lb. of NEM (~ 10,000,000 times as much per lb. as TNT)
- Difficult to make weapons larger than few 100 kt (Yields of tested weapons: 1–500 kt)

Thermonuclear weapons (“H-bombs”) —

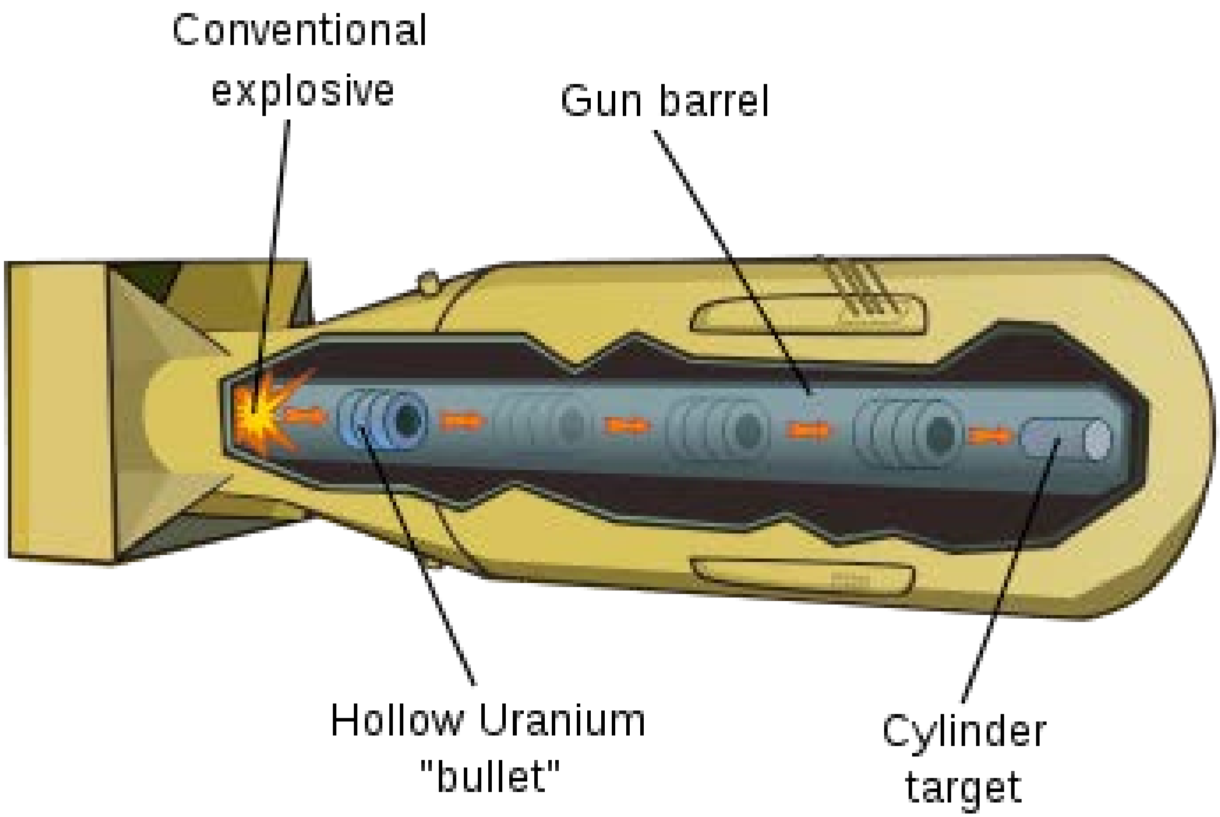
- Theoretical maximum yield-to-weight ratio: 25 kt TNT from 1 lb. of fusion material (~ 3 times as much per lb. as fission weapons)
- But there is no fundamental limit to the size of a thermonuclear weapon

Fission Weapons – Gun Type

Little Boy



Fission Weapons – Gun Type

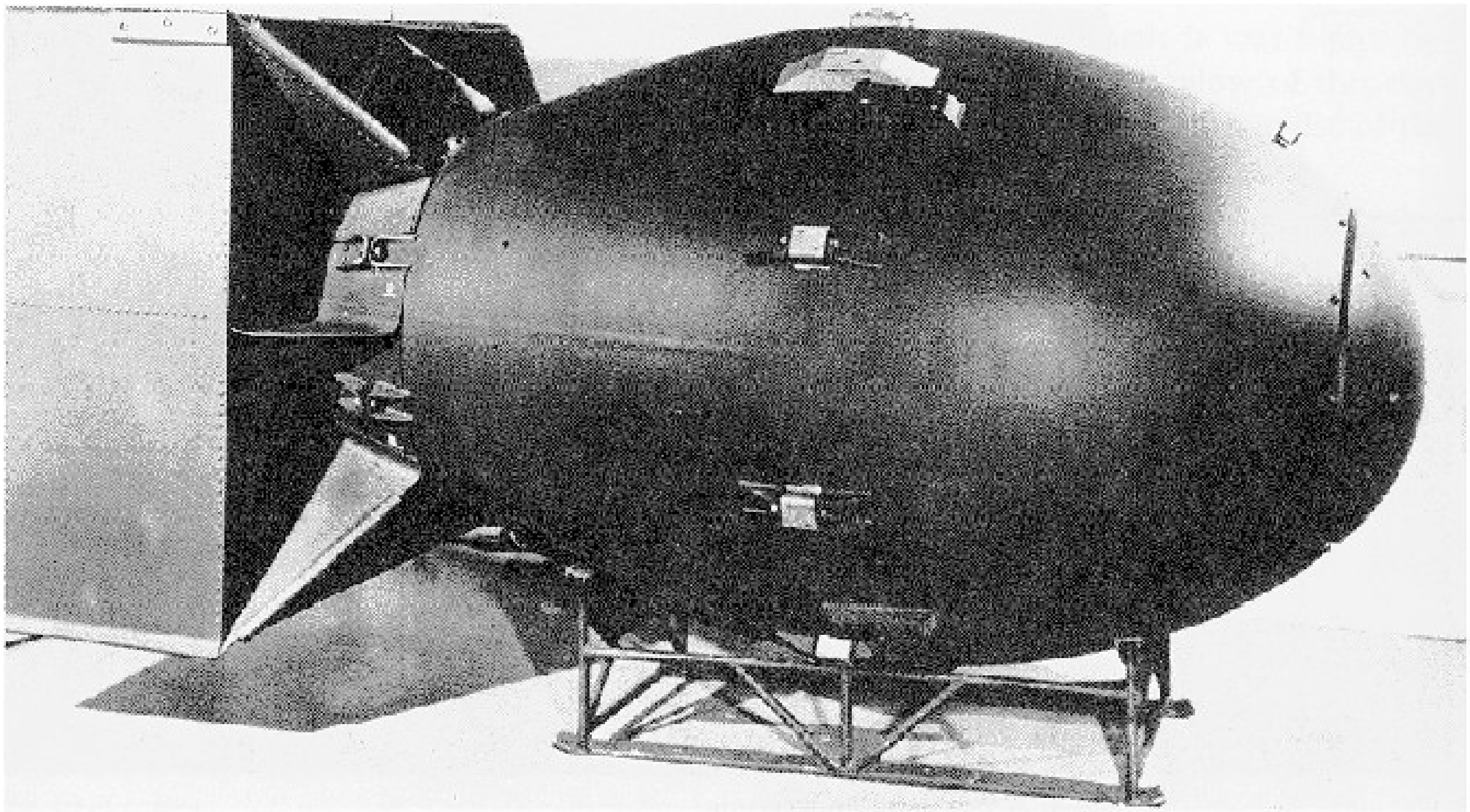


Works only with HEU

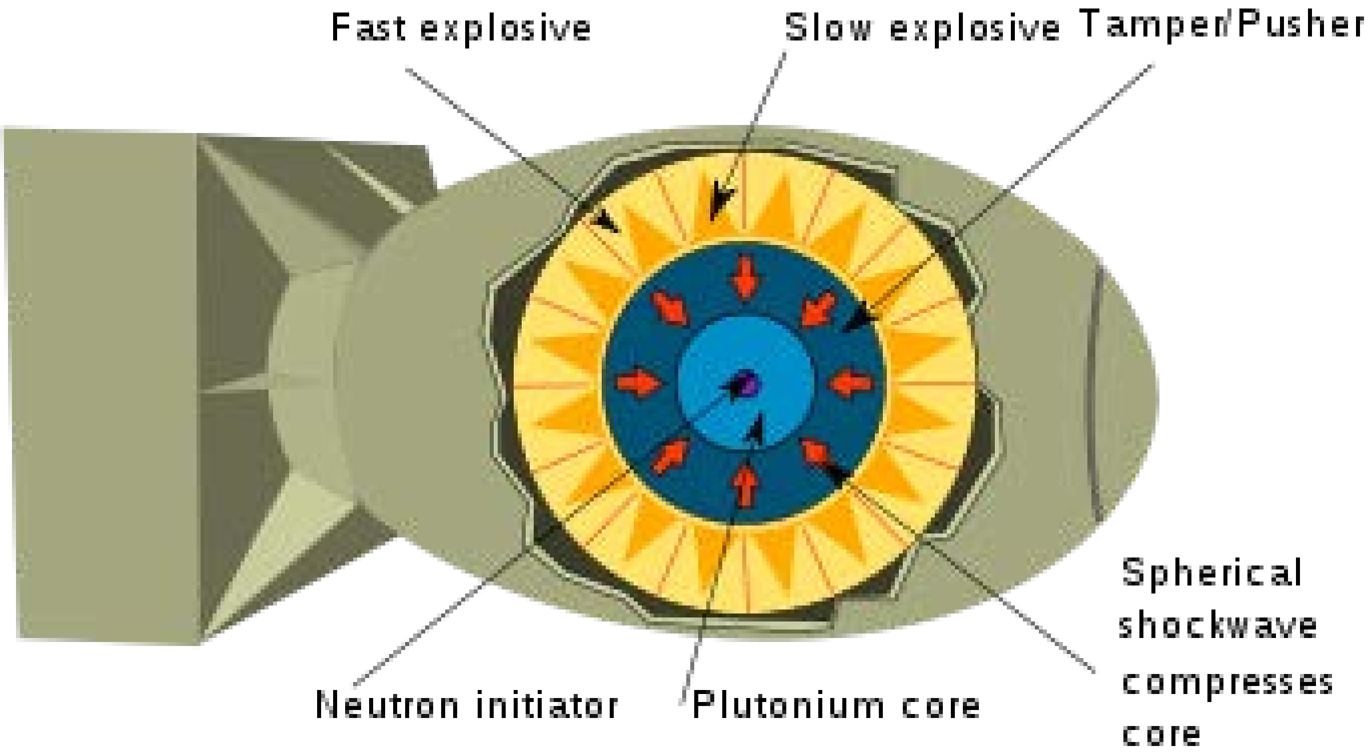
(relevant today mostly for terrorists or non-state groups)

Fission Weapons – Implosion Type

Fat Man

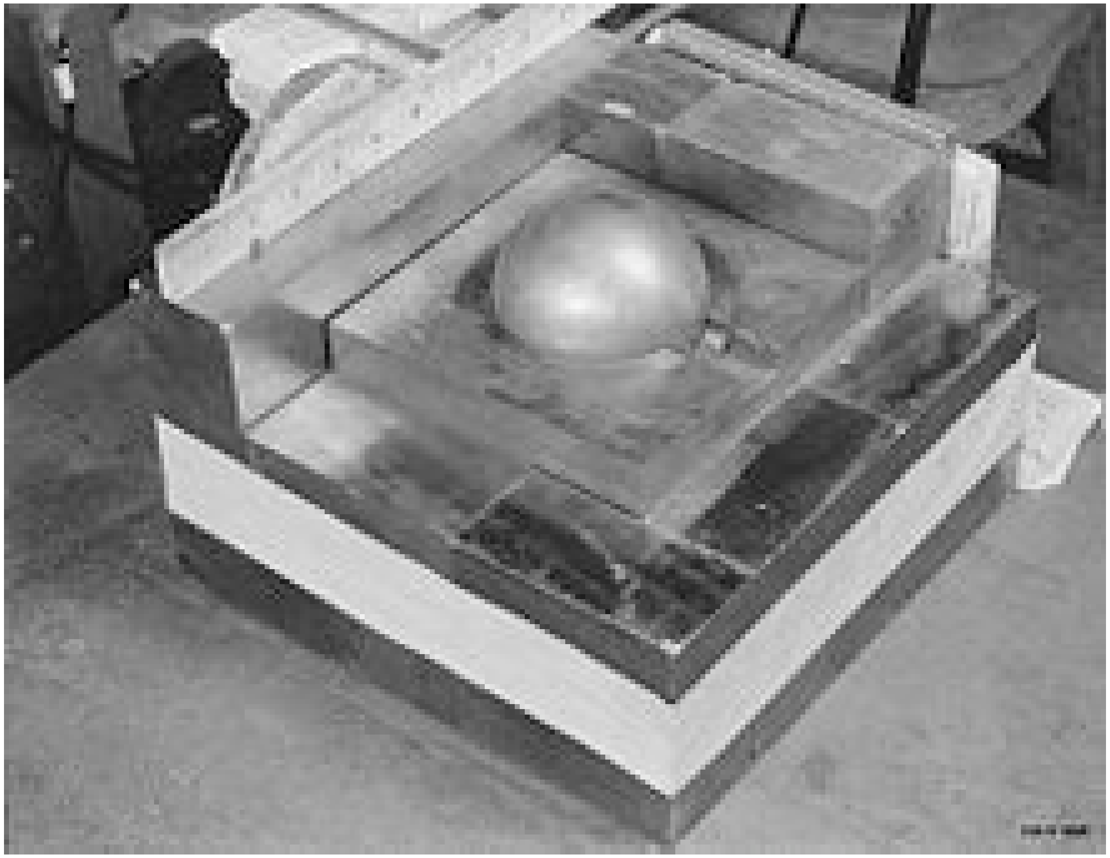


Fission Weapons – Implosion Type



Fission Weapons – Implosion Type

Plutonium Sphere ("Pit")



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*

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)

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

iClicker Answer

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

iClicker Question (Use Channel C-C)

The minimum amount of *highly enriched uranium* 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

iClicker Answer

The minimum amount of *highly enriched uranium* 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

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

iClicker Answer

China first tested a nuclear device in what year?

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

Physics 280: Session 7

Plan for This Session

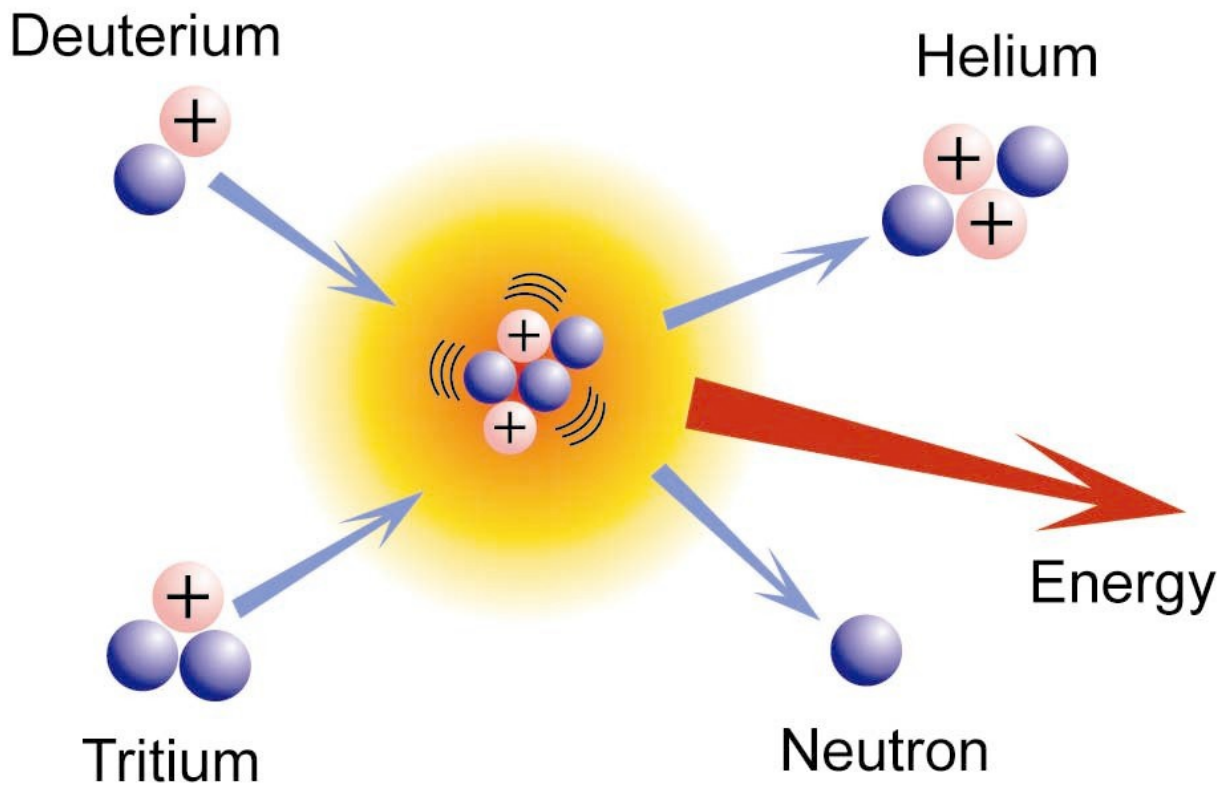
Announcements about the course

Questions about the course

Module 2: Nuclear weapons (conclusion)

Thermonuclear Weapons (“H-Bombs”)

Example Fusion Nuclear Reaction



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)

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 the simple “P280 design” for essays and exams

Two-Stage (Thermonuclear) Weapons – 2

- 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

Two-Stage (Thermonuclear) Weapons – 3

- 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

Two-Stage (Thermonuclear) Weapons – 4

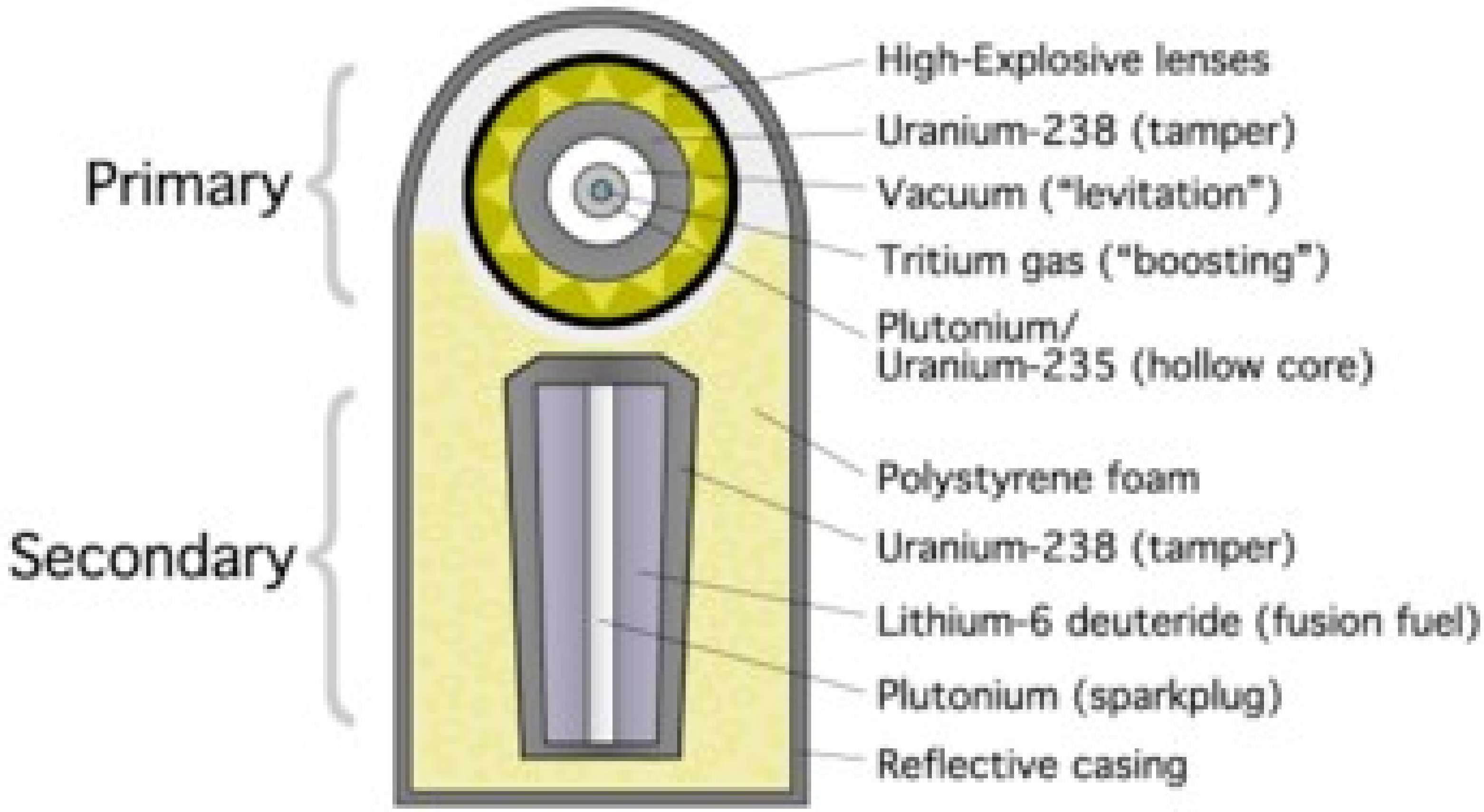
- Making a 50 Mt device makes no sense except (maybe) as a propaganda exercise, no matter how evil the intent
- U.S. developed and fielded H-bombs with yields up to 9 Mt
- As ballistic missile accuracies improved, the maximum yield of deployed US weapons dropped to 1 Mt or less, allowing an increase 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

Two-Stage (Thermonuclear) Weapons – 5

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

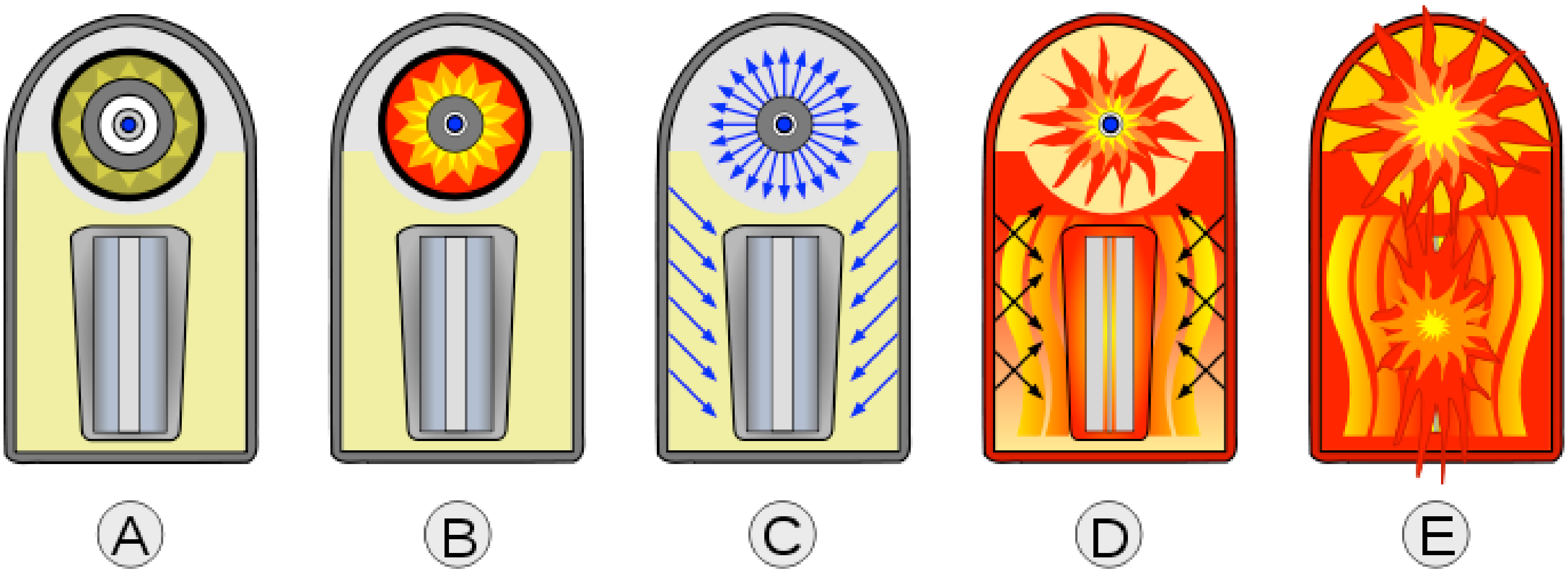
Two-Stage (Thermonuclear) Weapons – 6



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

Two-Stage (Thermonuclear) Weapons – 7

Sequence of events —



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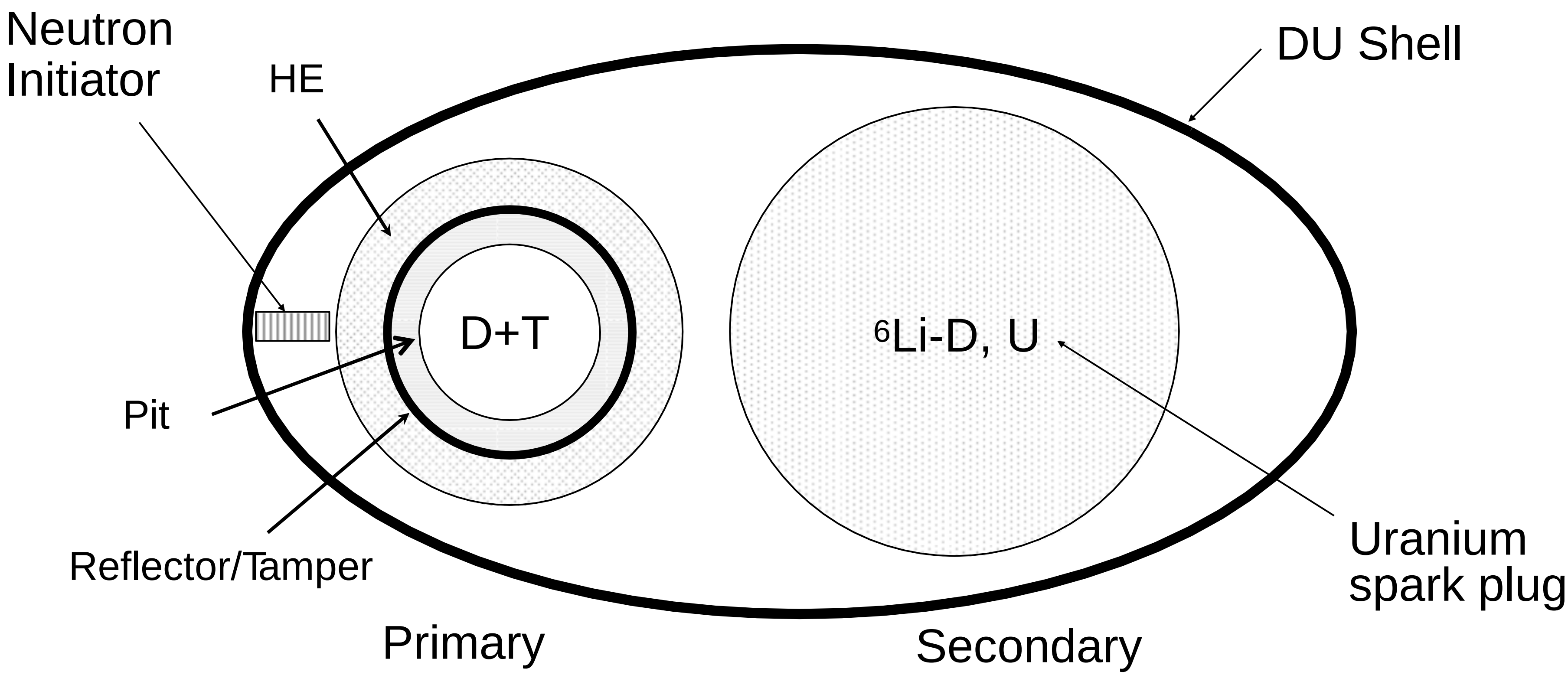
Two-Stage Nuclear Weapon ("P280 Design") Important



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

Review of Two-Stage Nuclear Weapons Important

- 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

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

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

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”

"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

B-61 Bomb

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

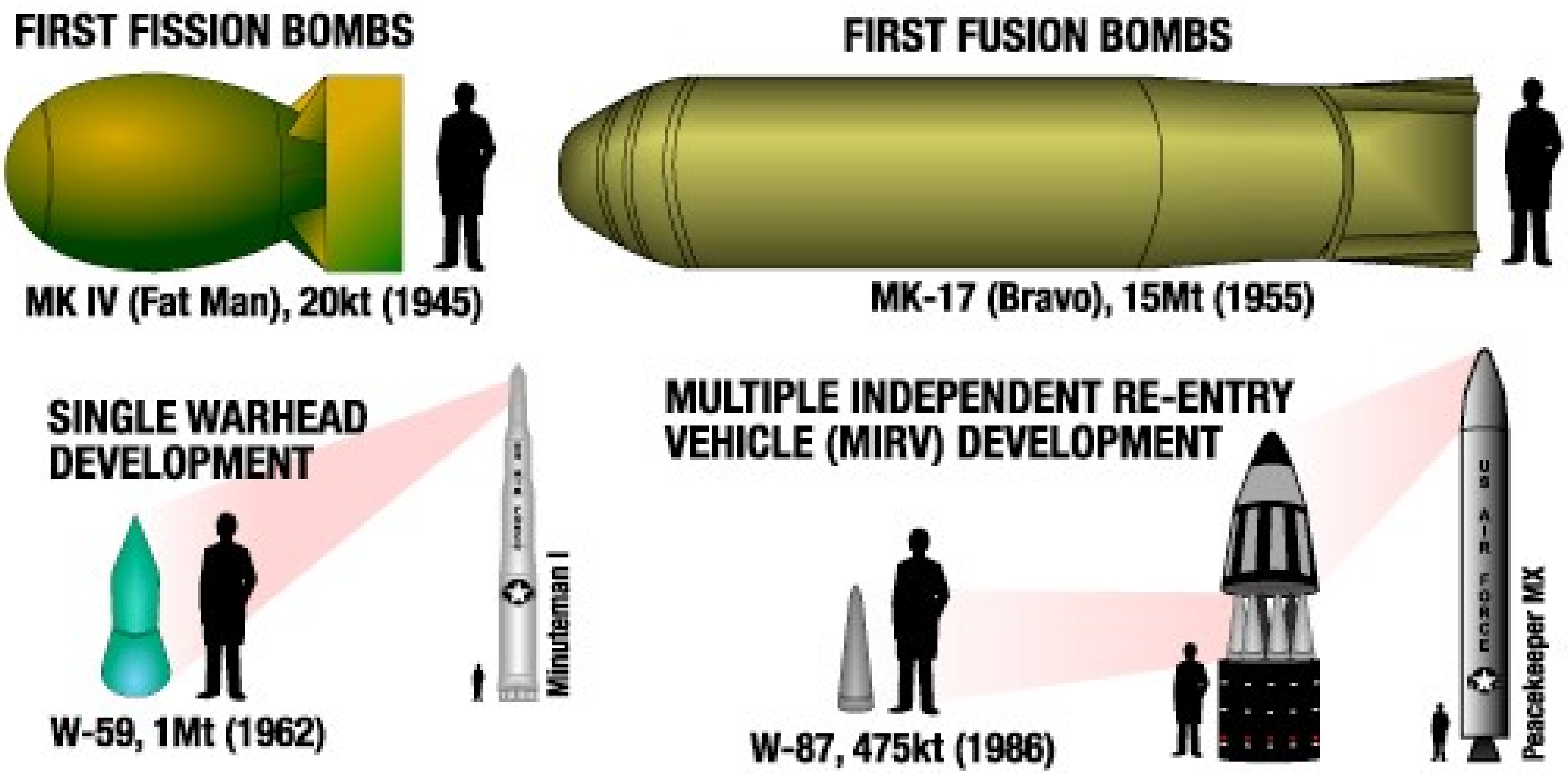
Physics and Engineering Requirements

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 the high accelerations that occur at stage burnout
- Able to survive buffeting, deceleration, and very high temperatures as the warhead re-enters the atmosphere at hypersonic speeds

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

Miniaturizing Massive Death and Destruction



iClicker Question

India first tested a nuclear device in what year?

A. 1964
B. 1968
C. 1974
D. 1988
E. 1998

iClicker Answer

India first tested a nuclear device in what year?

A. 1964
B. 1968
C. 1974
D. 1988
E. 1998

iClicker Question (Use Channel C-C)

Pakistan first tested a nuclear device in what year?

A. 1964
B. 1968
C. 1974
D. 1988
E. 1998

iClicker Answer

Pakistan first tested a nuclear device in what year?

A. 1964
B. 1968
C. 1974
D. 1988
E. 1998

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

iClicker Answer

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iClicker Question

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

iClicker Answer

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E. A nuclear explosion can be created using reactor fuel

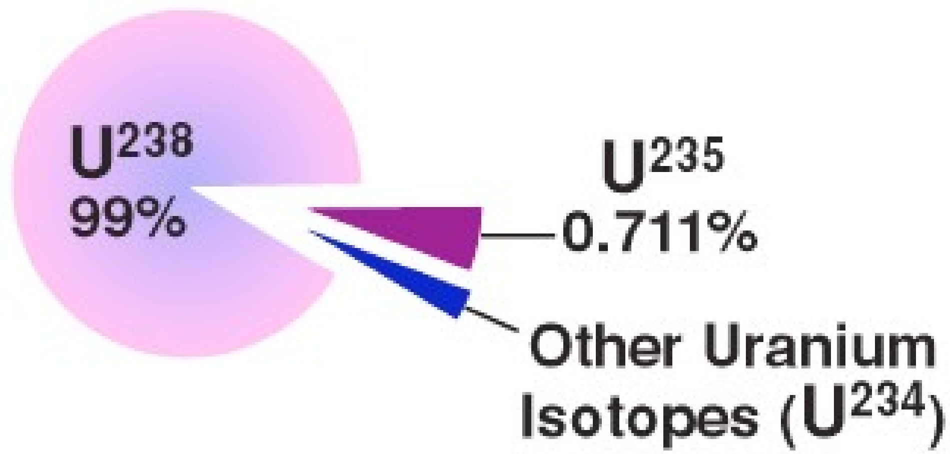
Production of Nuclear Explosive Material

Enrichment of U-235

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

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)



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.

Enriching Uranium – Overview

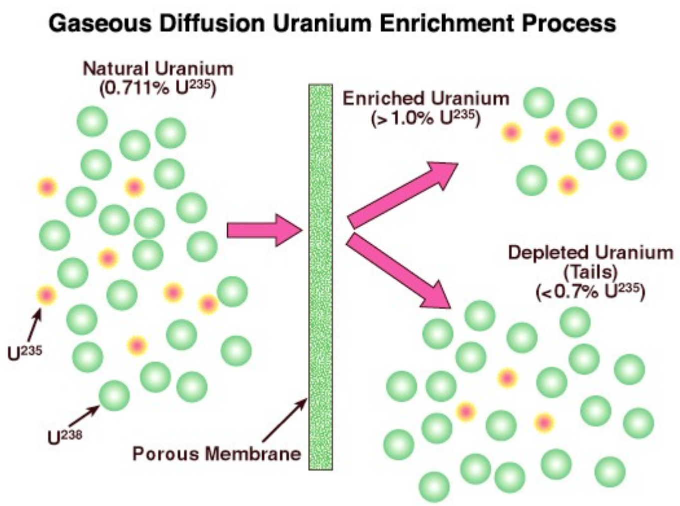
There are 4 main uranium enrichment techniques:

- 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.

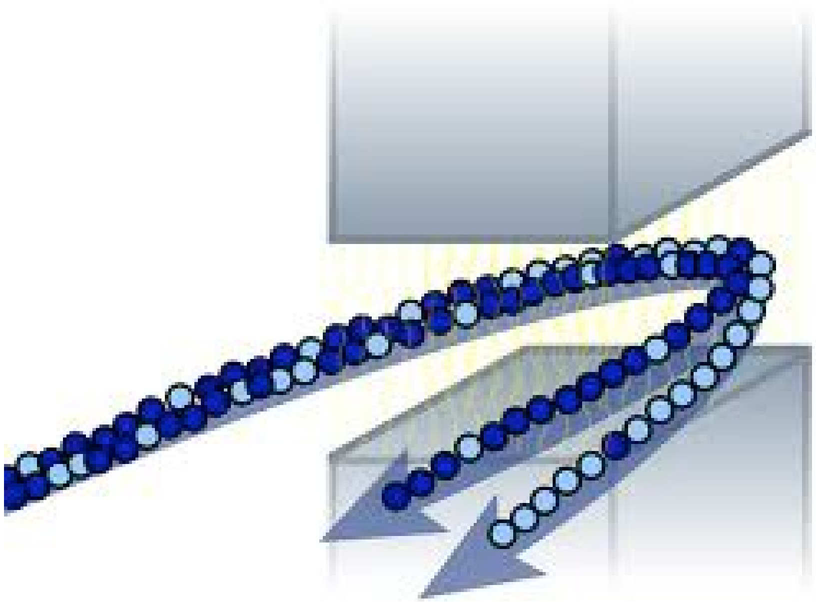
Enriching Uranium – Details 1

- 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



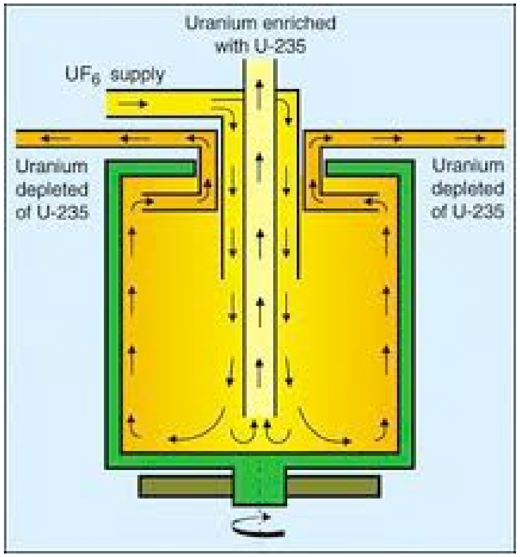
Enriching Uranium – Details 2

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



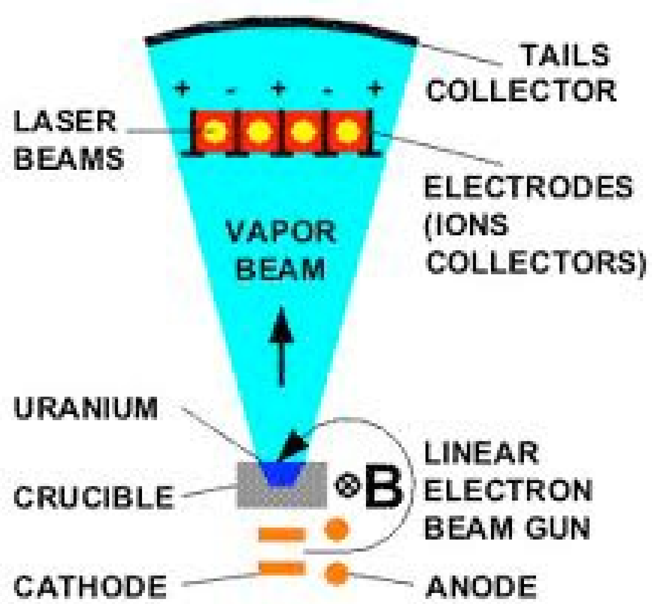
Enriching Uranium – Details 3

- 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



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



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)

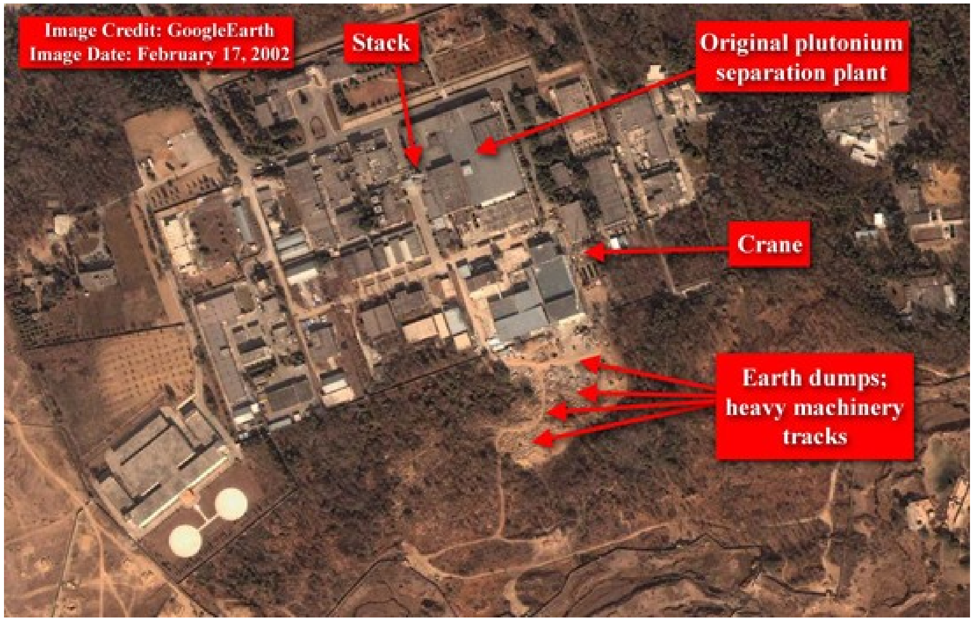
  (non-fissile) (fissile)

N Reactor, Hanford, WA

Reactor, Yongbyon, NK

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.

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.

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.

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.

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**.

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.

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.

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.

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

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

Supplementary Material

Unification of Physical Forces

- Electroweak Theory: (2) & (3)
  - —unified quantum theory of the electromagnetic and weak forces was proposed 20 years ago
  - —subsequently verified by experiment
  - —Nobel committee has already given out prizes
  - —one missing ingredient is the Higgs particle (Will it be discovered at Fermilab?)
- String Theory (Theory of Everything) (1)-(4)
  - —proposed unification of all fundamental interactions
  - —quantum theory of gravity proved to be the hardest of all interactions to bring into fold
  - —long, long way to go before before experimental evidence will be forthcoming
  - —For nuclear weapons purposes Electroweak and String Theory can be ignored

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)

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

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”)

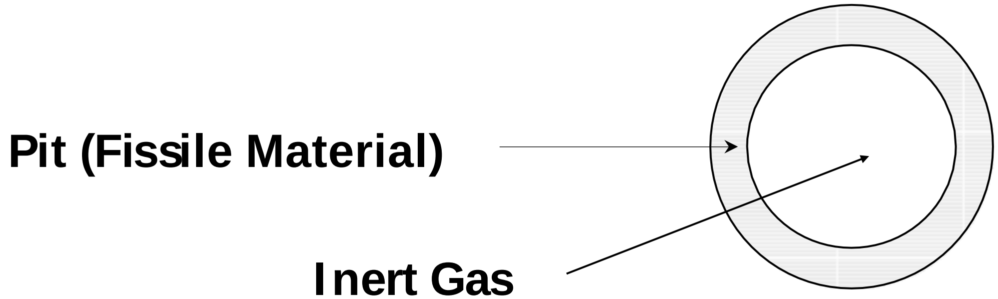
Importance of Delayed Neutrons for Controlling Nuclear Reactors

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.

Hollow “Pit” Implosion Design – Step 1

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



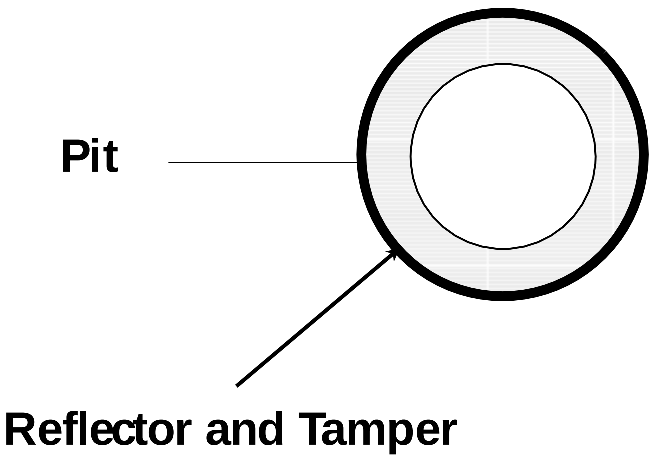
Advantage:

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

—Explain using an analogy

Hollow “Pit” Implosion Design – Step 2

Add a reflector and tamper —

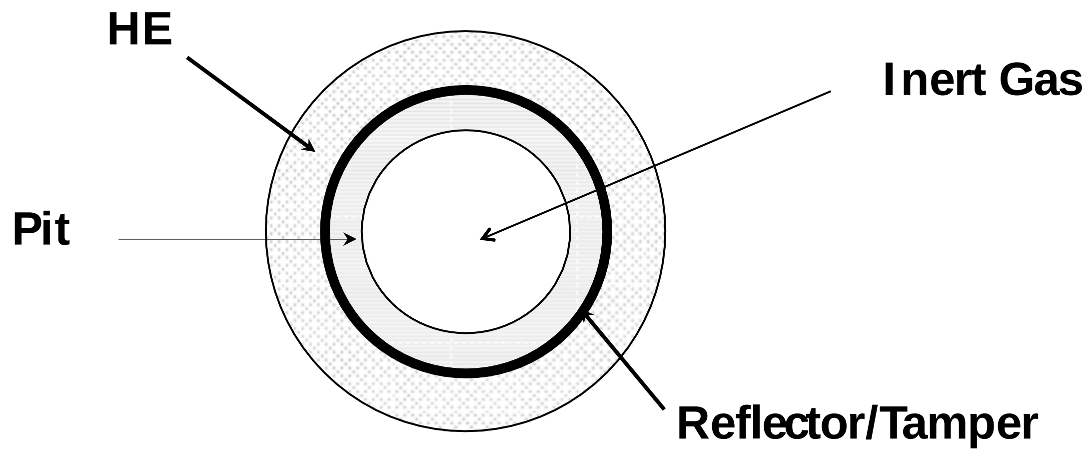


Advantages:

- 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

Hollow "Pit" Implosion Design – Step 3

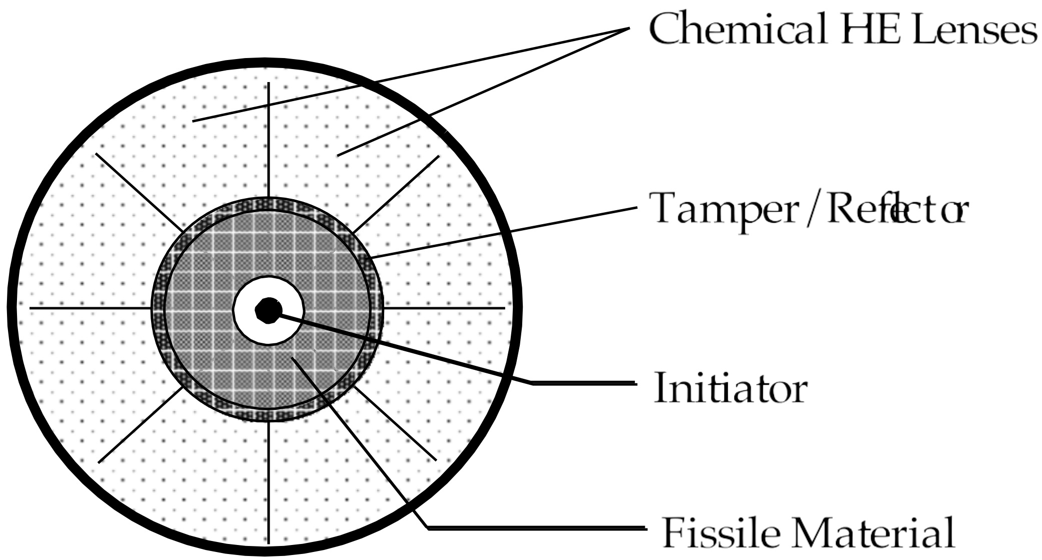
Add the HE lenses, initiator, and fusing and firings circuits (latter two parts not shown) —



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)

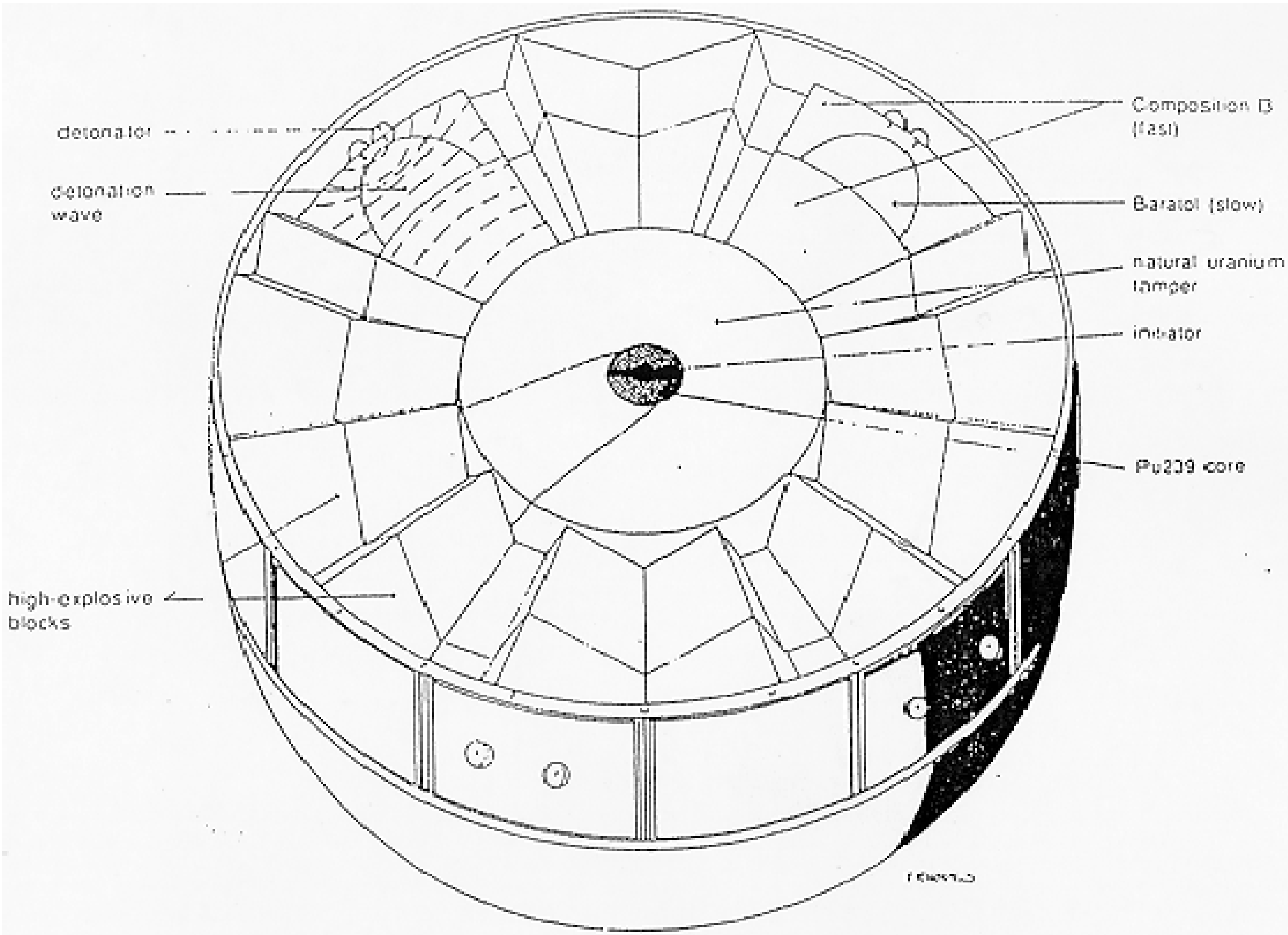
Fission Weapons – Implosion Type



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

Fission Weapons – Implosion Type

View of the interior of an implosion weapon



Initiators – 1

Example of a simple initiator —

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

    Po-218 → Pb-214 + α

    Po-216 → Pb-212 + α

    Po-210 → Pb-206 + α
  - —High probability nuclear reaction

    α + Li-7 → 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

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!

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.

Fusion Nuclear Reactions (Details)

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

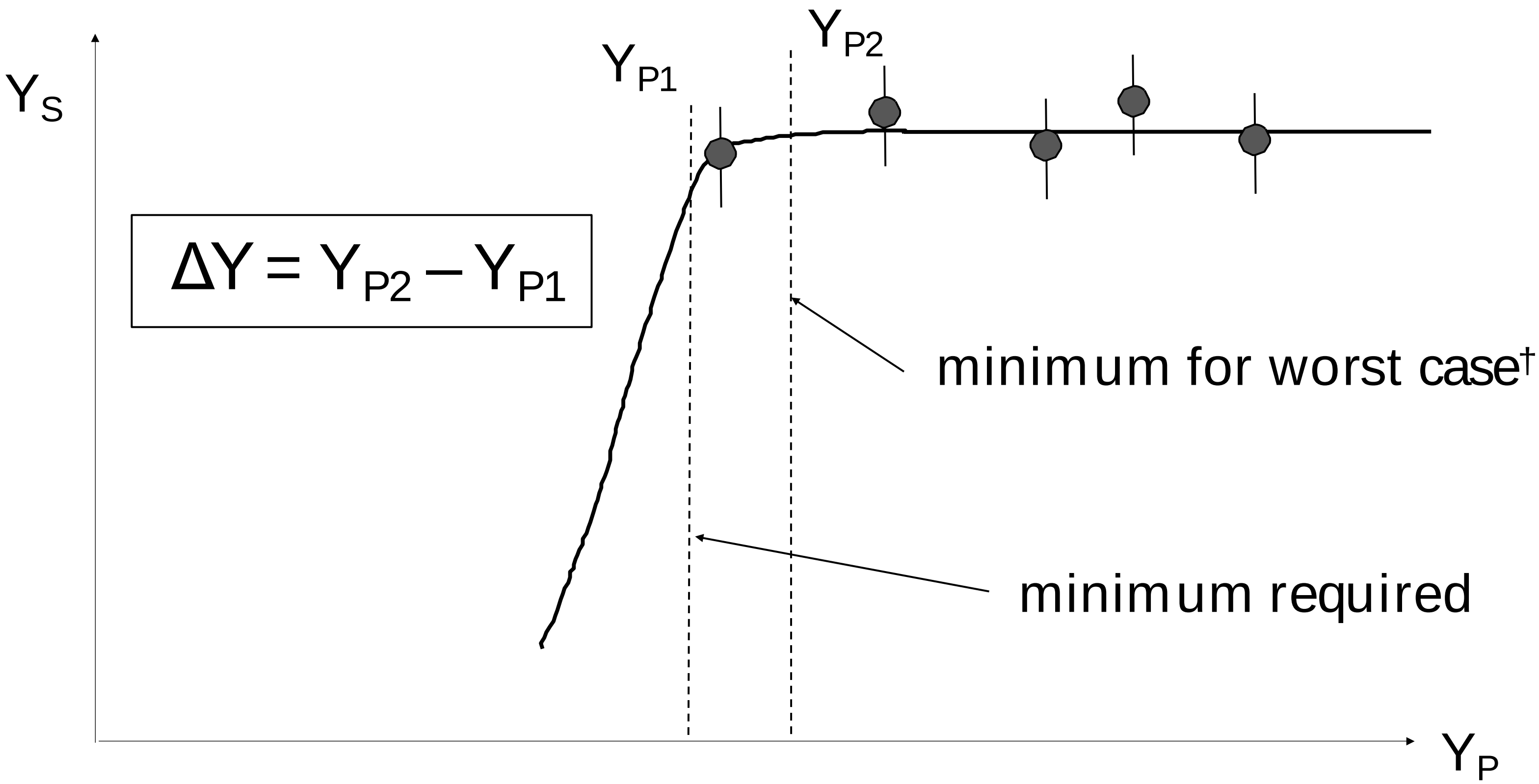
$$D + T \rightarrow {}^4He + n + 17.6 \text{ MeV (D-T fusion)}$$
$$n + {}^6Li \rightarrow {}^4He + T + 4.8 \text{ MeV (catalytic)}$$
$$D + D \rightarrow {}^3He + n + 3.2 \text{ MeV (catalytic)}$$
$$D + D \rightarrow {}^1H + T + 4.0 \text{ MeV (catalytic)}$$

- 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

True Thermonuclear Weapons

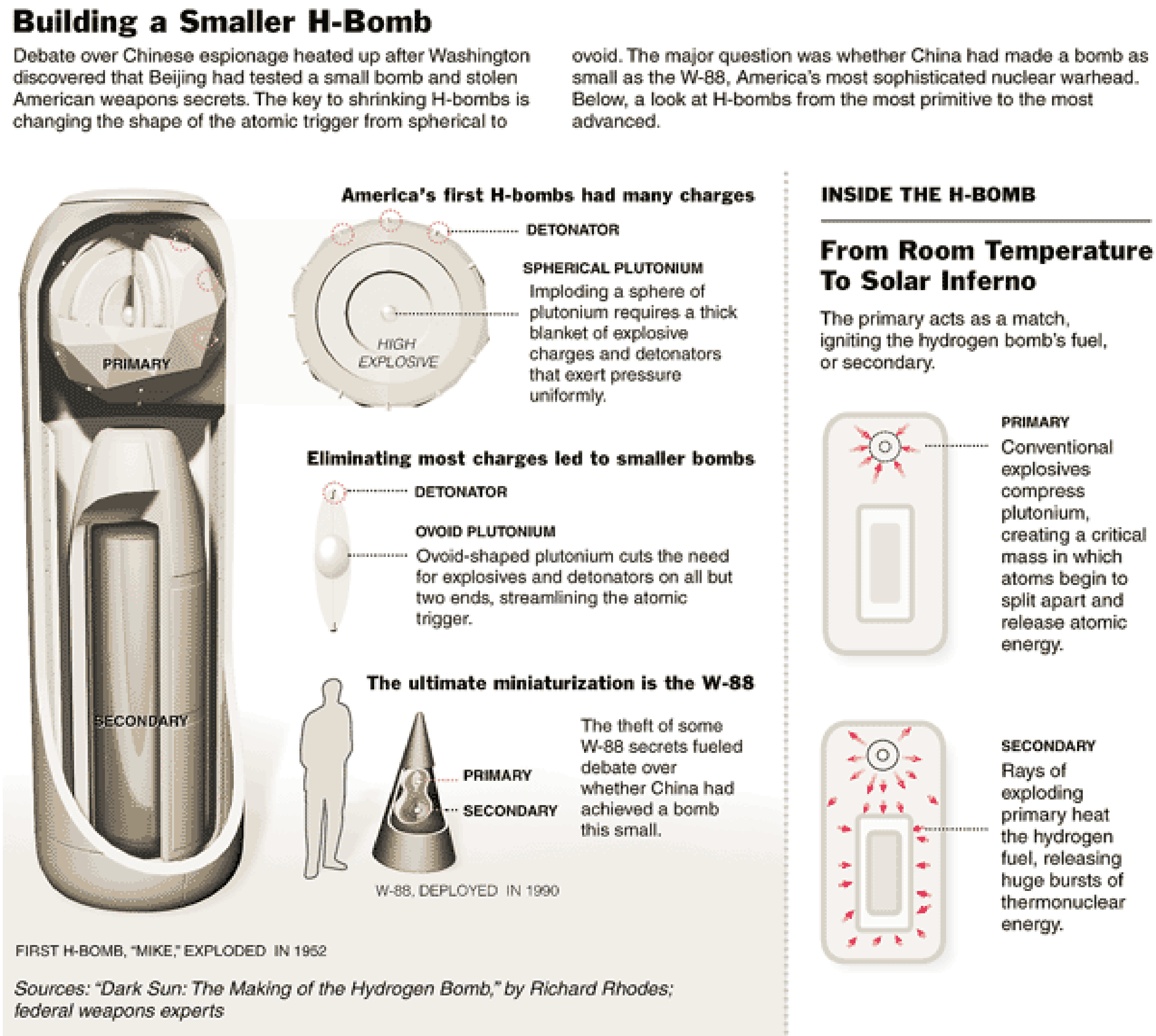
- Modern thermonuclear weapons have two stages: Primary (fission) and Secondary (fusion)
- The Mike device, the first US thermonuclear device, used liquefied D and T in the secondary
- All practical secondary designs use ^{6}Li-D
- Extra neutrons from the primary generate the initial T in the secondary 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

Primary Margin ΔY



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

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



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*

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.

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.

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

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.

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: β±

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

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

3. Gamma decay: γ

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

Four Types of Radioactive Decay (cont'd)

4. Spontaneous fission: fission products

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

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

$$ Z = Z_1 + Z_2 $$

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

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

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".*

Induced Fission

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

$$n + {}^{A}_{Z}T_{N} \rightarrow {}^{A_1}_{Z_1}\mathrm{X}_{\mathrm{N}_1} + {}^{A_2}_{Z2}\mathrm{Y}_{\mathrm{N}2} + \eta\,\mathrm{n} + \text{energy}$$

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

$$Z = Z_1 + Z_2,$$

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

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

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

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

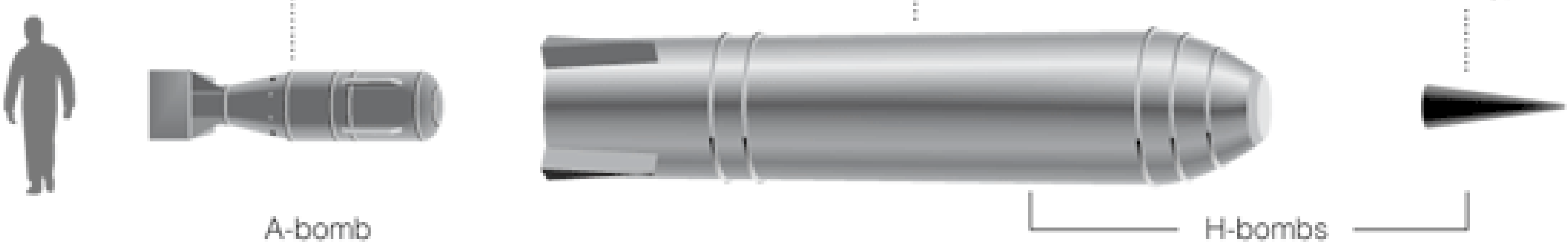
Miniaturizing Mass Destruction

Initially, nuclear devices grew in size along with their destructive power. As technology advanced, designers focused on trimming the warhead's dimensions, allowing multiple warheads to be carried by a single missile.

Little Boy *1940's*
Dropped on Hiroshima
Weight: 9,000 lbs.
Yield: 15 kilotons

B-17 *1950's*
Largest bomb deployed by U.S.
Weight:42,000 lbs.
Yield: 11 megatons
(as much as 1,000 times as powerful as Little Boy)

W-76 *1970's*
Some say it is the most abundant U.S. nuclear weapon
Weight: 362 lbs.
Yield: 100 kilotons
(7 times as powerful as Little Boy)



Source: GlobalSecurity.org

Relative scale is approximate.

The New York Times

Categories of Armed Conflict

International War: A large-scale armed conflict between the military forces of two or more States.

Pre-emptive War: A war initiated to disrupt an attack that is already underway or is imminent. Pre-emptive war is permissible under International Law only if (1) an attack is imminent and (2) there is no other way of preventing or stopping the attack, and (3) the pre-emptive action is proportionate to the threat.

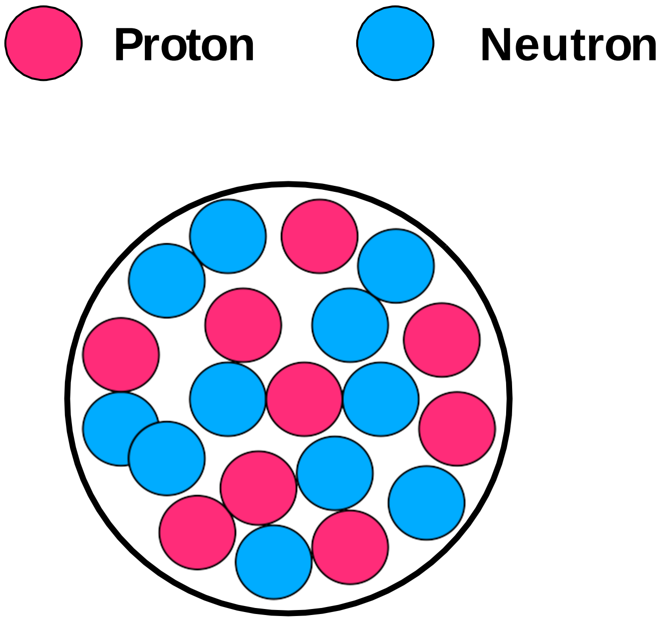
Preventive War: A war initiated in the absence of an imminent attack or without pursuing all other available means, with the goal of preventing an adversary from attacking at some future time. Such a war is a violation of International Law.

Note that the phrase “war on terror” is nonsensical, because an armed attack on an emotion (terror) is logically impossible. We will not use this term in Physics 280.

The phrase “war on terrorism” is also nonsensical, because an armed attack on a tactic (terrorism) is logically impossible. We will not use this term in Physics 280.

A “war on terrorists” would be a large-scale, sustained attack on terrorists by the military forces of a nation-state; while logically possible, it is not usually the most effective way to defeat terrorists.

Explanation of the Curve of Binding Energy



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 nuclear mass *M* and total binding energy B_T:

$$M(Z,N)c^2 = Zm_p c^2 + Nm_p c^2 - B_T$$

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

Nuclear Term **Electrical Term**

$$B_T > 0 \text{ for nucleus to be stable}$$

Eventually repulsion exceeds attraction: $B_T < 0$.

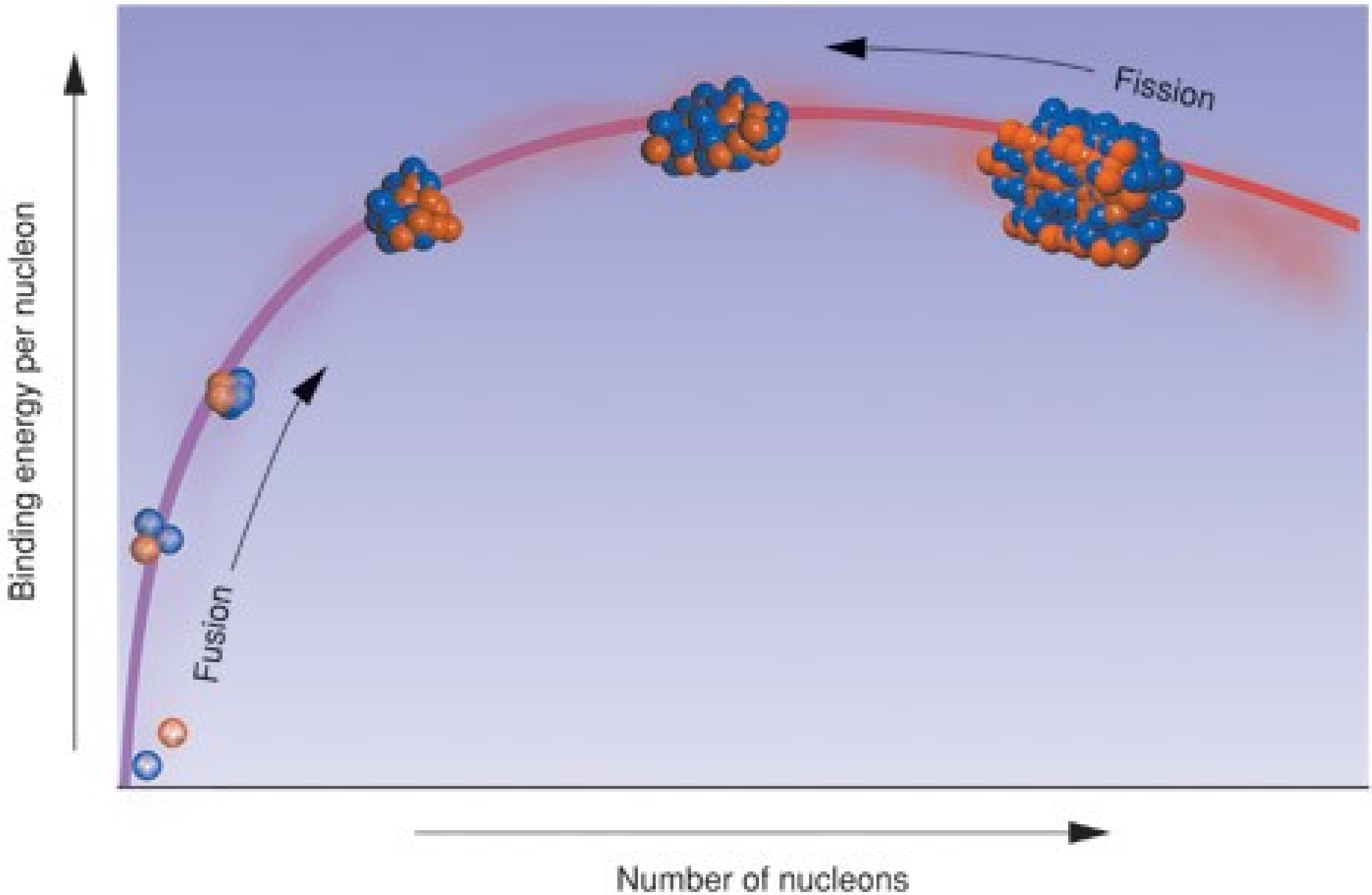
The Binding Energy Per Nucleon

- 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 —

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

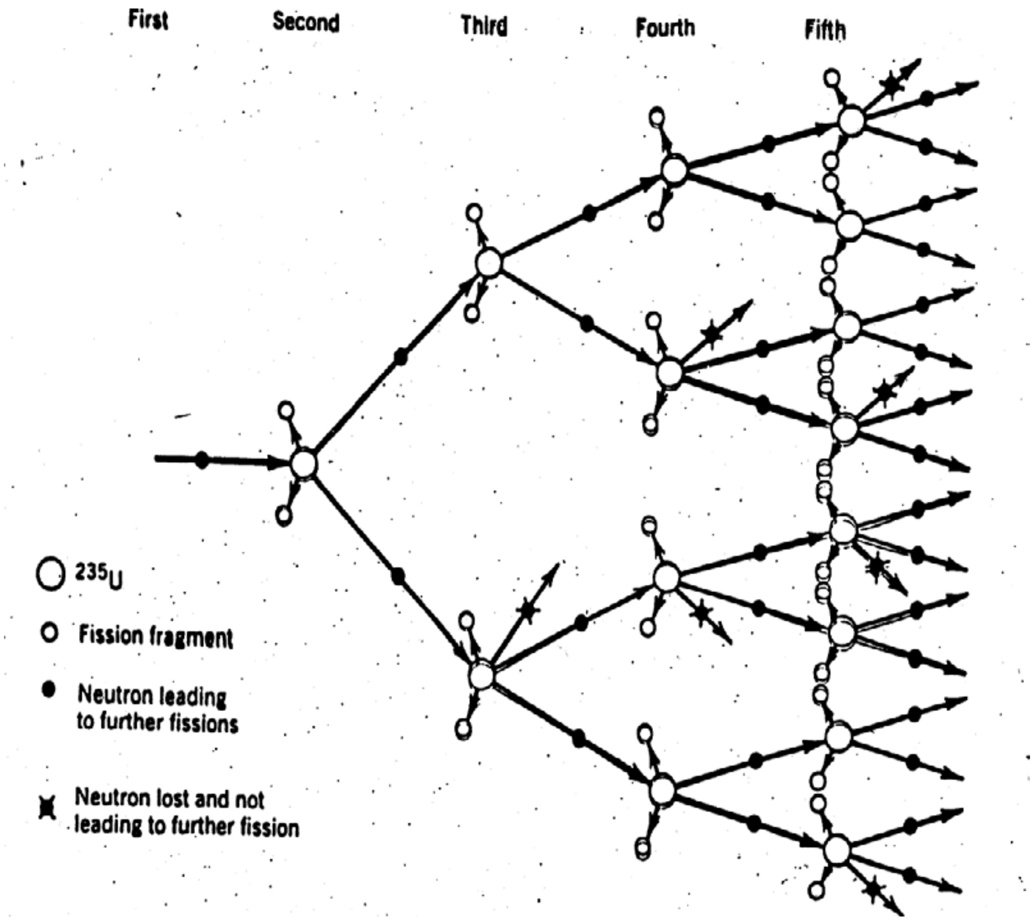
- The plot of *B* vs. *A* is called "the curve of the binding energy"

The Curve of Binding Energy (Important)

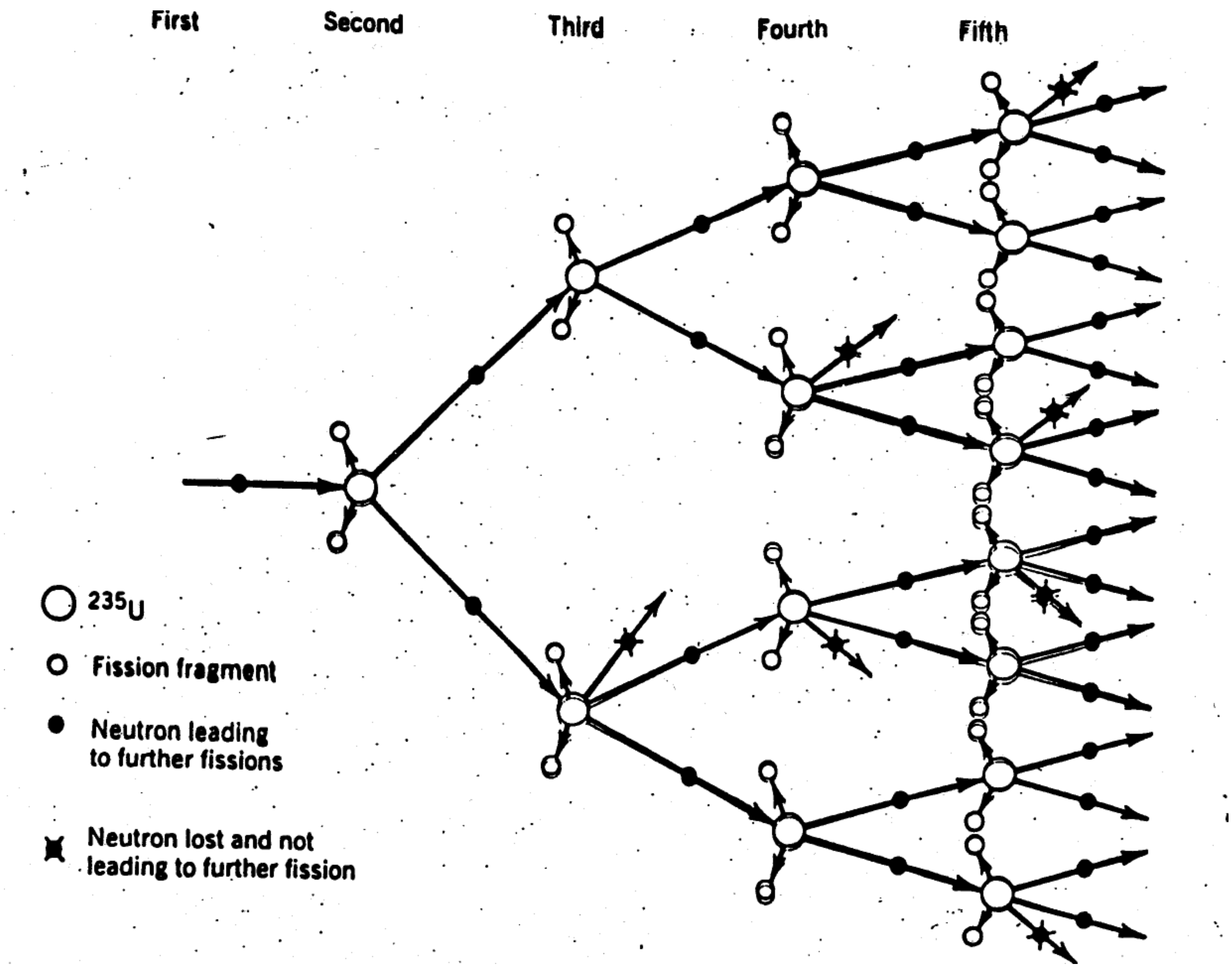


The Principle of a Nuclear Weapon

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.



Explosive Chain Reaction



[Mousetrap Demonstration]

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

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.

Types of Official Secrets

- Security secrets

  Example: thermonuclear weapon designs

- Diplomatic secrets

  Example: locations of certain overseas facilities

- Thoughtless secrets

  Example: information classified because it’s easy to do

- Political secrets

  Example: information that would undercut official policies or lies

- Embarrassing secrets

  Example: political or technical mistakes

- Silly secrets

  Example: well-known laws of physics

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.

News and Discussion

The Washington Post

Iran, perceiving threat from West, willing to attack on U.S. soil, U.S. intelligence report finds

By Greg Miller, Tuesday, January 31, 9:04 AM

U.S. intelligence agencies believe that Iran is prepared to launch terrorist attacks inside the United States in response to perceived threats from America and its allies, the U.S. spy chief said Tuesday.

News and Discussion

The New York Times

January 31, 2012

Intelligence Report Lists Iran and Cyberattacks as Leading Concerns

By ERIC SCHMITT

The comments by the official, James R. Clapper Jr., the director of national intelligence, in prepared testimony to the Senate Intelligence Committee, came as tensions between the United States and its allies with Iran over its nuclear program have escalated, with the United States trying to build support for increased sanctions against Iran.

Other intelligence officials indicated that while there was no evidence of other Iranian plots in the United States, Mr. Clapper's remarks were intended to put both the Iranians and the American intelligence community on notice that high priority would be given to ferreting out information about possible plans to stage attacks in this country.

News and Discussion

The written statement did not provide any details on what types of attacks Mr. Clapper thought were possible, and senators did not ask him about it during the panel's annual session to review global threats to the United States.

He reiterated the American intelligence assessment that "Iran is keeping open the option to develop nuclear weapons, in part by developing various nuclear capabilities that better position it to produce such weapons, should it choose to do so."

News and Discussion

FOREIGN AFFAIRS

Published by the Council on Foreign Relations

Time to Attack Iran

Why a Strike Is the Least Bad Option

By Matthew Kroenig

January/February 2012

Not Time to Attack Iran

Why War Should Be a Last Resort

By Colin H. Kahl

January 17, 2012

News and Discussion

The New York Times

Magazine

Will Israel Attack Iran?

Ronen Zvulun/Reuters

Ehud Barak, the Israeli defense minister, on right, with Prime Minister Benjamin Netanyahu.

By RONEN BERGMAN
Published: January 25, 2012