Physics/Global Studies 280: Session 3

Plan for This Session

Announcements

Questions

News

Module 2: Nuclear Weapons

Physics/Global Studies 280: Session 3

Announcements

(1) Deadline for electronic submission of RE1 is Wednesday at 10pm

(2) Reading assignment for today (could be subject to a pop quiz in Monday's writing lab!).

- Nuclear Policy and War Terms
- Essay: A More Effective Approach to US Security
- The Last Train from Hiroshima
- https://courses.physics.illinois.edu/phys280/sp2022/reading.html

(3) Office hours today: 5-6pm, Wednesday 1-4pm and 5-7pm!
- https://courses.physics.illinois.edu/phys280/sp2022/staff-info.html
  1-2pm and 6-7pm via zoom

News

World

Russia, China, Britain, U.S. and France say no one can win nuclear war

Reuters

News

MOSCOW/WASHINGTON, Jan 3 (Reuters) - China, Russia, Britain, the United States and France have agreed that a further spread of nuclear arms and a nuclear war should be avoided, according to a joint statement by the five nuclear powers published by the Kremlin on Monday.

It said that the five countries - which are the permanent members of the United Nations Security Council - consider it their primary responsibility to avoid war between the nuclear states and to reduce strategic risks, while aiming to work with all countries to create an atmosphere of security.

"We affirm that a nuclear war cannot be won and must never be fought," the English-language version of the statement read.

"As nuclear use would have far-reaching consequences, we also affirm that nuclear weapons — for as long as they continue to exist — should serve defensive purposes, deter aggression, and prevent war."

Chinese Vice Foreign Minister Ma Zhaoxu said the joint statement could help increase mutual trust and "replace competition among major powers with coordination and cooperation," adding that China has a "no first use" policy on nuclear weapons, state news agency Xinhua reported.

France also released the statement, underscoring that the five powers reiterated their determination for nuclear arms control and disarmament. They would continue bilateral and multilateral approaches to nuclear arms control, it said.

The statement from the so-called P5 group comes as bilateral relations between the United States and Moscow have fallen to their lowest point since the end of the Cold War, while relations between Washington and China are also at a low over a range of

News

The Pentagon in November sharply increased its estimate of China's projected nuclear weapons arsenal over the coming years, saying Beijing could have 700 warheads by 2027 and possibly 1,000 by 2030.
Washington has repeatedly urged China to join it and Russia in a new arms control treaty.
Geopolitical tensions between Moscow and Western countries have increased over concerns about Russia's military buildup near neighbouring Ukraine. Moscow says it can move its army around its own territory as it deems necessary.
Last Thursday U.S. President Joe Biden told his Russian counterpart, Vladimir Putin, that a possible move on Ukraine would draw sanctions and an increased U.S. presence in Europe.
U.S. and Russian officials will hold security talks on Jan. 10 to discuss concerns about their respective military activity and confront rising tensions over Ukraine, the two countries said.
A conference on a major nuclear treaty that was set to begin on Tuesday at the United Nations has been postponed until August due to the COVID-19 pandemic.
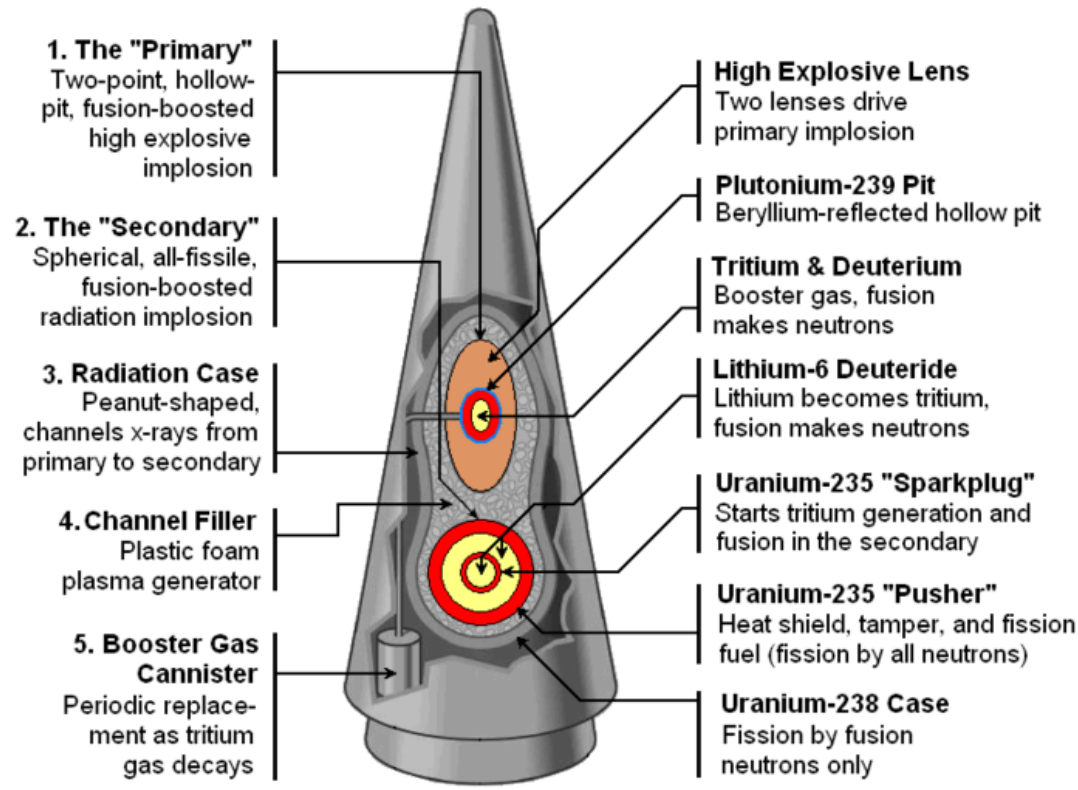
Physics/Global Studies 280

Module 2: Nuclear Weapons

Physics of Nuclear Weapons

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

W88 Warhead for Trident D-5 Ballistic Missile

1. The "Primary"
Two-point, hollow-pit, fusion-boosted high explosive implosion

2. The "Secondary"
Spherical, all-fissile, fusion-boosted radiation implosion

3. Radiation Case
Peanut-shaped, channels x-rays from primary to secondary

4. Channel Filler
Plastic foam plasma generator

5. Booster Gas Cannister
Periodic replacement as tritium gas decays

High Explosive Lens
Two lenses drive primary implosion

Plutonium-239 Pit
Beryllium-reflected hollow pit

Tritium & Deuterium
Booster gas, fusion makes neutrons

Lithium-6 Deuteride
Lithium becomes tritium, fusion makes neutrons

Uranium-235 "Sparkplug"
Starts tritium generation and fusion in the secondary

Uranium-235 "Pusher"
Heat shield, tamper, and fission fuel (fission by all neutrons)

Uranium-238 Case
Fission by fusion neutrons only

Physics of Nuclear Weapons

A basic understanding of the nuclear physics and design of nuclear weapons is helpful in developing 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?

- What are status and costs for missile defense programs?

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 concerned. This is by far the most technical part of the course. We will not use math!

It's important to know about this material, and the remainder of the course will be far less technical.

Physics of Nuclear Weapons

Atoms and Nuclei

Atomic Nature of Matter

6 protons
+ 6 neutrons

- electron
+ proton
- neutron

Carbon atom

- All matter on earth 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: quarks (this fact is unimportant for nuclear weapons)
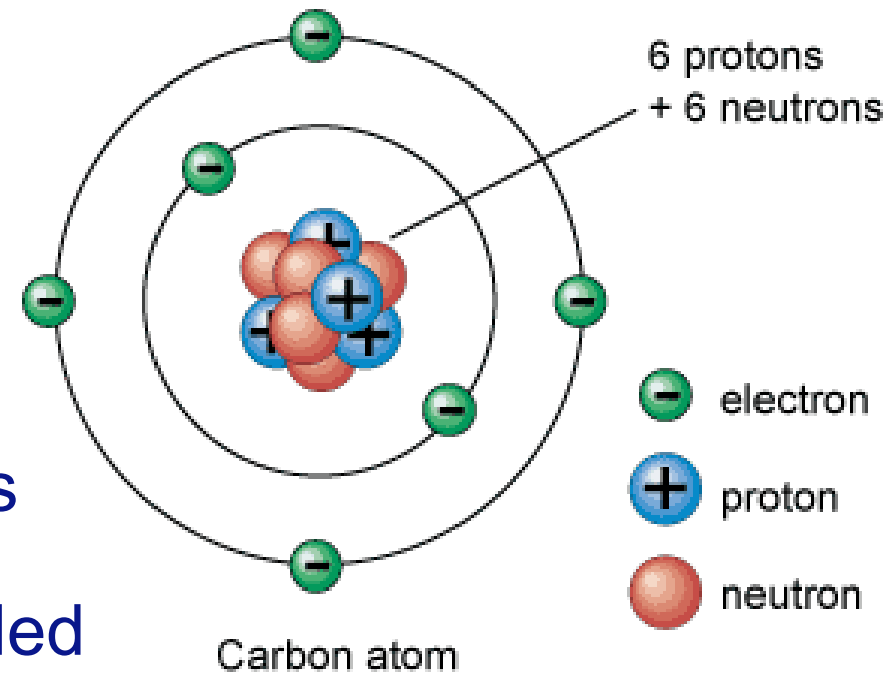
Fundamental Forces of Nature – 1

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

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

- Always attractive, weakest but first to be discovered

- Strength decreases as $1/r^2$ ("long-range", r -> distance between objects)
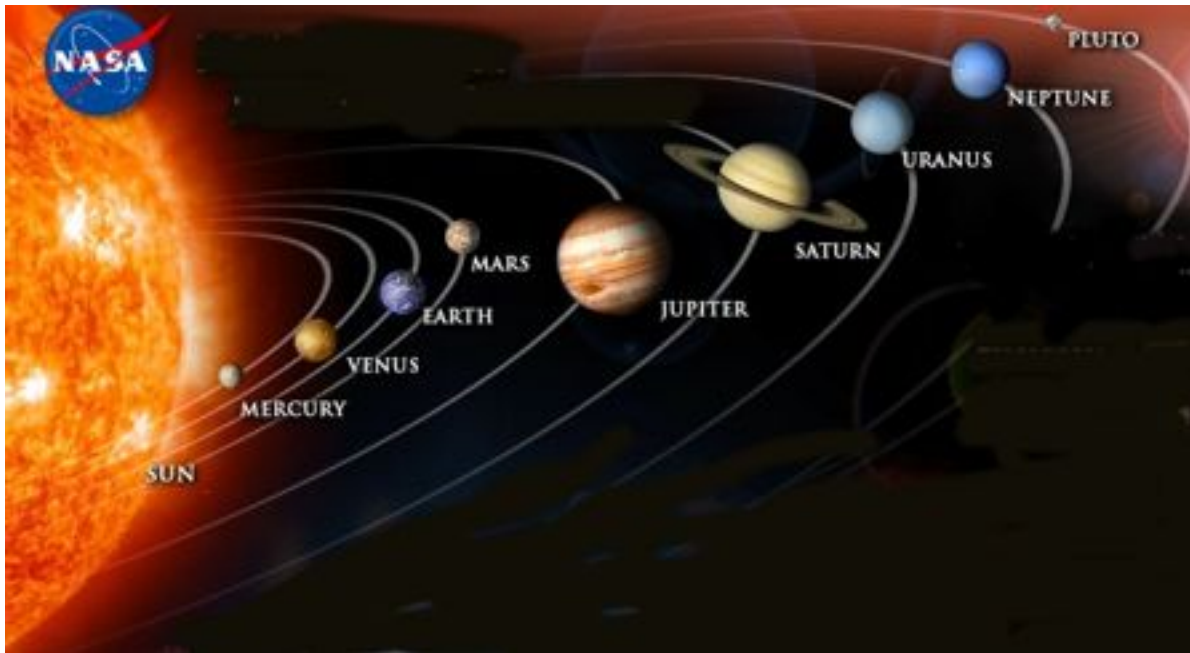
Gravity:
Relative Strength

10^{-41}

Fundamental Forces of Nature – 2

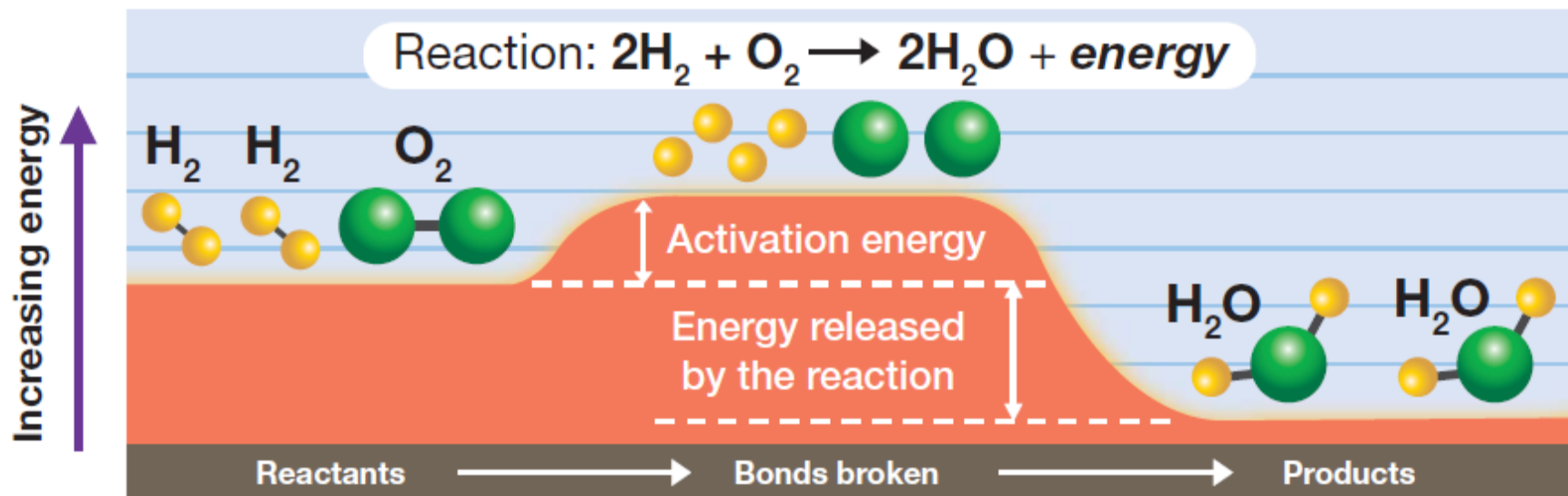**2. Electromagnetic force** (structure of atoms and molecules)

- Can be attractive or repulsive

- Classical electrical force decreases as $1/r^2$ ("long-range")

- Described by the theory of electromagnetism, developed in the late 19th Century

- The quantum theory of electromagnetism is called Quantum Electrodynamics
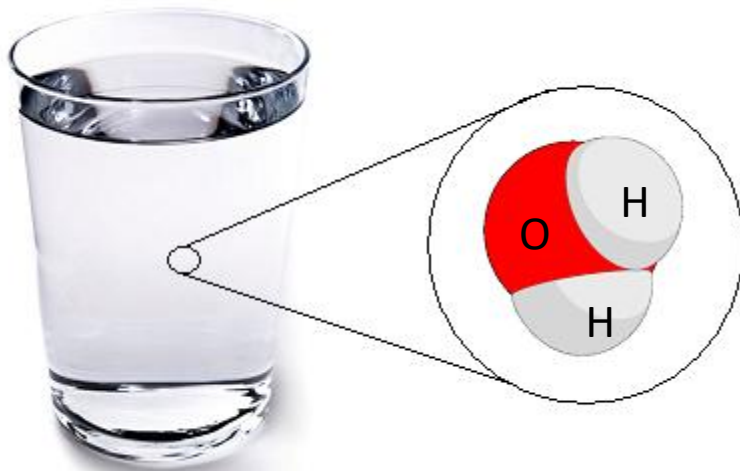
Electromagnetic Force
Relative Strength

1

O
H
H
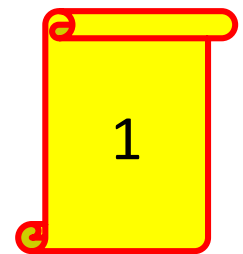
Energy Released by Electromagnetic Reactions between Atoms and Molecules

Reaction: $2H_2 + O_2 \rightarrow 2H_2O + energy$

Increasing energy

H_2 H_2 O_2

Activation energy

Energy released by the reaction

H_2O H_2O

Reactants → Bonds broken → Products

We use electromagnetic energy from chemical bounds frequently:

wood fire
car engine
coal electrical power plant
explosives

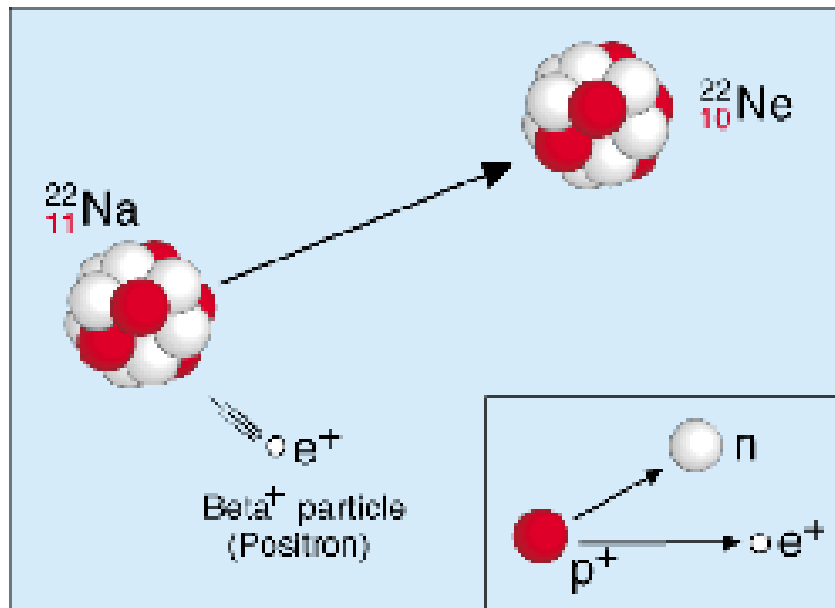# Fundamental Forces of Nature – 3

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

Radioactive Decay of a Sodium Nucleus into a
Neon Nucleus (used in PET scanners in hospitals)

Weak Nuclear Force:
Relative Strength

10^{-7}

Fundamental Forces of Nature – 4

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

- The strongest known force, it holds protons and neutrons together in the atomic nucleus

- 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
- Nuclear binding energies are about 1,000,000 times larger compared to atomic binding energies
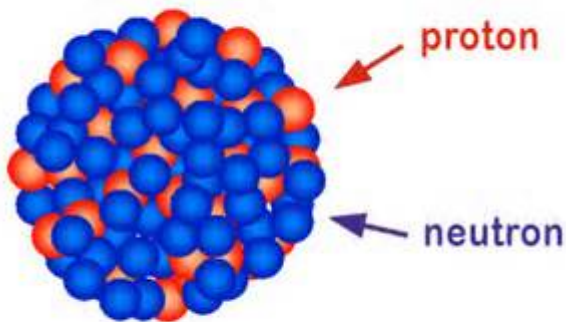
proton

neutron

Uranium Nucleus

Strong force binds 235 protons and neutron into the large Uranium-235 nucleus

Strong Nuclear Force Relative Strength

100
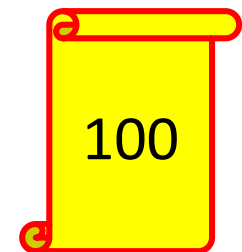
Annual US Electricity Consumption:

How much coal or uranium fuel would be needed to generate the annual electricity consumed in the US?

About 2,200,000,000 tons of coal or 220 Million truck loads

➔ energy taken from electromagnetic force fields in chemical bounds

About 5,000 tons of Uranium fuel or 500 truck loads

➔ energy taken from nuclear force fields inside nuclei

"Nuclear fire" burns ~ 1 million times hotter than "chemical fire"

Fundamental Forces of Nature – Summary

Luke, the Force is Strong with you …

… yeah, all four!

…
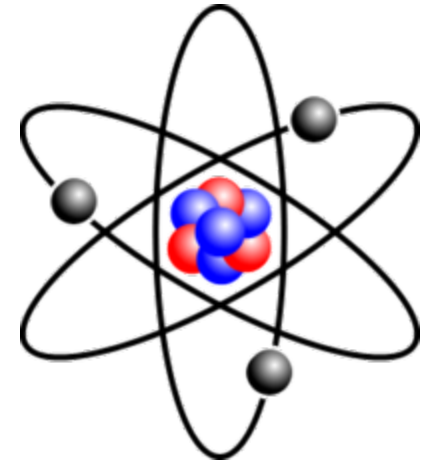
Gravitation keeps me on the ground

…

Electromagnetism holds my Molecules and atoms together.

…

The strong force forms nuclei and the weak force makes them decay.

Atoms and Nuclei

Sizes of atoms and nuclei

- The size of an *atom* is defined by the extent of its electron cloud : ~ 10^{-10} m

- The size of a *nucleus* is defined by the size of a nucleon ~ 10^{-15} m and the number of nucleons it contains.
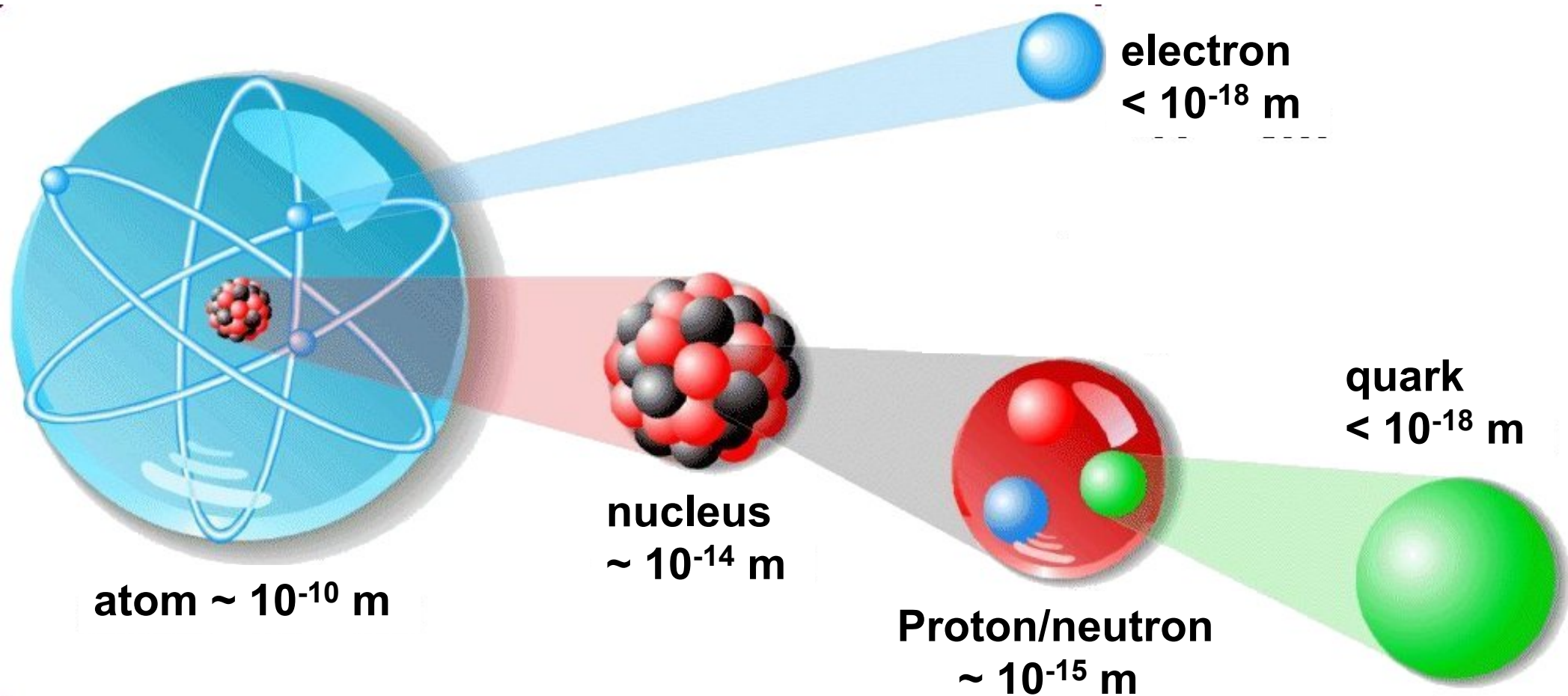
$$\textit{Size of an Atom: } r_{atom} \approx 10^{-10} \text{m} = 0.1 \text{ nm}$$
$$\textit{Size of a nucleus} : r_{nucleus} \approx 10^{-14} \text{m} = 0.0001 \text{ nm} ,$$

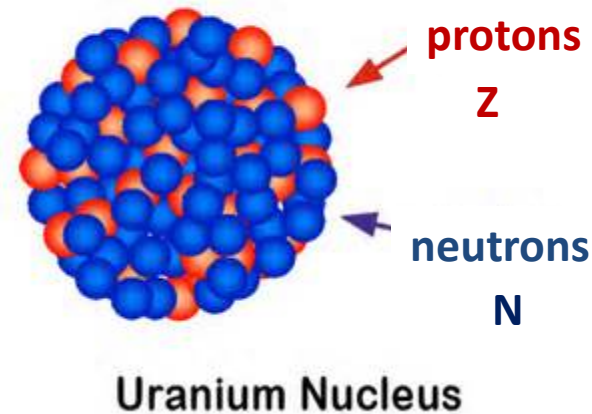$$1.0 \text{ nm} = 1 \text{ billionth of a meter}$$

Masses of Protons and Neutrons compared to Electrons

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

Atomic Structure and Length Scales

electron
< 10^{-18} m

quark
< 10^{-18} m

nucleus
~ 10^{-14} m

atom ~ 10^{-10} m

Proton/neutron
~ 10^{-15} m

Atomic Nuclei

protons
Z

neutrons
N

Uranium Nucleus

- A given 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.

- **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.

Plan for This Session

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Module 2: Nuclear Weapons

Announcements

(1) Please turn in paper copy on table upfront in class room

(2) Reading assignment this week (could be subject to a pop quiz in Monday's writing lab!).

- Nuclear Policy and War Terms
- Essay: A More Effective Approach to US Security
- The Last Train from Hiroshima
- https://courses.physics.illinois.edu/phys280/sp2022/reading.html

(3) TopHat: Please let me know if you did not receive an invite!

The New York Times | https://www.nytimes.com/2022/01/25/world/asia/north-korea-launches-missiles-kim.html

Why Is North Korea Suddenly Launching So Many Missiles?

Experience has shown Kim Jong-un that saber-rattling is the best way to get Washington's attention, especially when global affairs are already in a precarious state.

By Choe Sang-Hun

Jan. 25, 2022

SEOUL — North Korea began the new year by convening a meeting for the ruling Workers' Party during which very little was said about the United States. That ominous silence didn't last long.

Kim Jong-un, the country's ruler, has launched six ballistic missiles in four weapons tests since Jan. 5, almost as many missiles in one month as North Korea launched in all of last year. On Tuesday, the South Korean military confirmed that the North had fired two cruise missiles in its fifth test of 2022.

The message was clear: The North Korean leader feels he is being ignored and wants to push the Biden administration to re-engage and pay attention to his economically ailing nation.

Individually, the tests may not amount to much — they involved missiles that have already been tested or weapons that are still under development. But taken together, they signal that Mr. Kim plans to use 2022 to jolt the Biden administration out of its diplomatic slumber.

Mr. Kim needs Washington to engage with him on economic concessions so that he can fix his country's devastated economy. Over the years, he has learned that the best way to grab the attention of an American president is with weapons. And that the best time to do it is when the world can least afford the instability.

According to that playbook, 2022 looks like a promising year.

China is busy preparing for the Beijing Olympics next month. South Korea elects a new president in March. Russia has hinted at a potential invasion of Ukraine, keeping the Biden administration on tenterhooks.

During a Politburo meeting last Wednesday, Mr. Kim suggested that his government might once again begin testing long-range missiles and nuclear devices after suspending such tests before his 2018 summit meeting with President Donald J. Trump.

News

"2022 calls for continued saber-rattling, punctuated by some major missile tests," said Lee Sung-yoon, a North Korea expert at the Fletcher School at Tufts University. "Kim's goal is to routinize short-range ballistic missile flights as a fact of life without any repercussions, after which he will move on to bigger provocations by resuming intermediate- and long-range missile tests punctuated by a nuclear test, as he did in 2017."

That year, North Korea tested what it called a hydrogen bomb and also launched three intercontinental ballistic missiles. It was also the year Mr. Trump took office after a vicious campaign in the United States. South Korea had just impeached its president.

Wednesday was the second time Mr. Kim threatened to lift the moratorium on long-range missile and nuclear tests. After his diplomacy with Mr. Trump ended without an agreement in 2019, he said he no longer felt bound by the commitment. But he did not follow through with any such tests, and his country was soon plunged into the chaos of the coronavirus pandemic.

Kim Jong-un, the leader or North Korea, attending a meeting at the office building of the Party Central Committee, in Pyongyang last week. Korean Central News Agency, via Agence France-Presse — Getty Images

Atoms with Different Nuclei:
Isotopes and Isotones

protons
Z

neutrons
N

Uranium Nucleus
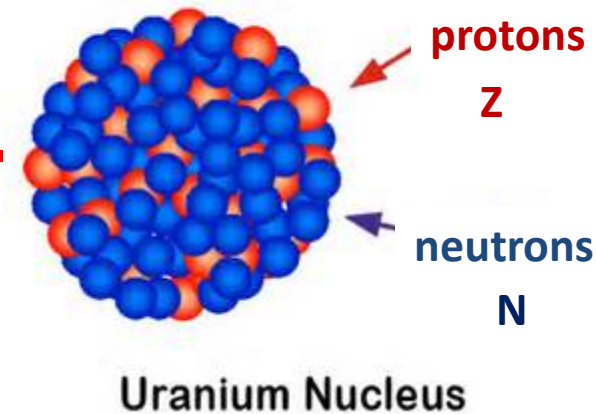
Several notations are in common use for nuclides –

$$^A X = {}^A_Z X_N = {}^A X_Z = X(A)$$

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

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 element (Z = 1)

- Every naturally occurring element beyond Bismuth (Z = 83) has only unstable isotopes

- Uranium (U) is the heaviest element (Z = 92)

- Only 91 elements are found in nature because the element Technetium (Z = 43) decays quickly and is not found in nature.

- Over 20 *transuranic* (Z > 92) elements have been created in the laboratory; all their isotopes are unstable

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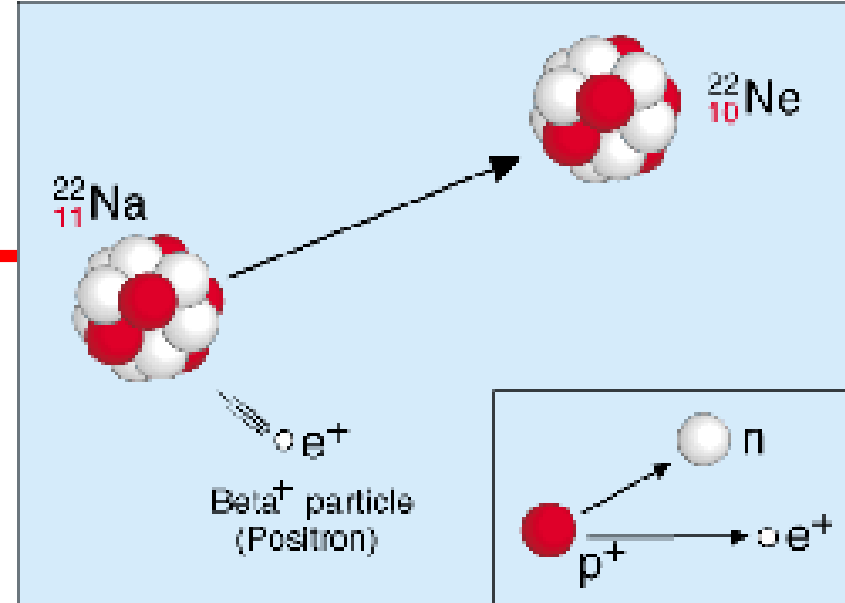
Radioactivity is a *spontaneous* process in which one nuclide changes into another, either a different isotope of the original chemical element or a different chemical element, *without any outside influence*.

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* т$_{1/2}$ or, equivalently, its *mean life* = 1.44 т$_{1/2}$

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)

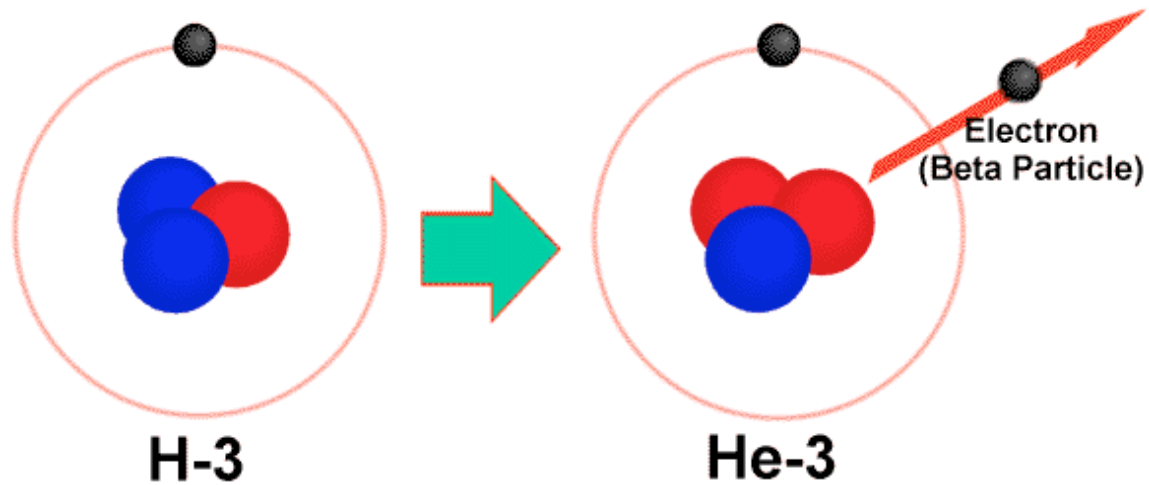*3. Gamma decay*

      Parent —> Daughter + gamma-ray

4. Spontaneous fission

# Illustration of Alpha Decay
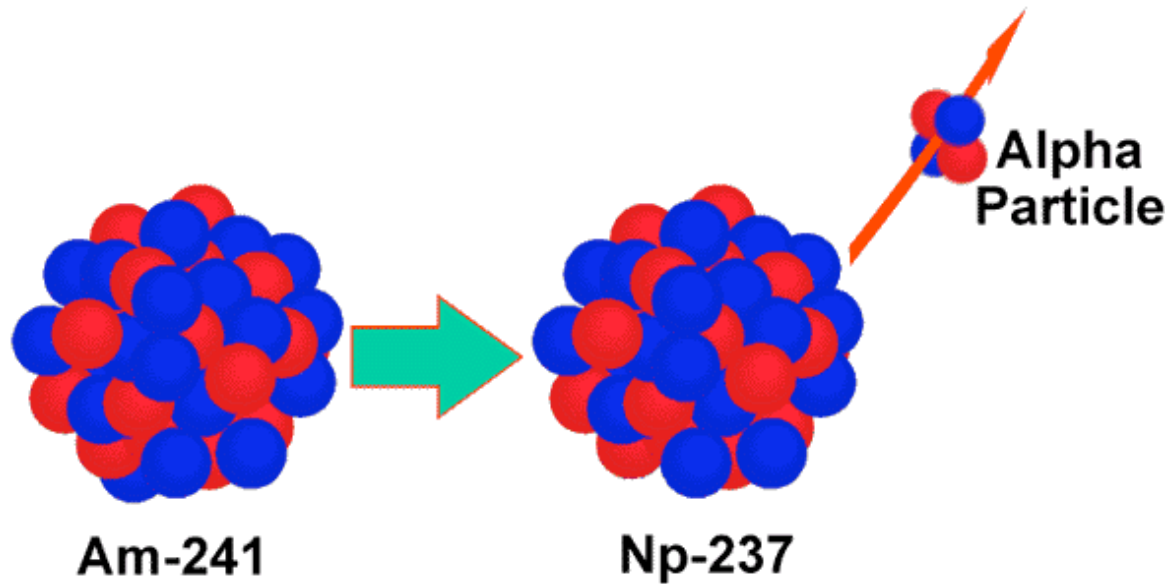
Americium as 95 protons and 136 neutrons

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

Illustration of Negative Beta Decay (Electron Emission)


H-3 → He-3

Electron (Beta Particle)

Tritium is a hydrogen isotope and decays into He-3, a helium isotope
Negative Beta Decay increases Z !

Illustration of Positive Beta Decay (Positron Emission)

C-11   →   B-11   + Positron
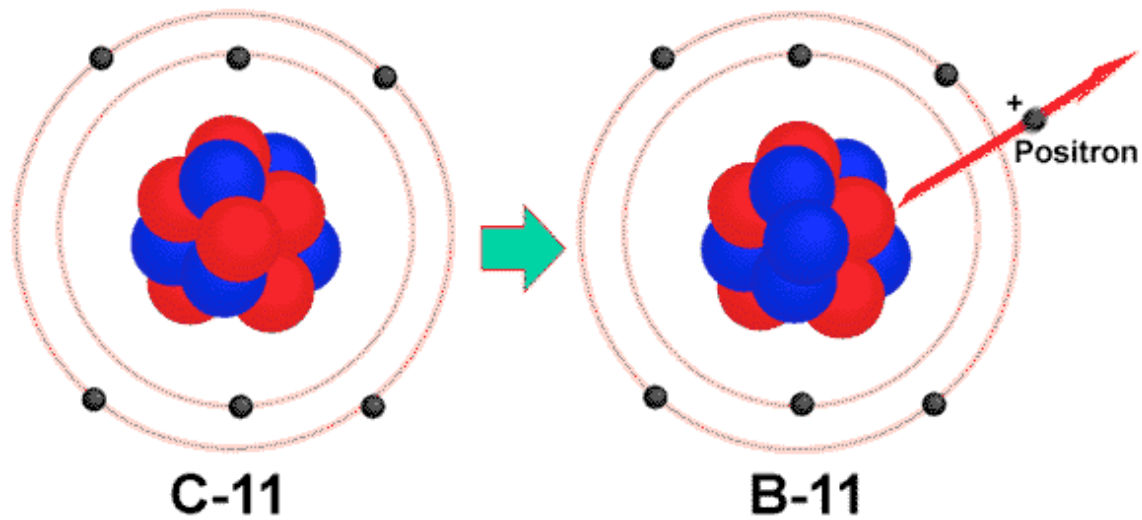
The positron from a positive beta decay is the anti-particle to the electron!
Positive Beta Decay decreases Z !

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

ring of Photon detectors

dec...
pos...
emis...

γ

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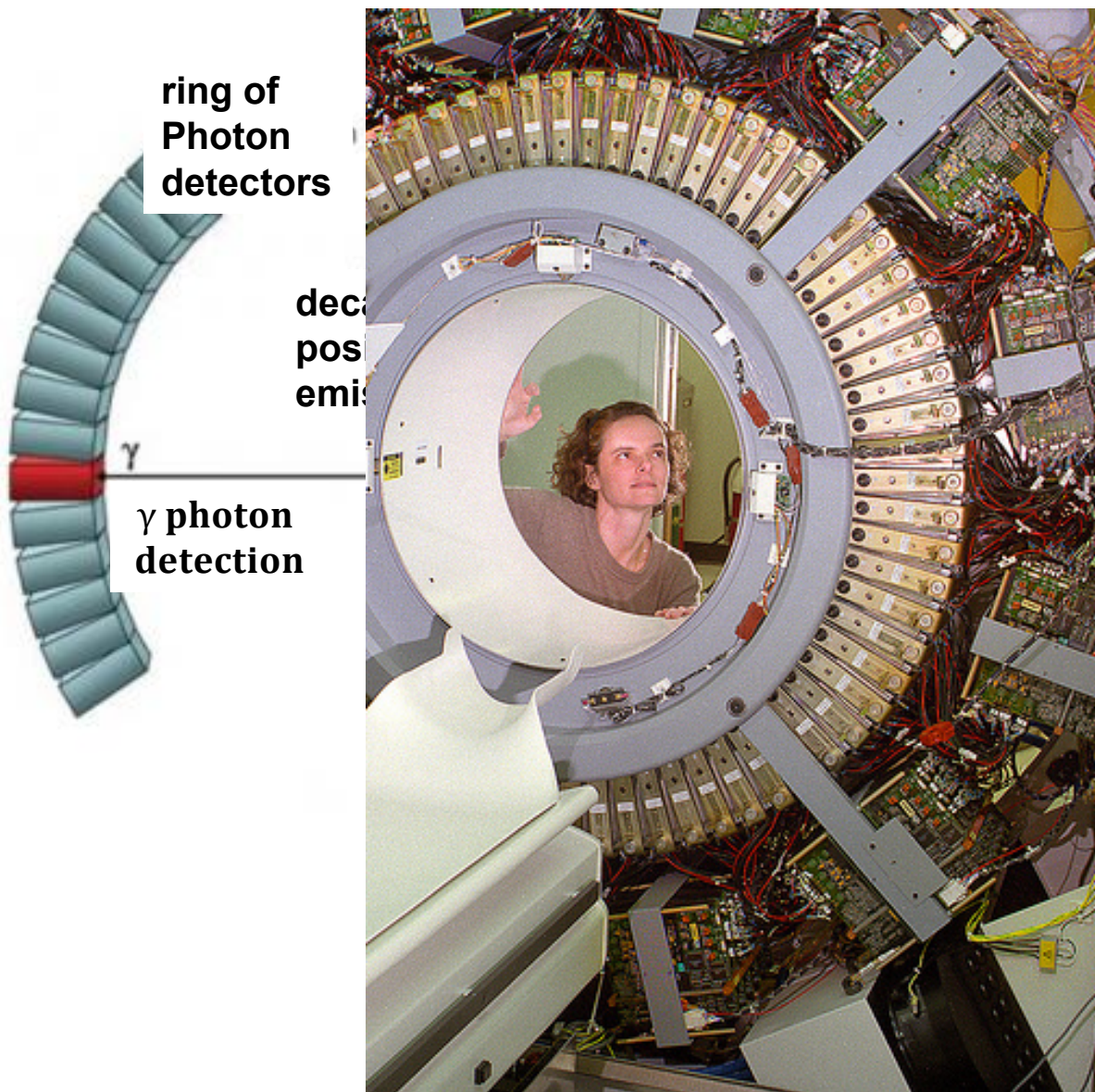
Positron emitting radioactive isotopes and gamma rays from Electron-positron annihilation are used for medical imaging

Normal

Parkinson

Pre
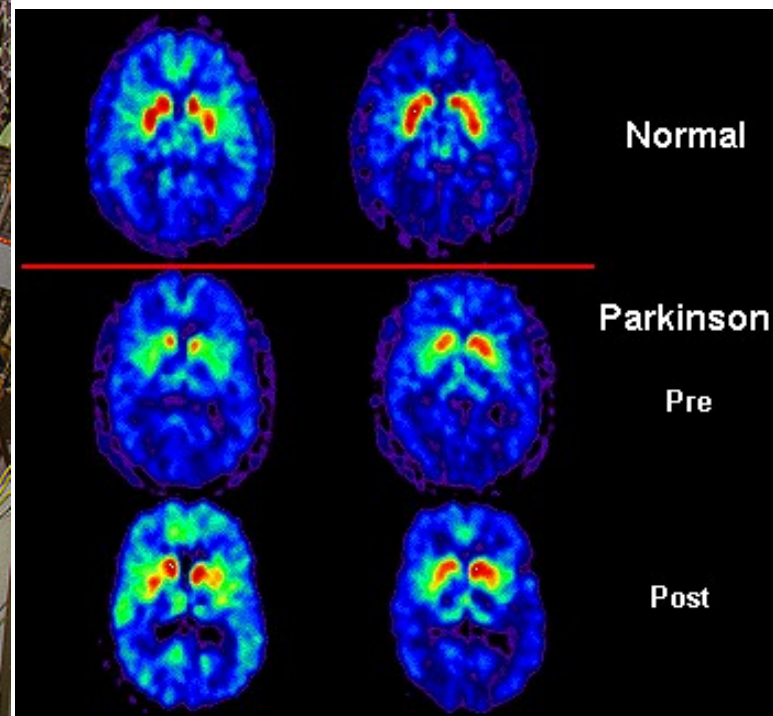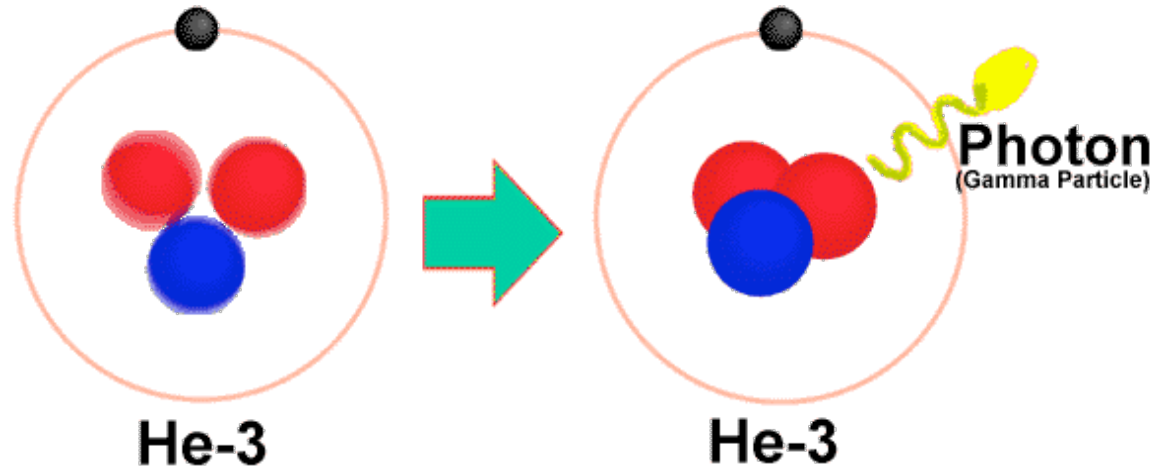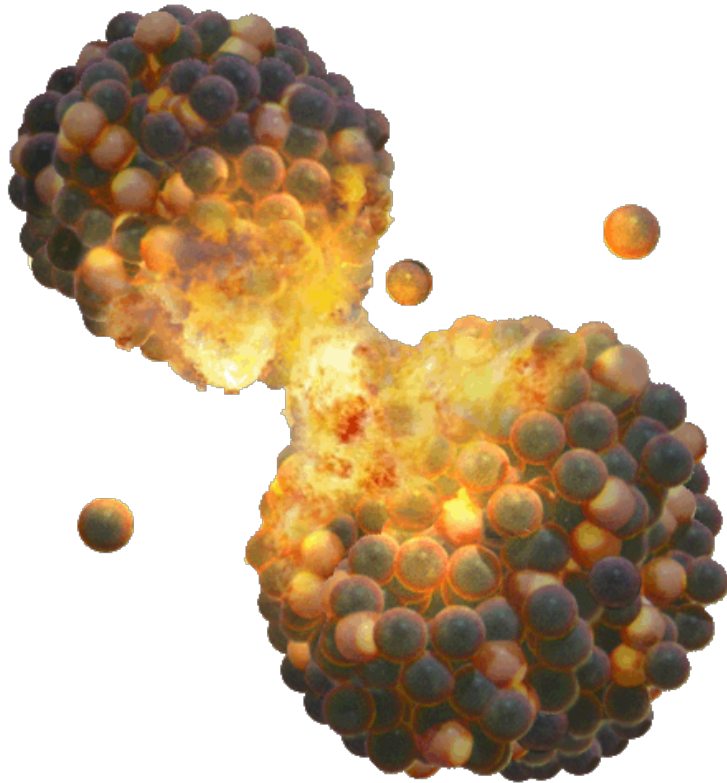
Post

Illustration of Gamma-Ray Emission

He-3 → He-3 + Photon (Gamma Particle)

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

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

Fission: a large nucleus splits into two daughter nuclei. In the process a small number of neutrons are emitted.

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-radiation)

- Energy is released in the form of kinetic energy of the products and as excitation energy of the (radioactive) fission fragments
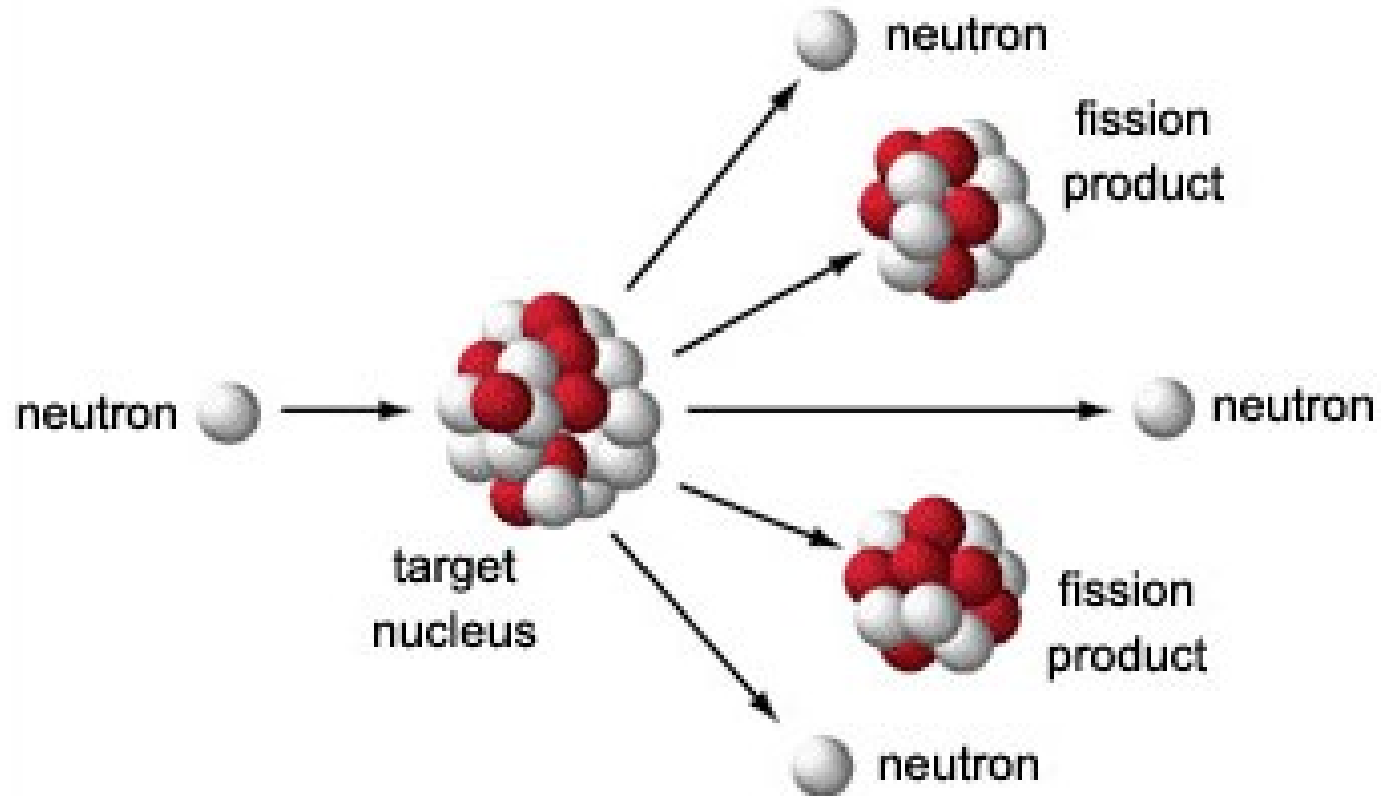
Induced fission —

- 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

Illustration of Spontaneous Fission
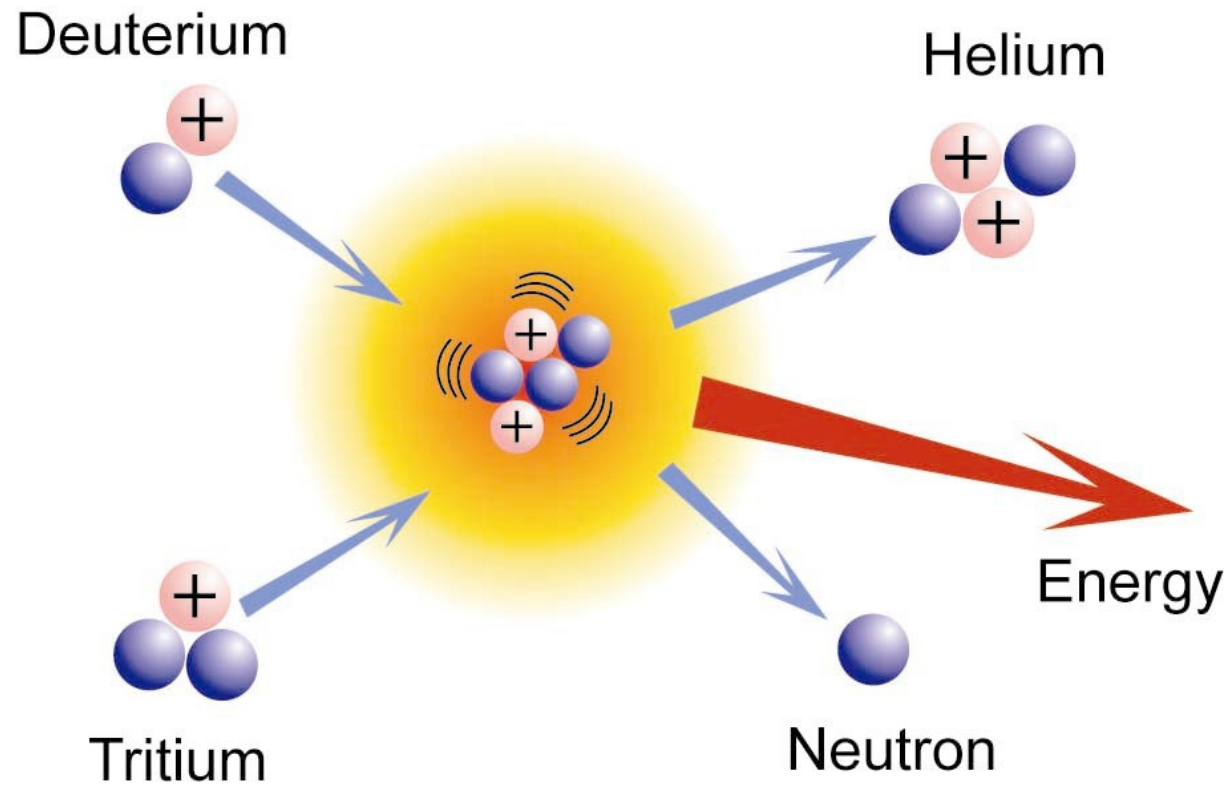## of a Californium, Cf-252 Nucleus
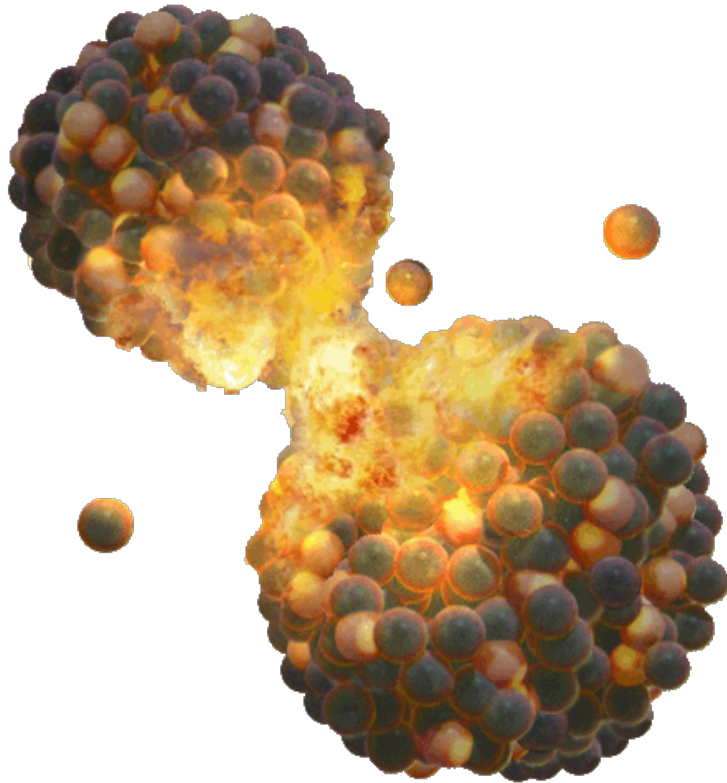
Fission: a large nucleus splits into two daughter nuclei. In the process a small number of neutrons are emitted.

Induced Fission

Fusion

Deuterium

Tritium
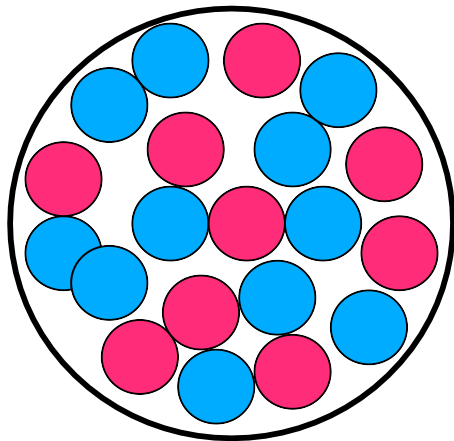
Helium

Neutron

Energy

Why can both, Fission and Fusion
Reactions Yield Energy ?

Deuterium

Helium

Tritium

Fusion

Neutron

Energy

Fission

neutron

fission product

neutron

neutron

target nucleus

fission product

neutron

Binding Energy of Nucleons in a Nucleus

Proton (red circle)   **Neutron** (blue circle)
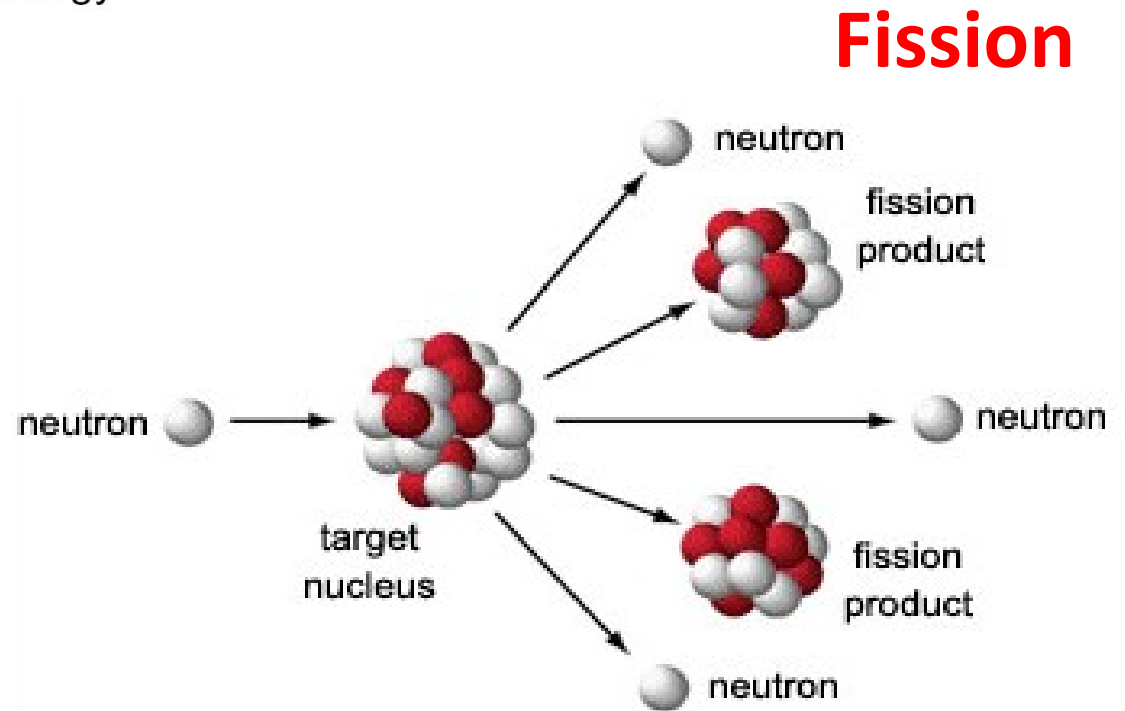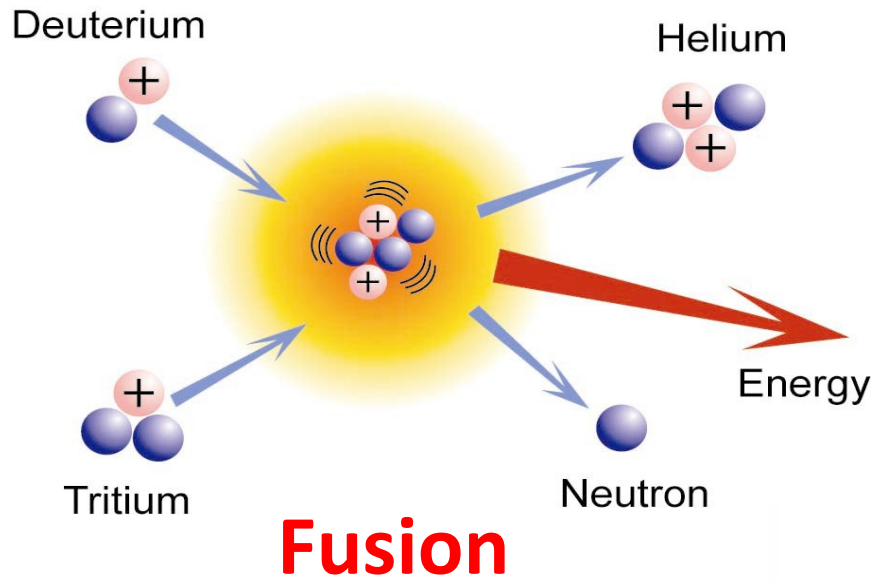
(1) Attractive nuclear force between nearest neighbor nucleons (short range)

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

Nucleus: _N, Z_

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 —

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

- A graph of *B (binding energy)* vs. *A (atomic weight)* 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.

The Curve of Binding Energy (Important)
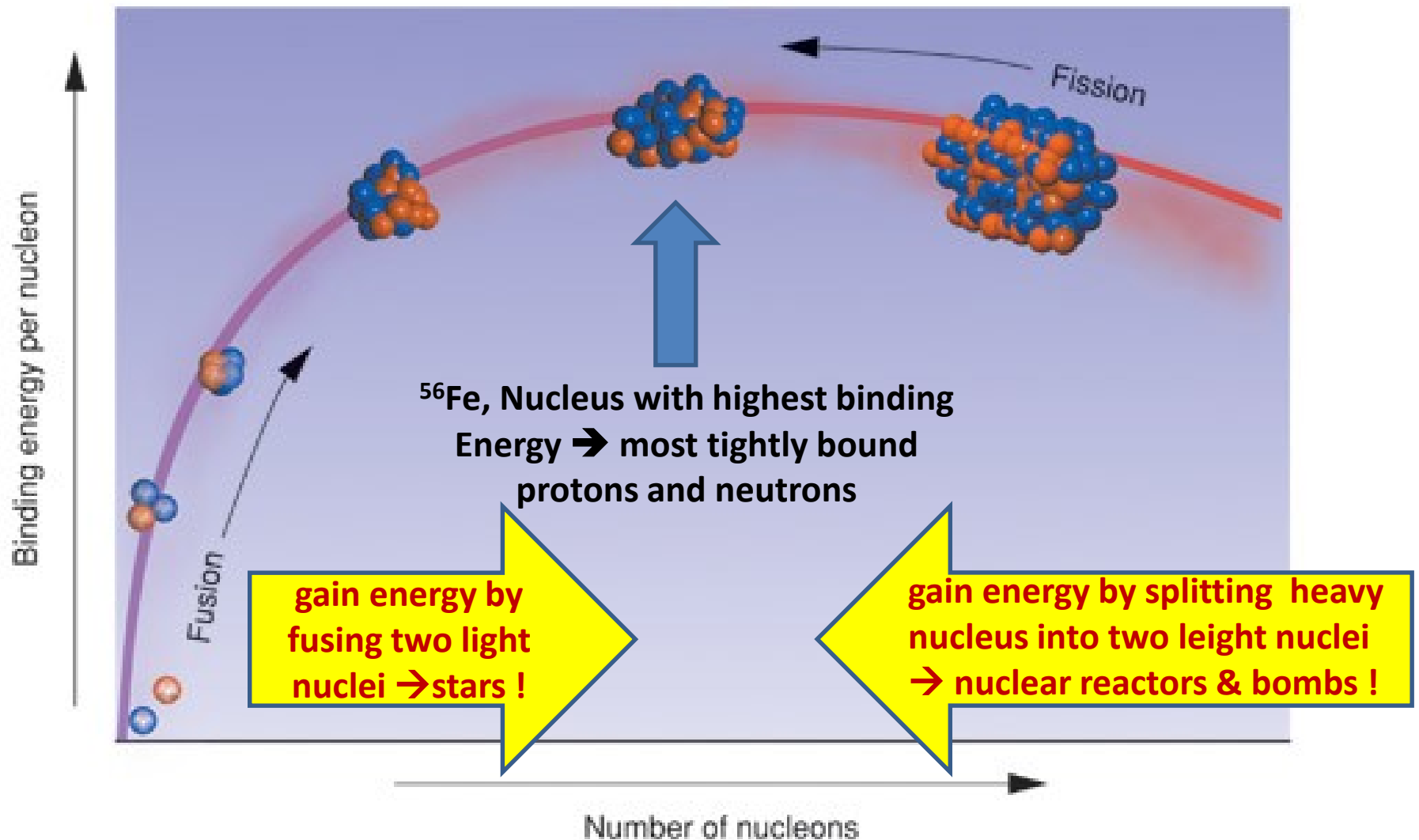
Nuclides Important for Fission Bombs

Heavy elements (high Z) —

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

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

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

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

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

$$^{240}_{94}Pu = Pu(240) \quad **$$
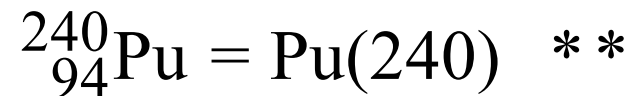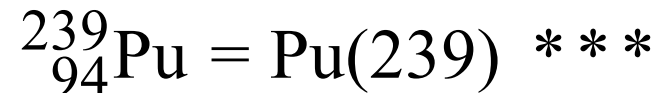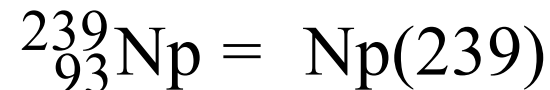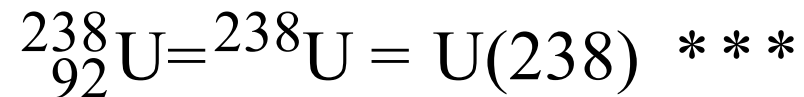
*, **, *** denotes increasing importance

Nuclides Important for Fusion Bombs

Light elements (low Z) —

^1_1H = P (proton)

^2_1H = D (deuteron), stable ***

^3_1H = T (triton), unstable   ***

^4_2He = He(4) = α (alpha particle), very stable

^3_2He = He(3) , stable (indirectly relevant to NWs) *

^6_3Li = Li(6) , stable   **

^7_3Li = Li(7), stable (no relevance to NWs)

^9_4Be = Be(9) stable (lighest metal) *

*, **, *** denotes increasing importance

The Neutron –
Similar to Proton but without Electric Charge

- 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

Initial State

Final State

Z, N

Z, N+1

n
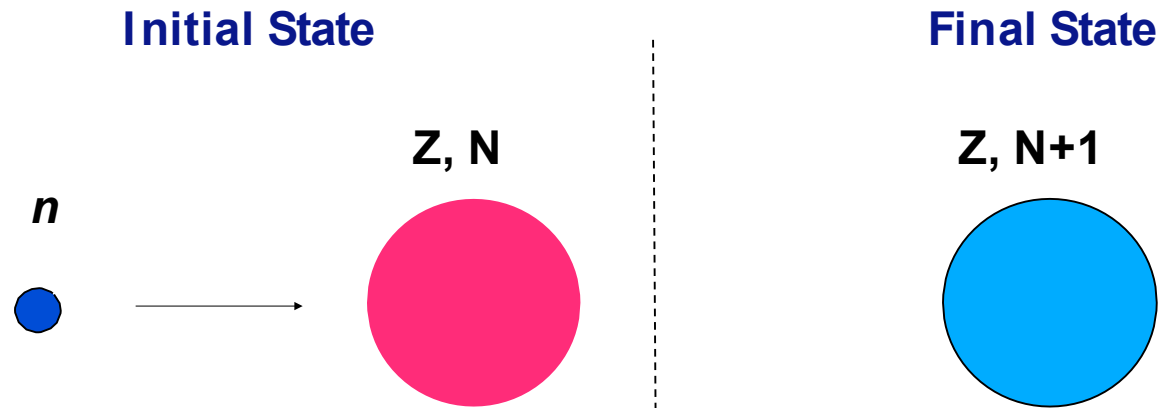
The resulting nucleus may be stable or unstable.

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

$$\,_{0}^{1}n + \,_{92}^{238}U \rightarrow \,_{92}^{239}U \rightarrow \,_{93}^{239}Np + e^{-} + \bar{\nu}_{e}$$
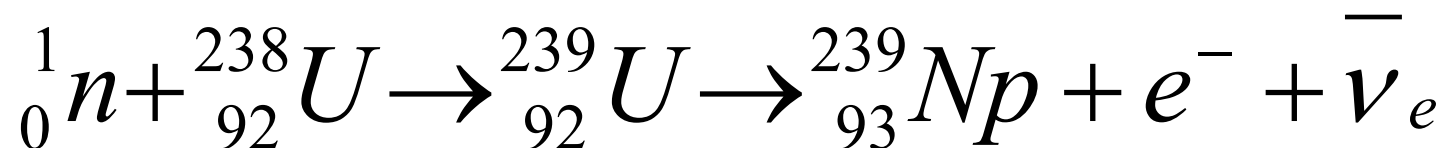
Average Nucleon Binding Energy ➜ Amount of Energy Released if 1 Neutron is Captured in Nucleus

Average Binding Energy [MeV]

56Fe, 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 !

Fusion —>
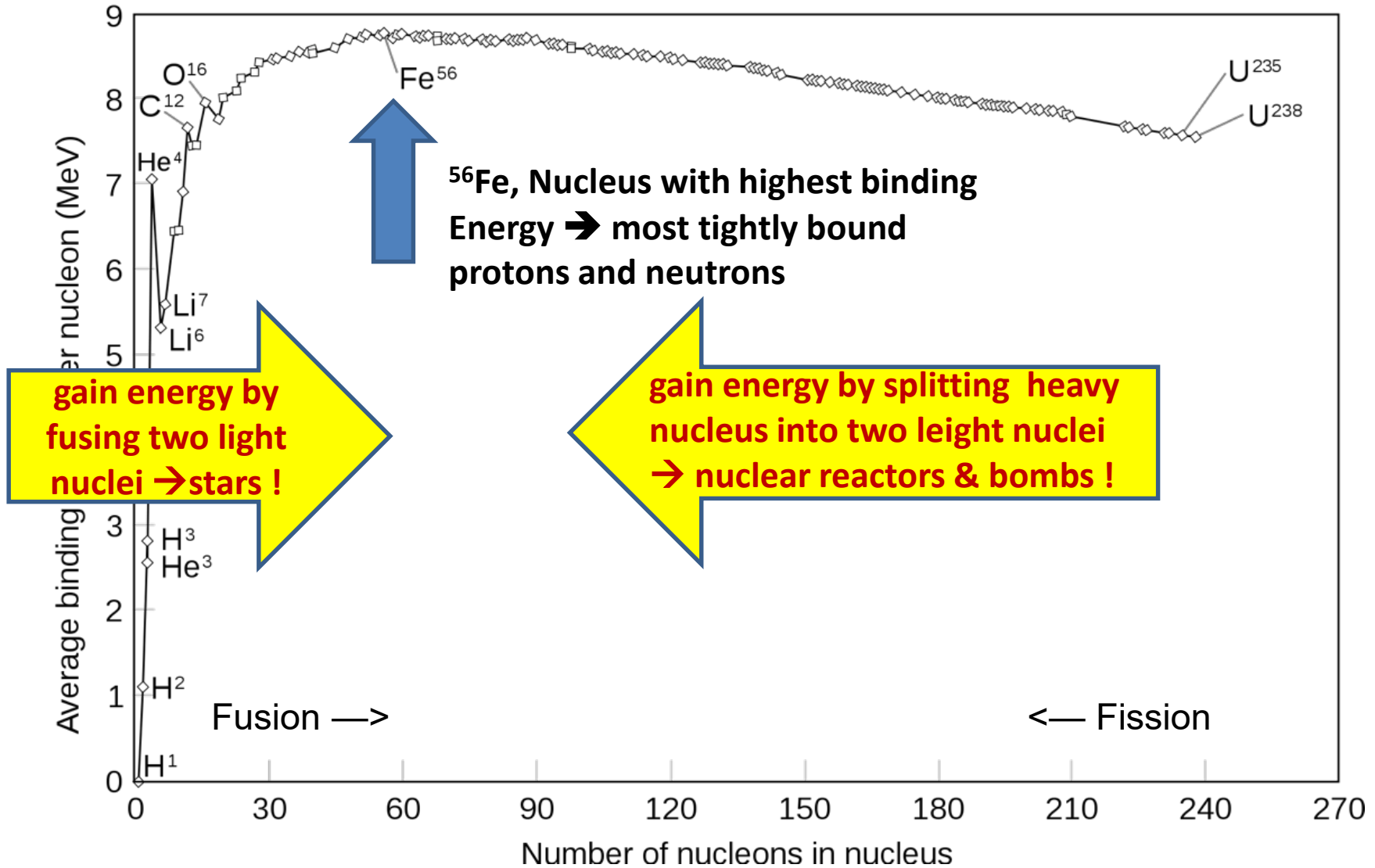
<— Fission

Physics/Global Studies 280: Session 5

Plan for This Session

Announcements

Questions

Module 2: Nuclear weapons cont'd

Physics/Global Studies 280: Session 5

Announcements

RE2v1 will be due tomorrow, Wednesday, 2-2
- o Electronic submission (**10pm**)

- o RE2v1 prompt is posted on course web-page
  https://courses.physics.illinois.edu/phys280/sp2022/re2.html

- o Follow all instructions stated in the prompt

- o Peer review of RE2v1 will be assigned Friday night:
  https://courses.physics.illinois.edu/PHYS280/sp2022/re2.html#re2-peer-review

  Peer review assignment will be due Monday at 10am
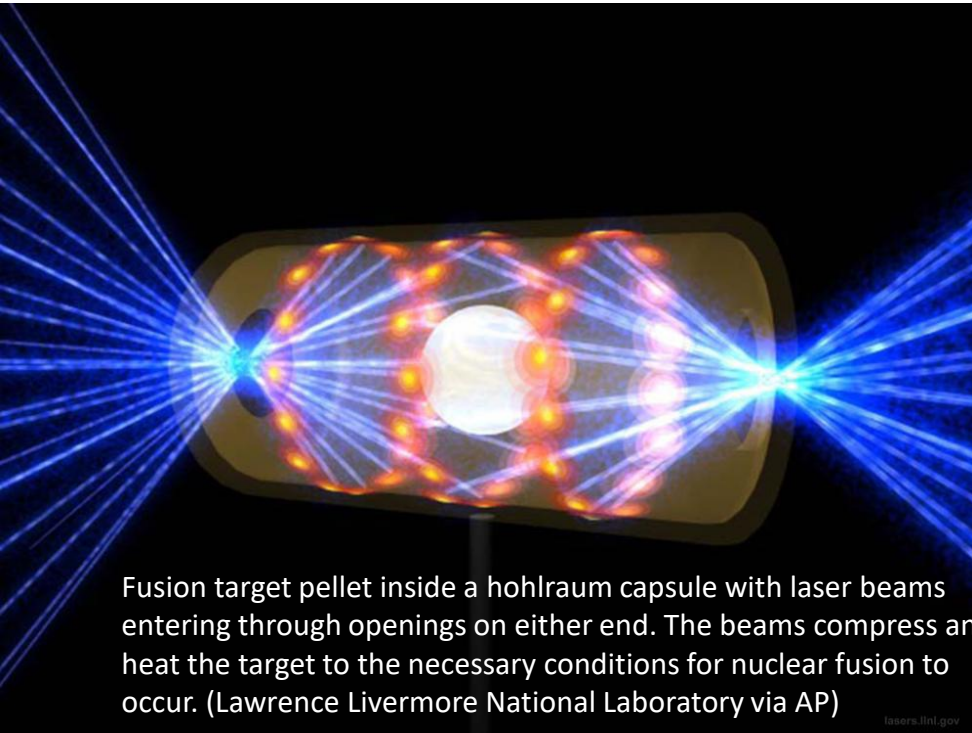 for discussion with your peer review partner during writing lab.
  Peer review is 10% of RE2v1 grade.

- o Course slides (module 1 and 2) available on TopHat
  and on course webpage

Hot stuff: Lab hits milestone on long road to fusion power

By SETH BORENSTEIN   January 26, 2022

Fusion target pellet inside a hohlraum capsule with laser beams entering through openings on either end. The beams compress and heat the target to the necessary conditions for nuclear fusion to occur. (Lawrence Livermore National Laboratory via AP)

With 192 lasers and temperatures more than three times hotter than the center of the sun, scientists hit — at least for a fraction of a second — a key milestone on the long road toward nearly pollution-free fusion energy.

Researchers at the National Ignition Facility at the Lawrence Livermore National Lab in California were able to spark a fusion reaction that briefly sustained itself — a major feat because fusion requires such high temperatures and pressures that it easily fizzles out.

The ultimate goal, still years away, is to generate power the way the sun generates heat, by smooshing hydrogen atoms so close to each other that they combine into helium, which releases torrents of energy.

A team of more than 100 scientists published the results of four experiments that achieved what is known as a burning plasma in Wednesday's journal Nature. With those results, along with preliminary results announced last August from follow-up experiments, scientists say they are on the threshold of an even bigger advance: ignition. That's when the fuel can continue to "burn" on its own and produce more energy than what's needed to spark the initial reaction.

22p280 Nuclear Weapons, p.   71
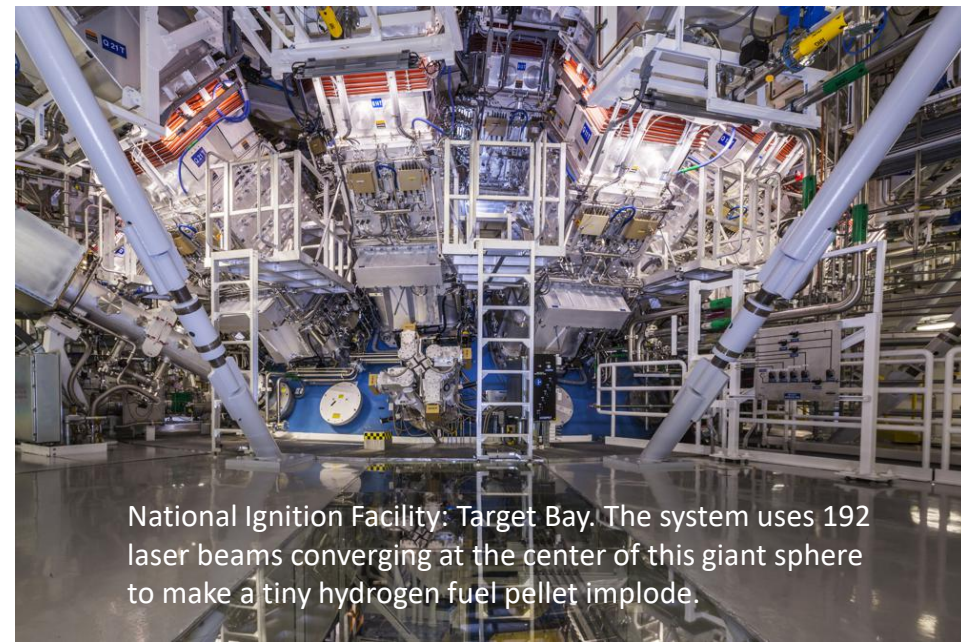
National Ignition Facility: Target Bay. The system uses 192 laser beams converging at the center of this giant sphere to make a tiny hydrogen fuel pellet implode.

Induced Fission – 1
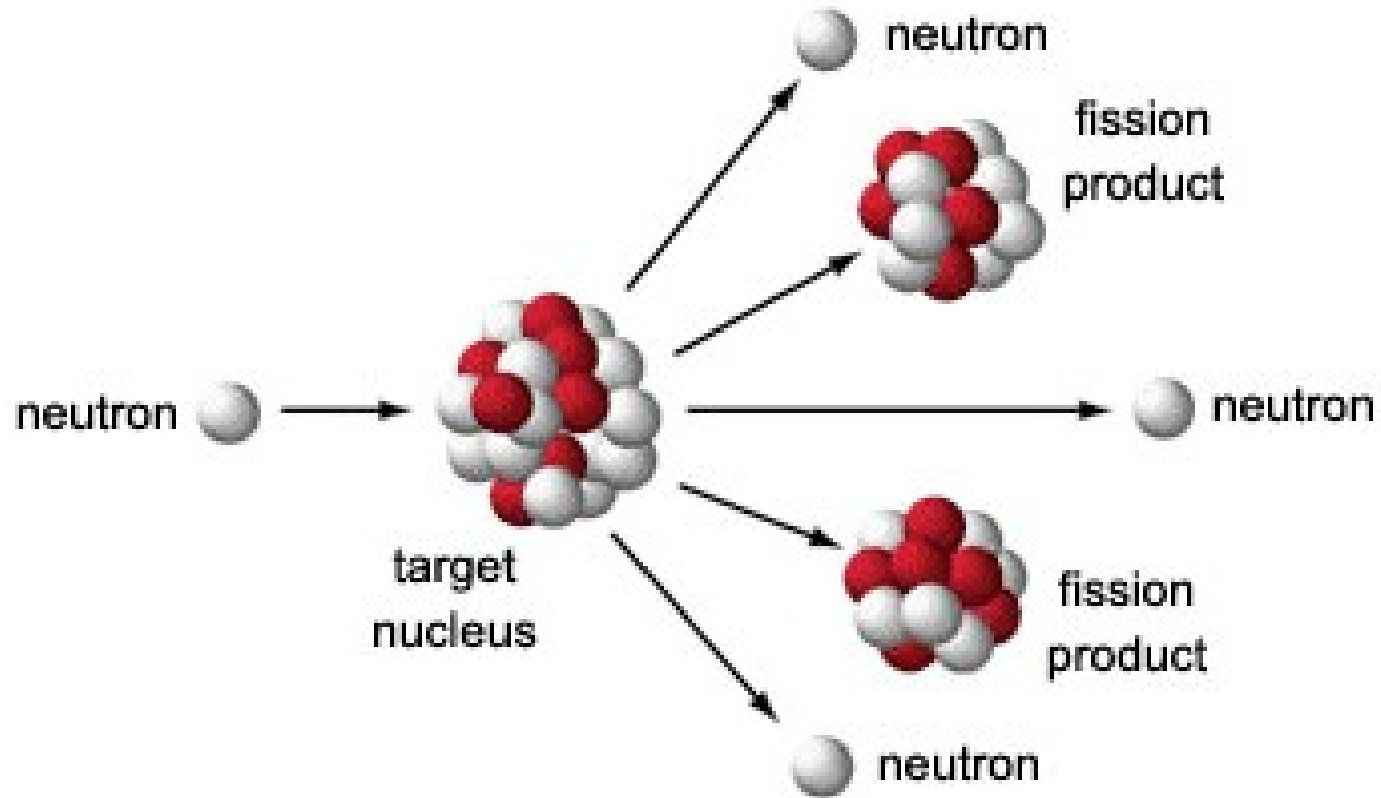
Induced Fission – 2

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 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!

Element 109, Meitnerium, is named in her honor.

Lise Meitner's Concept of Fission

parent nucleus
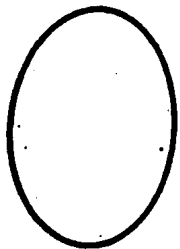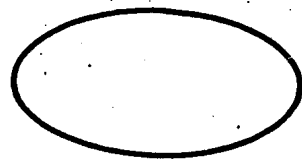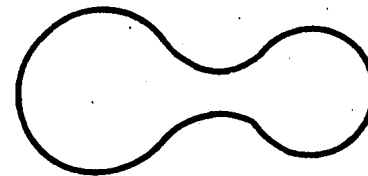
daughter nuclei
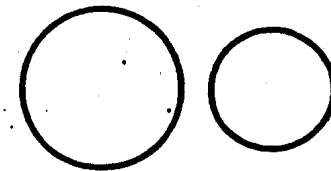
A   B   C   D

deformation of parent nucleus

Distribution of Fission Fragment Masses

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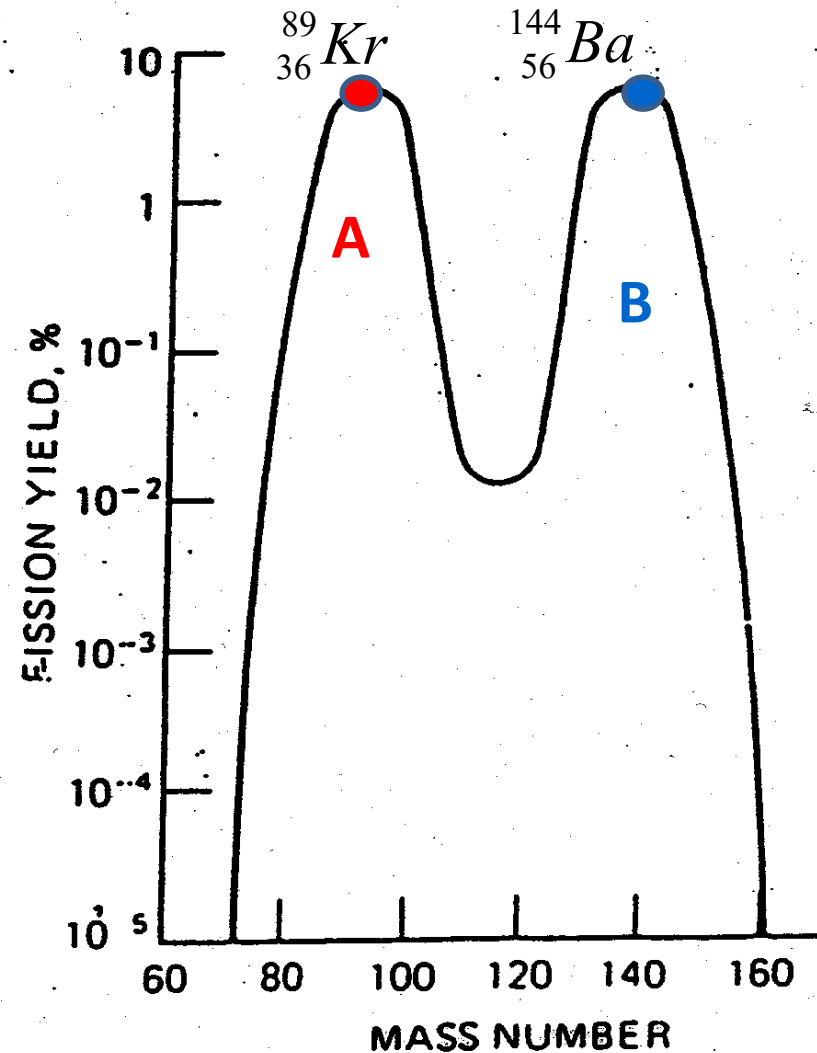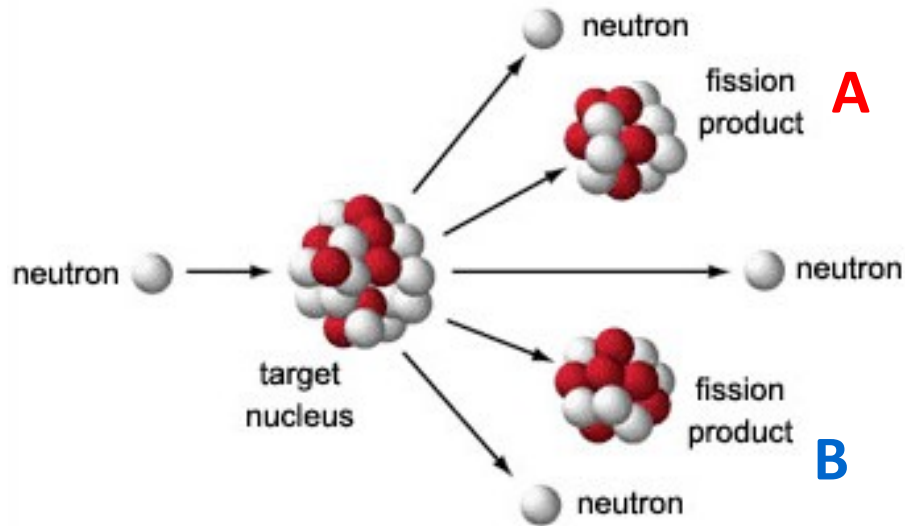
Induced Fission – 3

- 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

First Second Third Fourth Fifth

○ ^{235}U

○ Fission fragment

● Neutron leading
to further fissions

✹ Neutron lost and not
leading to further fission
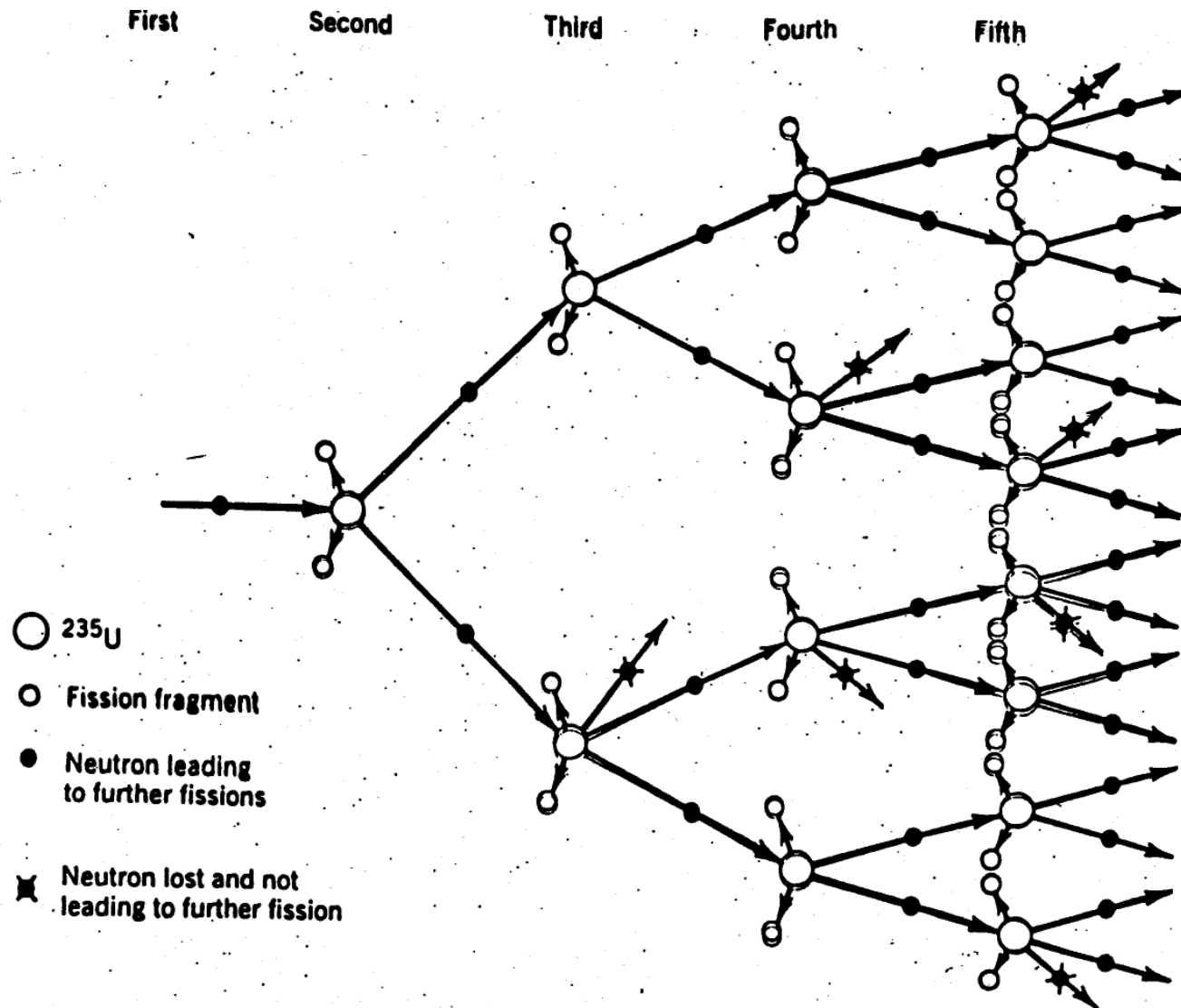
Physics of Nuclear Weapons

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" R?

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 nuclei

Non-fissionable

Fissionable but non-fissile can be fission-ed by neutrons above an energy threshold
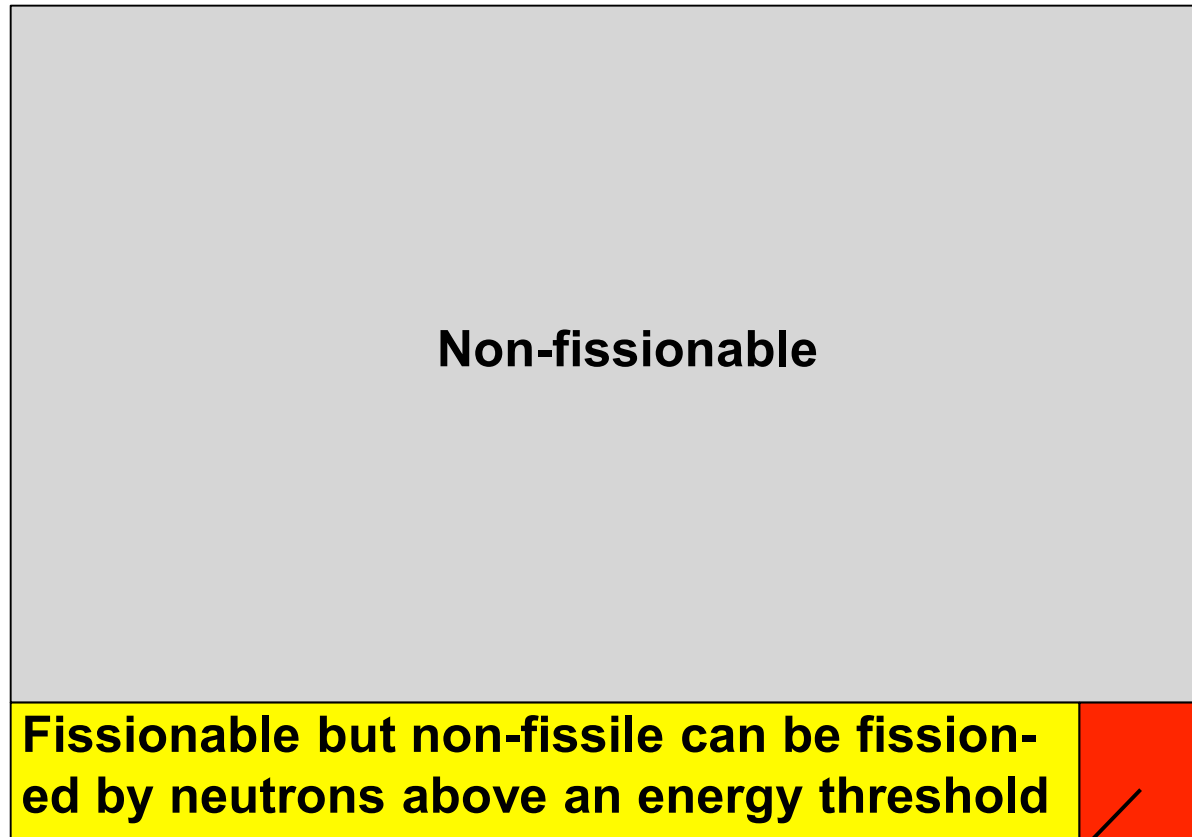
**Fissionable and fissile
can be fissioned by neutrons
of any energy**

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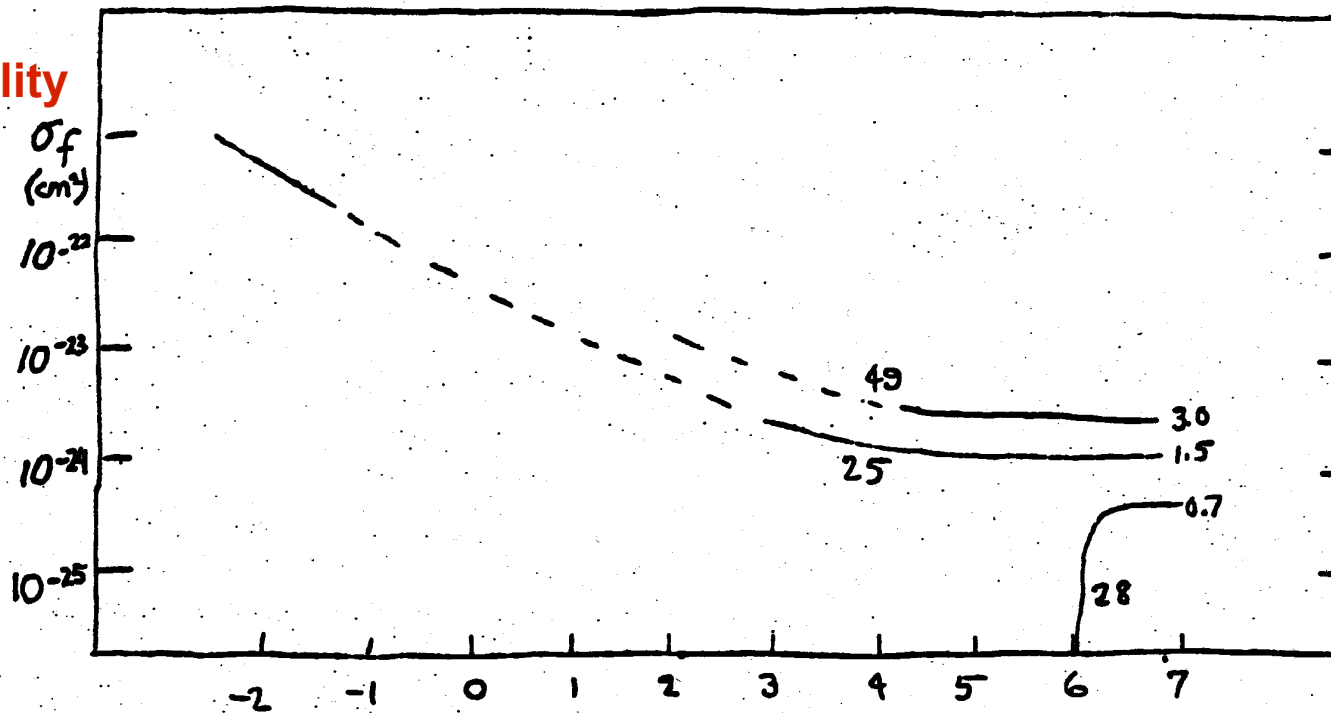
(thermal) log neutron energy in EV.
Fig. 1

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.

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 ➡ Breed Nuclear Explosive Nuclides

Fertile Nuclides can be used to "breed" Nuclear Explosive Nuclides in Nuclear Reactors. The NEM then are harvested through chemical reprocessing of the reactor fuel. Example, Uranium-238:

fertile nuclide

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

$$_{92}^{239}U \rightarrow {}_{93}^{239}Np + e^{-} + \bar{\nu}_{e} \qquad \text{Beta-decay}$$

$$_{93}^{239}Np \rightarrow \boxed{_{94}^{239}Pu} + e^{-} + \bar{\nu}_{e} \qquad \text{Beta-decay}$$

nuclear explosive nuclide
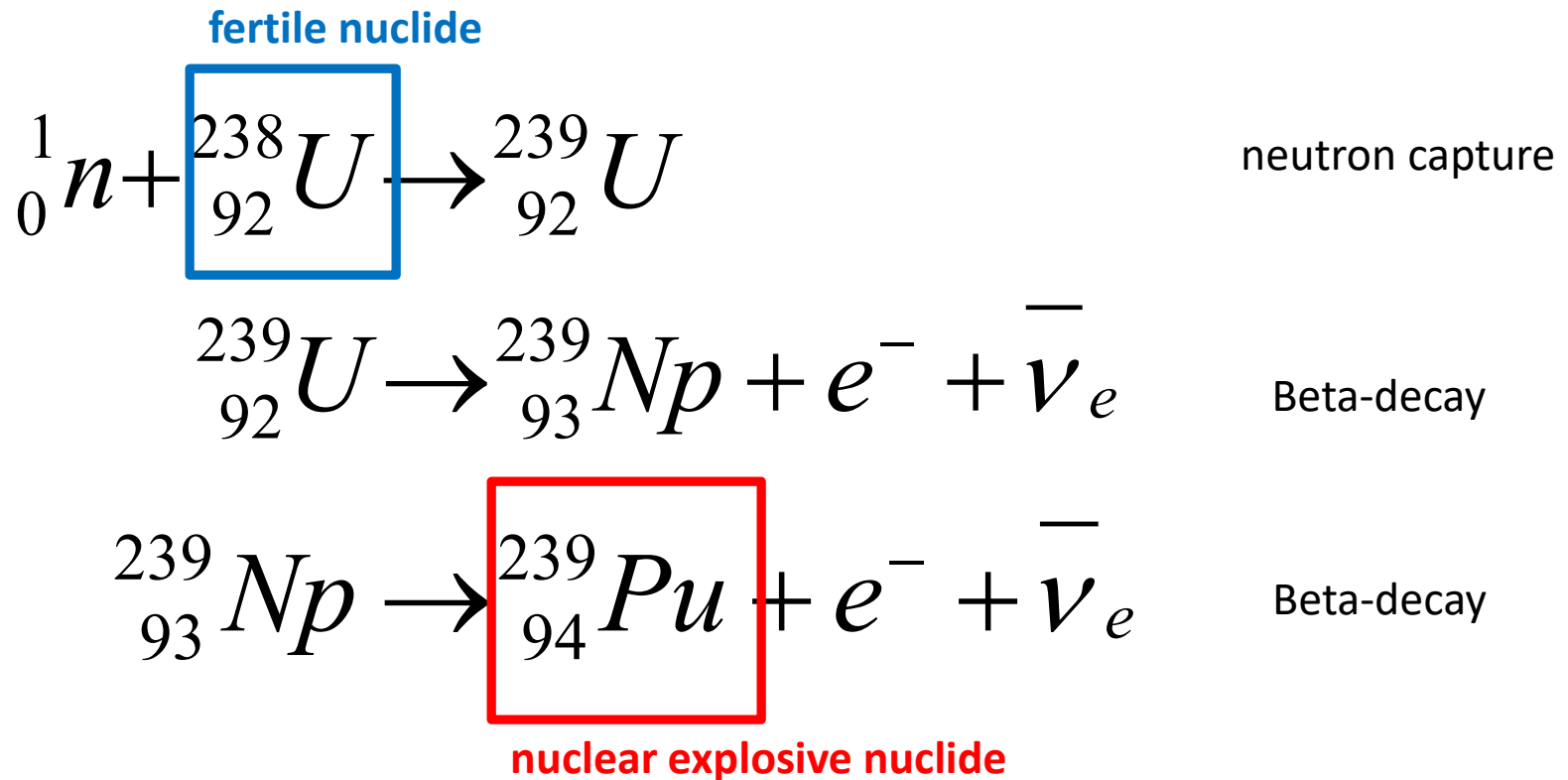
Definitions of Fission and Nuclear Materials Summary – Important !

- **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.

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

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
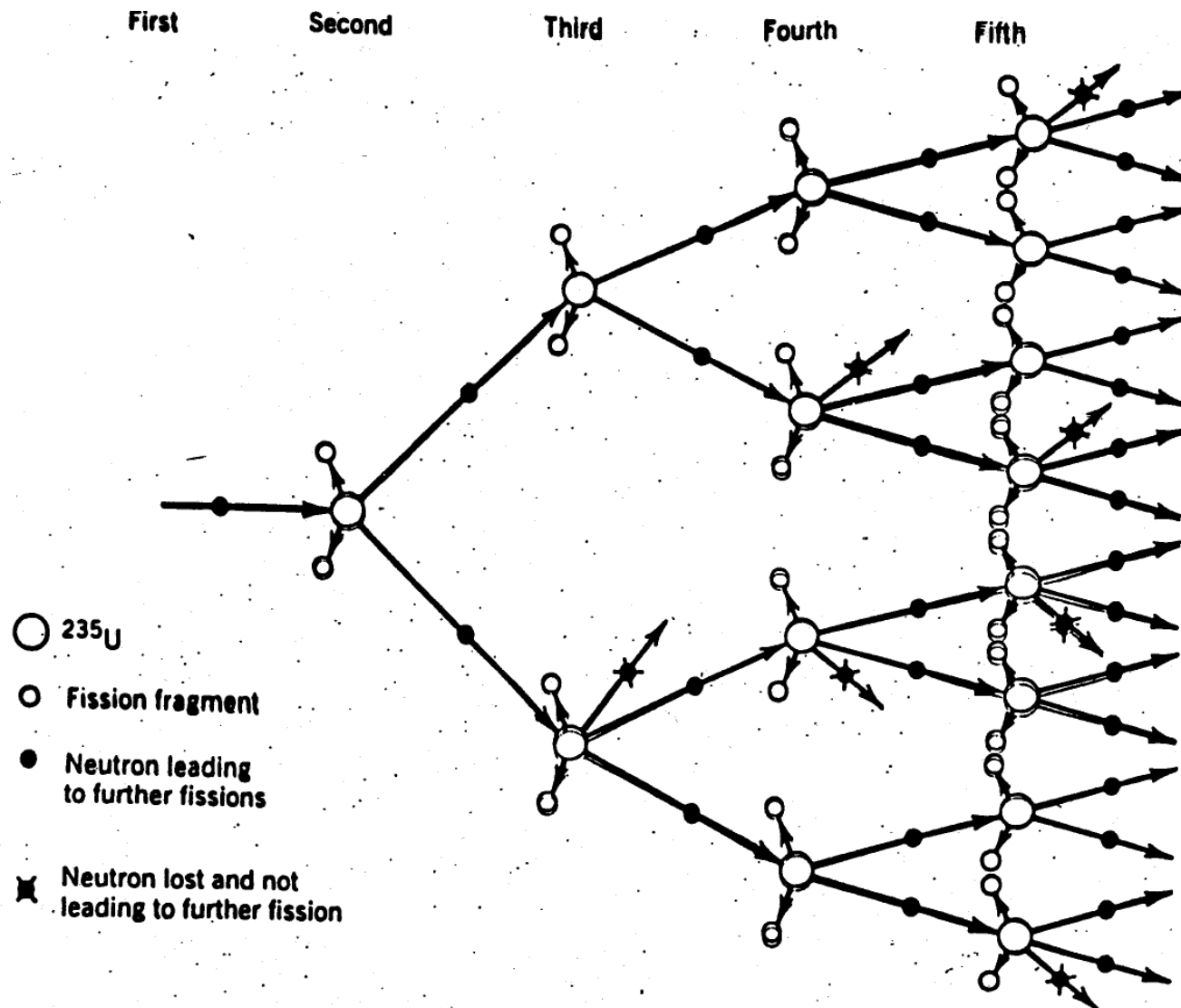
Number of Fissions When a Nuclear Weapon is Exploded

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	$2^{69} = 5.9 \times 10^{20}$	0.025% of Yield
79	$2^{78} = 3.0 \times 10^{23}$	12% of Yield
80	$2^{79} = 6.0 \times 10^{23}$	25% of Yield
81	$2^{80} = 1.2 \times 10^{24}$	50% of Yield
82	$2^{81} = 2.4 \times 10^{24}$	100% of Yield

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.

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	$2^3 = 2 \times 2 \times 2 = 8$	**88% of total Yield (explosive energy) are released in the 3 final generations of chain reactions!**
5	$2^4 = 2 \times 2 \times 2 \times 2 = 16$	
10	$2^9 = 512$	
30	$2^{29} = 5.3 \times 10^8$	
70	$2^{69} = 5.9 \times 10^{20}$	0.025% of Yield
79	$2^{78} = 3.0 \times 10^{23}$	12% of Yield
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Each generation lasts about 1 "shake" = 10^{-8} sec = 1/100,000,000 sec.

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

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

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

MGP, Dep. Of Physics © 2022

Reducing the Fast-Neutron Critical Mass – 1

Critical Mass versus the Concentration of the Fissile Material
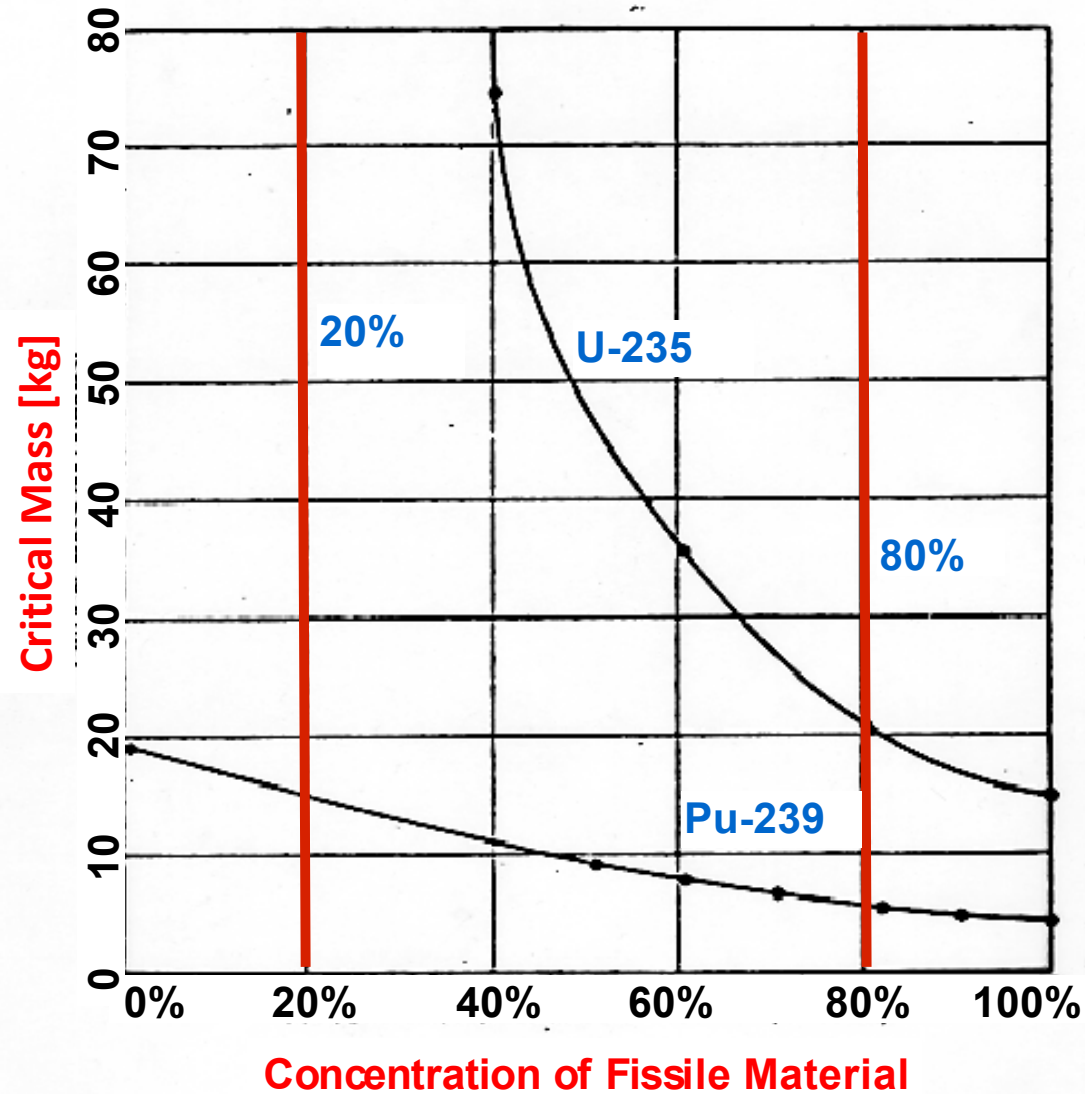
Dependence on the Density ρ of the Fissile Material

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

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   kg of Highly Enriched U for

Technical Capability   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.

Physics of Nuclear Weapons

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
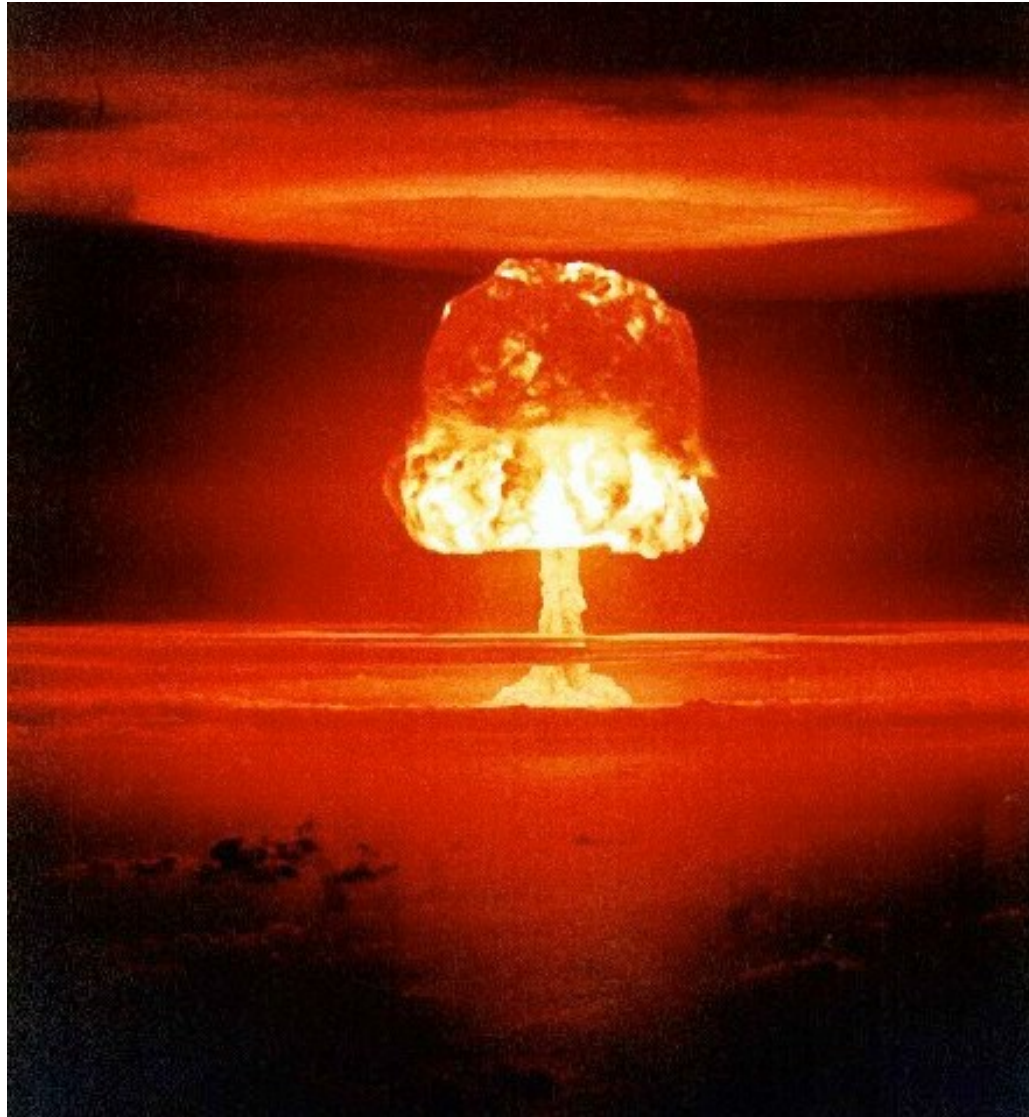
Stages —

- Explosive is ignited

- Fuel and oxidizer burn (chemically), releasing ~ 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

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 fragments) + (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

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
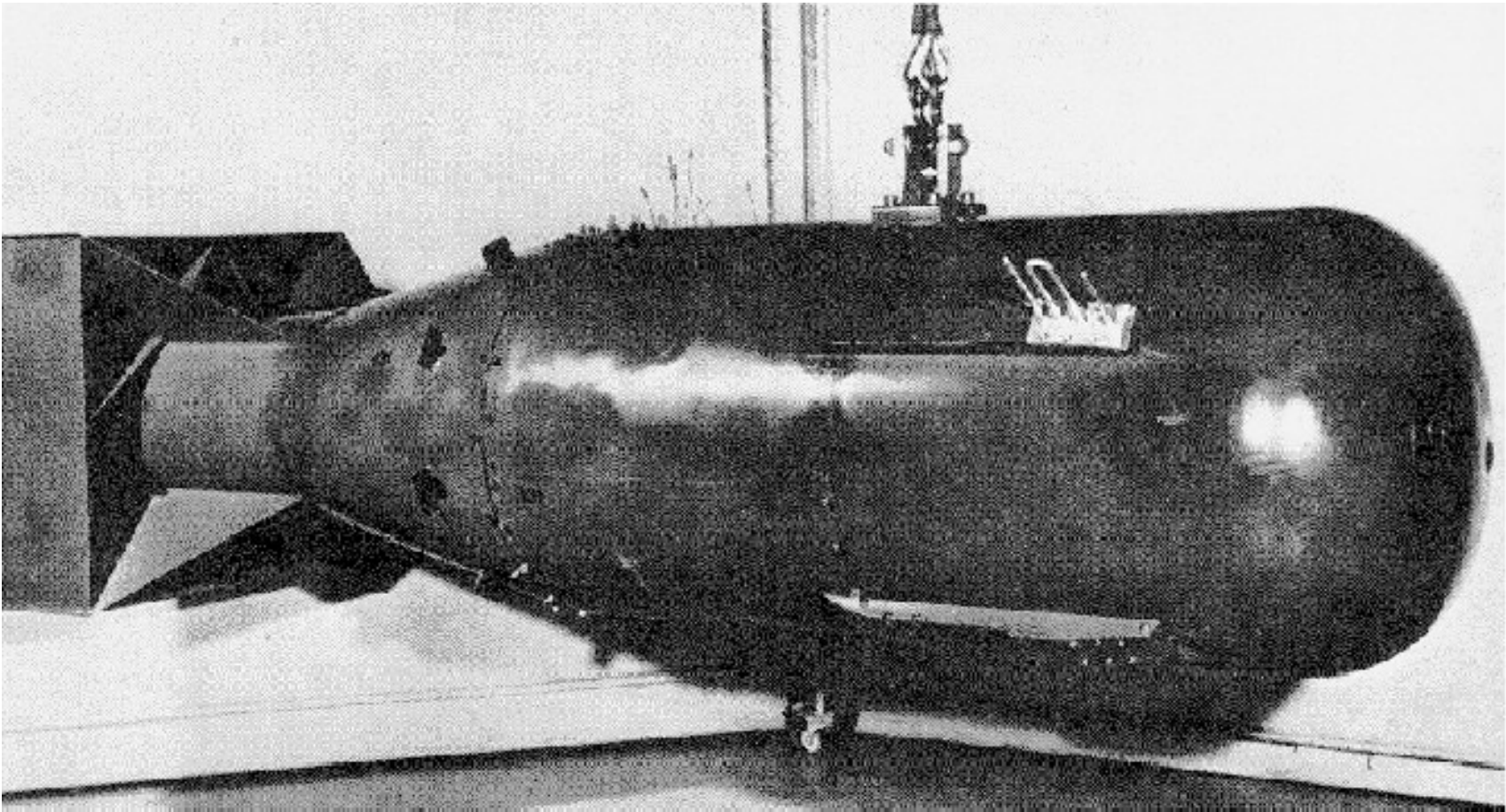
Fission weapons ("A-bombs") —

- 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
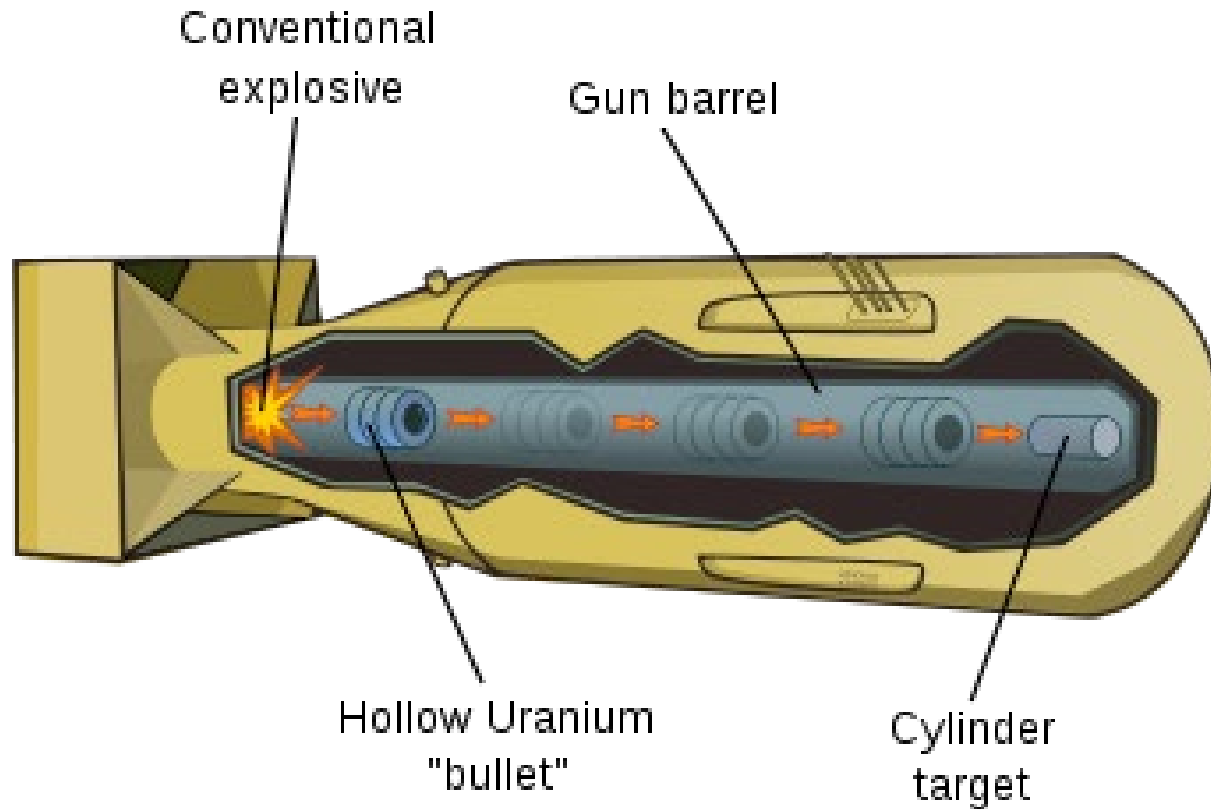 kt TNT from 1 lb. of fusion material
  (~ 3 times as much per lb. as fission weapons)

- There is no fundamental limit to the size of a
  thermonuclear weapon

Fission Weapons – Gun Type

Little Boy

Fission Weapons – Gun Type

Conventional explosive

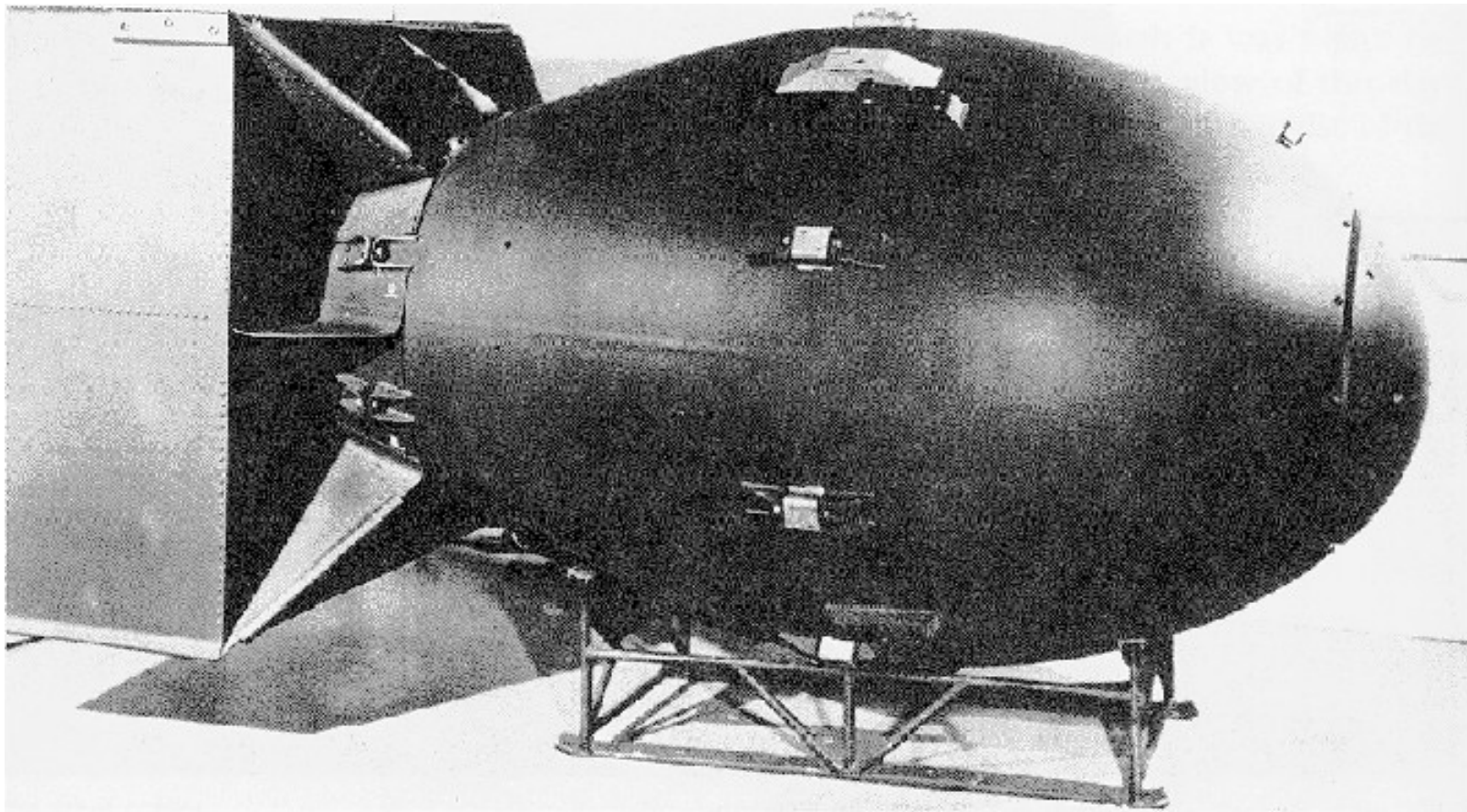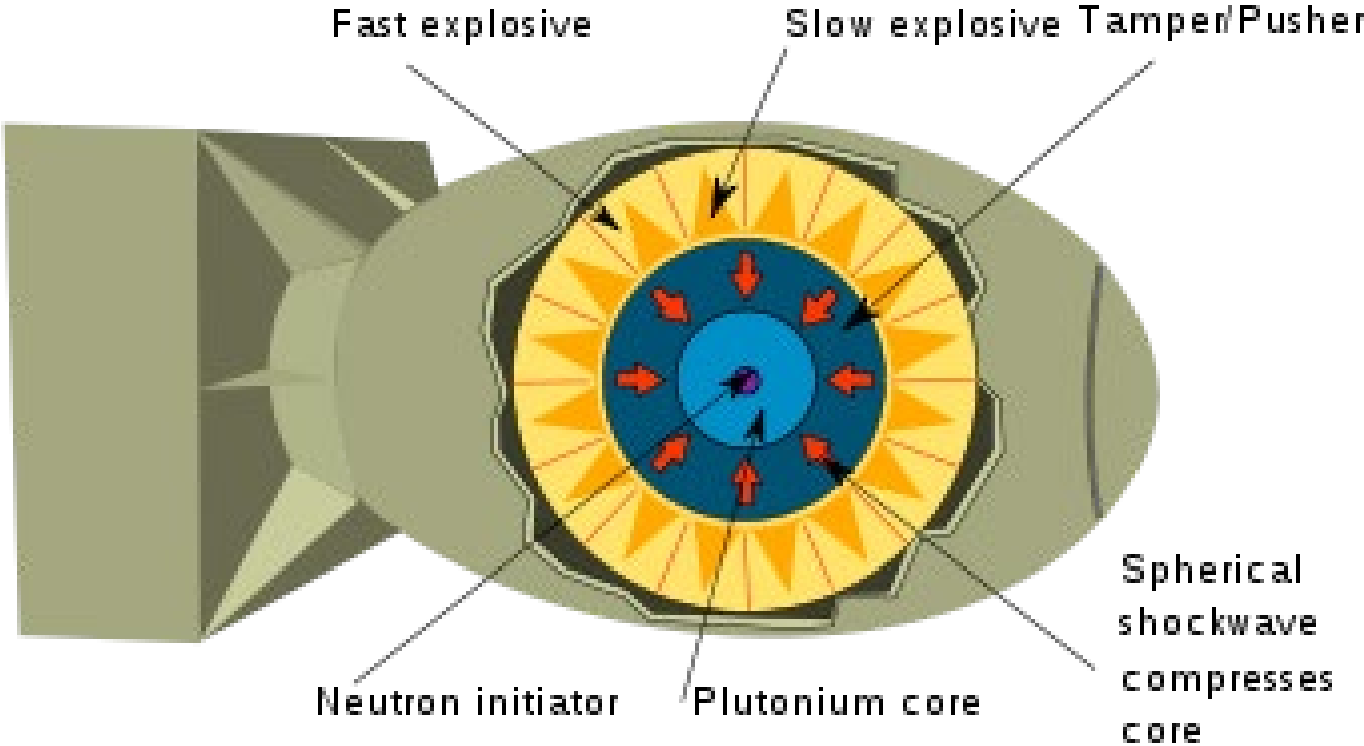Gun barrel

Hollow Uranium "bullet"

Cylinder target

Works only with HEU
(relevant today mostly for non-state groups)

Fission Weapons – Implosion Type

Fat Man

Fission Weapons – Implosion Type

Fast explosive   Slow explosive Tamper/Pusher

Neutron initiator   Plutonium core   Spherical shockwave compresses core

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)

Physics of Nuclear Weapons

Thermonuclear Weapons ("H-Bombs")

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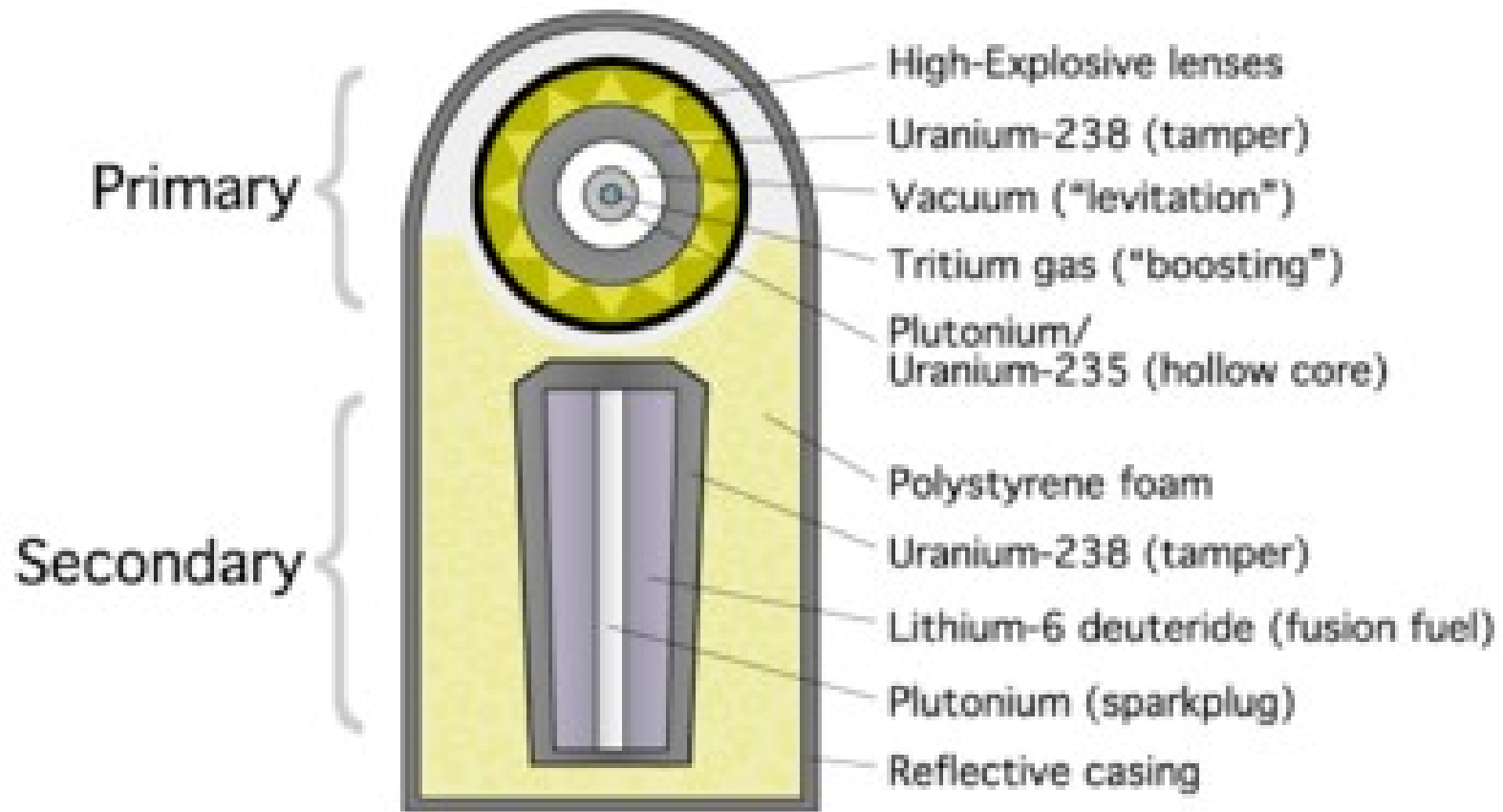- triton (T)
- He-4 (alpha)
- neutron (n)

Example Fusion Nuclear Reaction

Deuterium

Helium

Tritium

Neutron

Energy
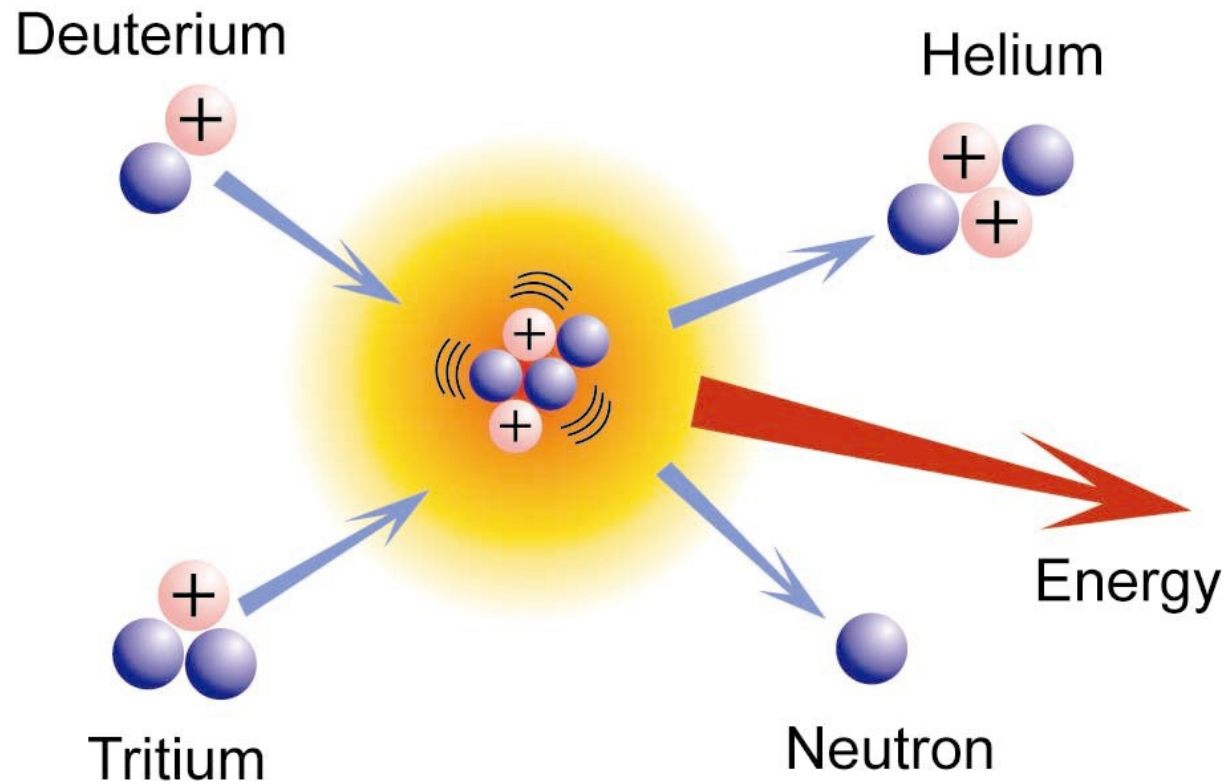
Two-Stage (Thermonuclear) Weapons – 1

- 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

Two-Stage (Thermonuclear) Weapons – 2

High-Explosive lenses
Uranium-238 (tamper)
Vacuum ("levitation")
Tritium gas ("boosting")
Plutonium/
Uranium-235 (hollow core)

Polystyrene foam
Uranium-238 (tamper)
Lithium-6 deuteride (fusion fuel)
Plutonium (sparkplug)
Reflective casing

Primary
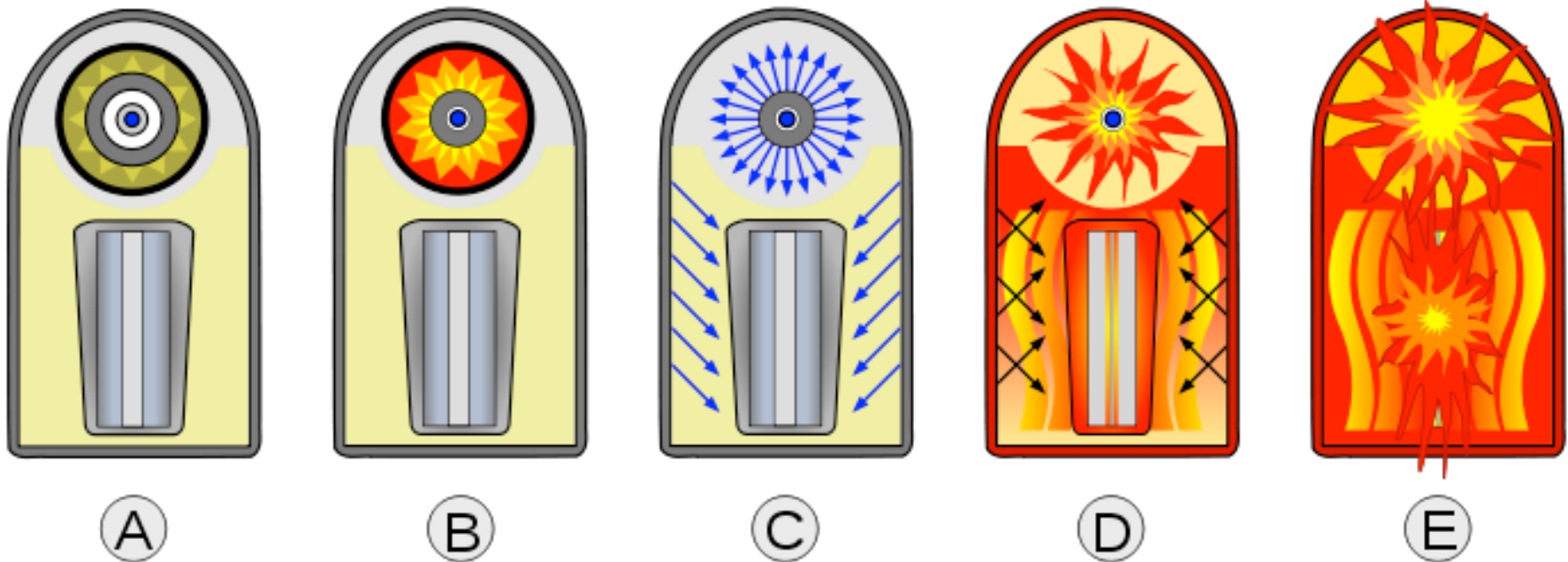Secondary

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

Two-Stage (Thermonuclear) Weapons – 3

Sequence of events —

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

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

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 – (Tsar test, October 30th 1960)

  - The U.S. concluded that this particular design was capable of releasing 100 Mt

Two-Stage (Thermonuclear) Weapons – 6

- Making a 50 Mt device makes no military/economic sense. Historic example served propaganda purposes.

- 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 – 7

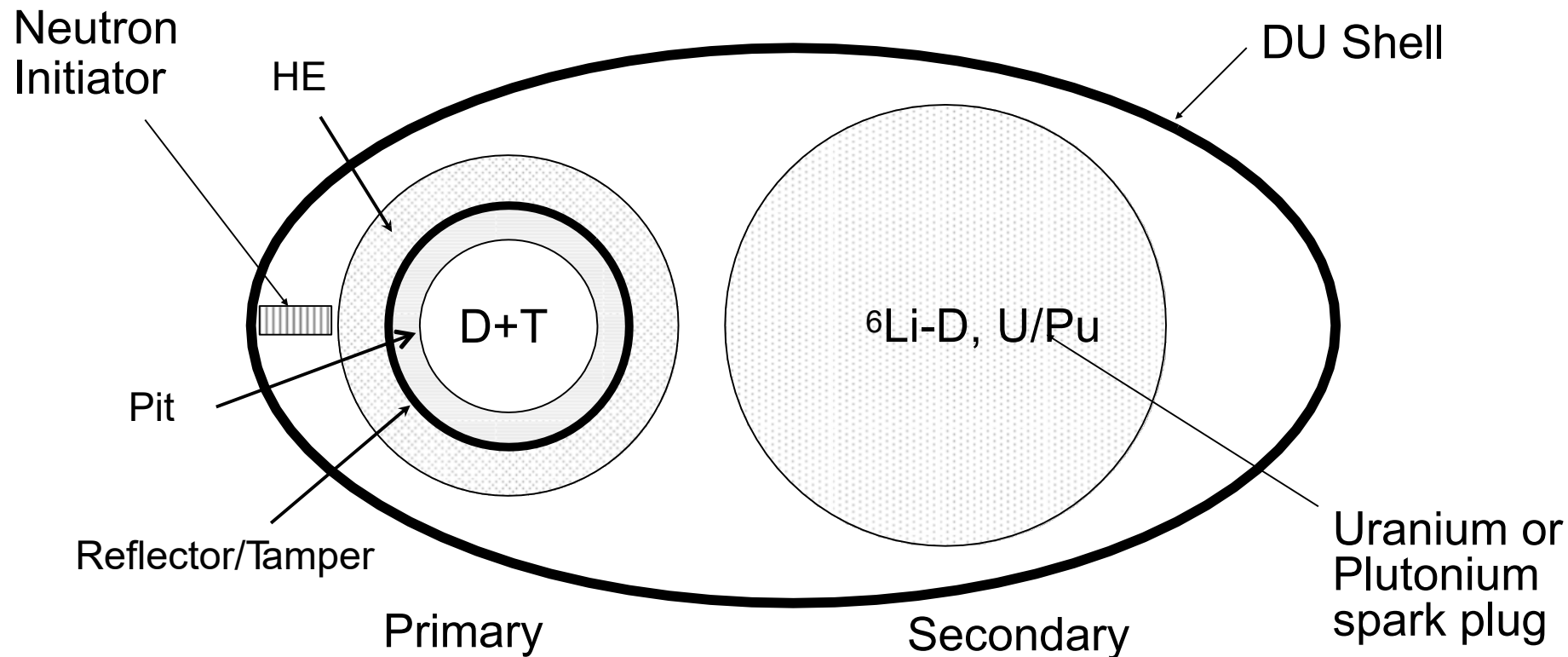HEU, DU, natural U, or Pu are used to increase the yield —

• 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

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

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

Neutron Initiator

HE

DU Shell

D+T

^{6}Li-D, U/Pu

Pit

Reflector/Tamper

Primary

Secondary

Uranium or Plutonium spark plug

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

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"

Lecture Question

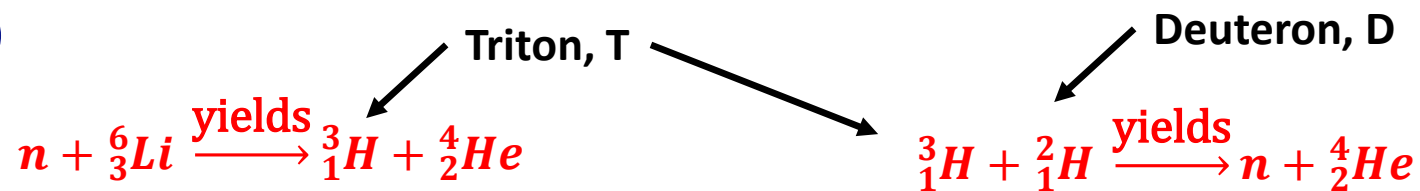How is ^{6}LiD used as fusion fuel in a two stage thermo nuclear weapon?

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.

Lecture Question Answer

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.

^{6}LiD

Triton, T

Deuteron, D

$$n + {}^6_3Li \xrightarrow{\text{yields}} {}^3_1H + {}^4_2He$$

$$ {}^3_1H + {}^2_1H \xrightarrow{\text{yields}} n + {}^4_2He$$

(I) preparation of fusion fuel

(II) fusion reaction

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

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

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

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 buffeting, deceleration, and very high temperatures as the warhead re-enters the atmosphere at hypersonic speeds
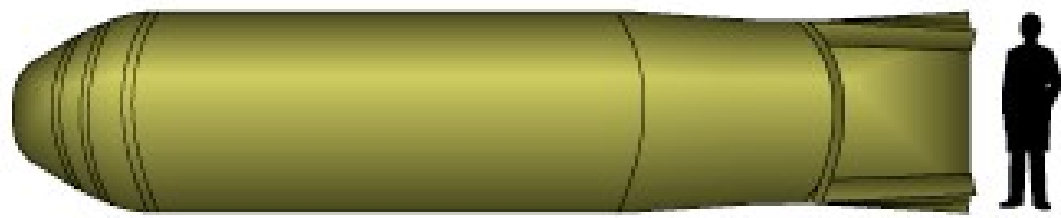
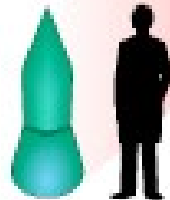## Miniaturizing Massive Death and Destruction

FIRST FISSION BOMBS
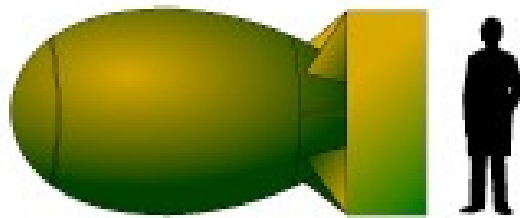
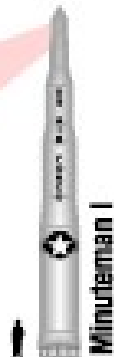MK IV (Fat Man), 20kt (1945)

FIRST FUSION BOMBS

MK-17 (Bravo), 15Mt (1955)
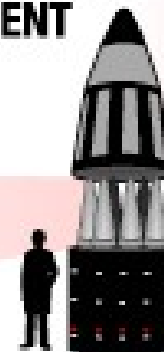
SINGLE WARHEAD DEVELOPMENT

W-59, 1Mt (1962)

Minuteman I

MULTIPLE INDEPENDENT RE-ENTRY VEHICLE (MIRV) DEVELOPMENT

W-87, 475kt (1986)

Peacekeeper MX

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

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

Lecture 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

Lecture Question Answer

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

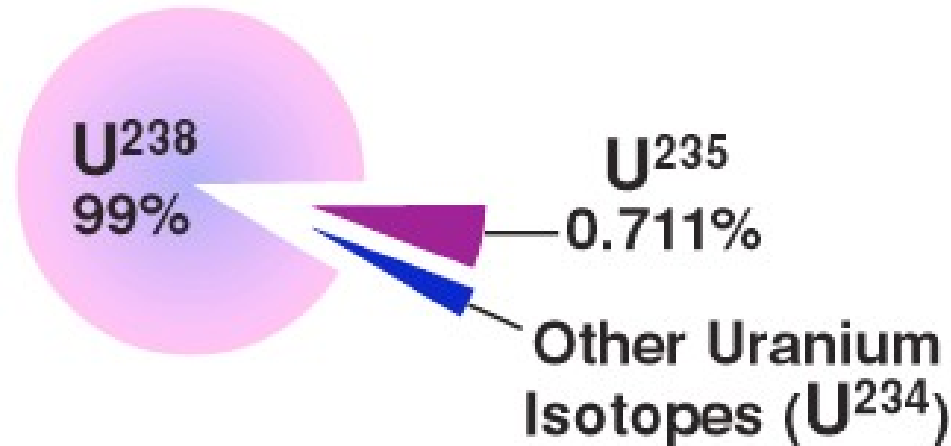E) Production of fusion fuel

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)

U238 99%

U235 0.711%

Other Uranium Isotopes (U234)

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.

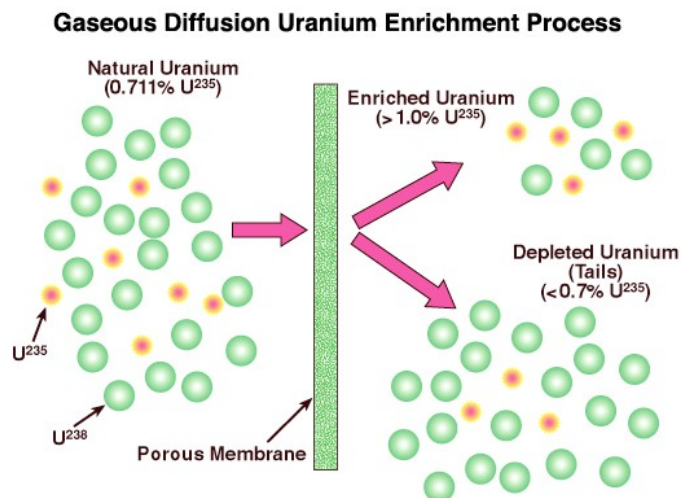# Enriching Uranium – Overview

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

Gaseous Diffusion Uranium Enrichment Process

Natural Uranium (0.711% U^{235})

U^{235}

U^{238}

Porous Membrane

Enriched Uranium (> 1.0% U^{235})

Depleted Uranium (Tails) (<0.7% U^{235})

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
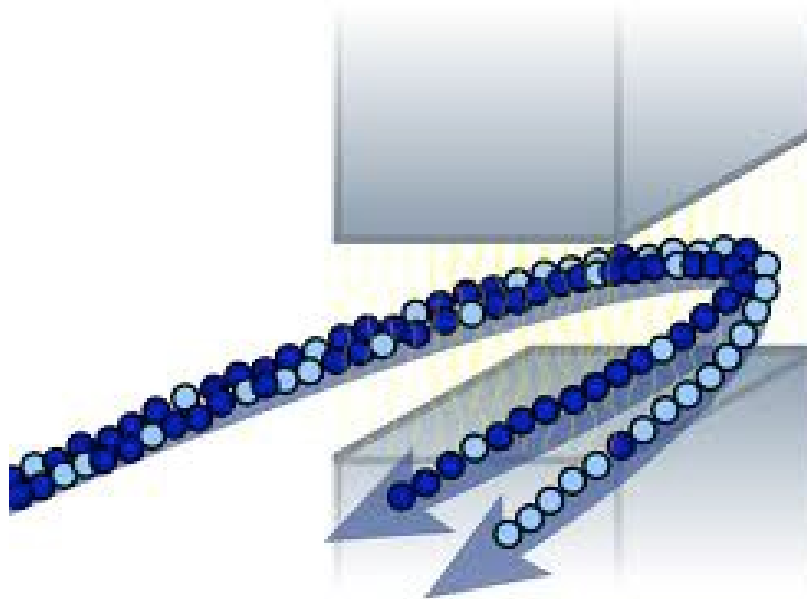
Enriching Uranium – Details 3

- 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
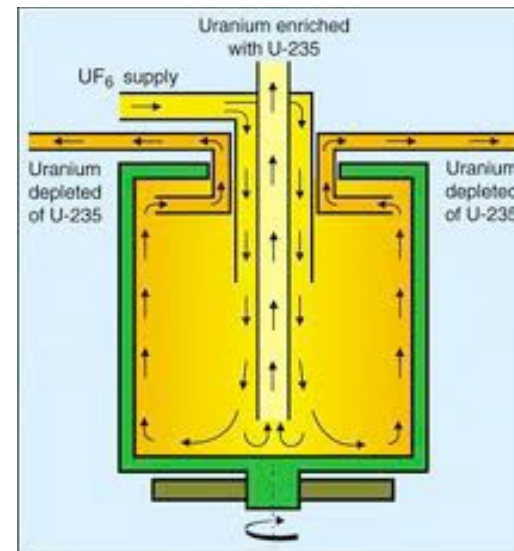
Enriching Uranium – Details 4

- **Molecular laser isotope separation**
  - High-tech and compact (only 1 to 3 stages required)
  - Based on (very 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
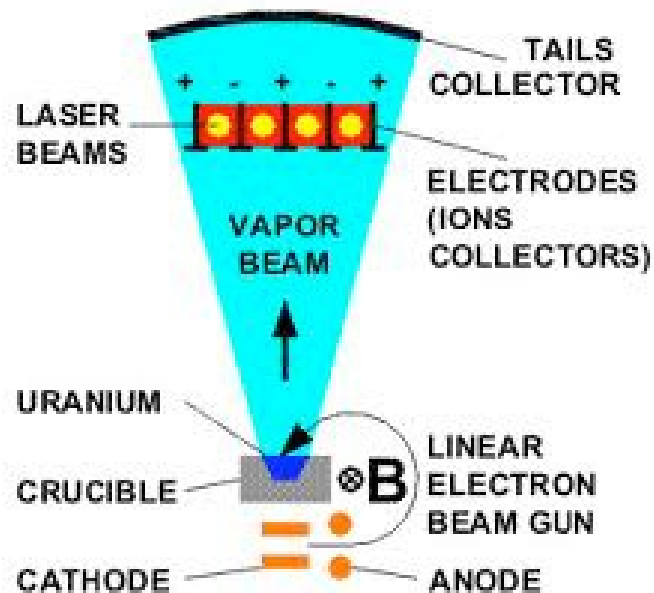
Plutonium Is Created in Nuclear Reactors

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

Physics/Global Studies 280: Session 6

Plan for This Session

Announcements:

Peer Review: you will receive assignments
to peer review another student's essay. This will count
for 10% of your v2 grade. Peer Reviews are due
Sunday at 10 pm through the assignment upload server.
Locations of essays to be reviewed:
https://courses.physics.illinois.edu/phys280/secure/assignments/RE2v1/OnTime/

https://courses.physics.illinois.edu/phys280/secure/assignments/RE2v1/Late/

WL11	Reviewer	Reviewee
	jjflore3	pzukows2
	jang51	jjflore3
	kulchit2	jang51
	mrogals2	kulchit2
	seidner2	mrogals2
	rshanle2	seidner2
	jlstein3	hmatz2
	pzukows2	nnshah8

Module 2: Nuclear weapons cont'd

Plan for This Session

WL11	Reviewer	Reviewee
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Module 2: Nuclear weapons cont'd