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/sp2026/reading-assignments.html

(3) Office hours Tuesdays, today: 3.30-5.30pm , Loomis Lab Room 426
Wednesday 3-6pm, Loomis Lab Room 426
https://courses.physics.illinois.edu/phys280/sp2026/staff-info.html

News

Foreign Policy

(foreignpolicy.com)

ARGUMENT *An expert's point of view on a current event.*

Why Trump Should Accept Putin's New START Offer

Extending the nuclear treaty is not about trust—it's about pragmatism.

By **Ariel Petrovics**, a visiting scholar at the University of Denver's Josef Korbel School of International Studies and research associate at the University of Maryland School of Public Policy.

U.S. President Donald Trump greets Russian President Vladimir Putin at Joint Base Elmendorf-Richardson in Anchorage, Alaska, on August 15, 2025. ANDREW HARNIK/GETTY IMAGES

The United States is approaching a decisive moment in its management of nuclear risk. New START—the last remaining arms control agreement between the United States and Russia—is scheduled to expire on Feb. 5. Signed in 2010, New START has helped limit nuclear competition between the world's largest arsenals by capping warheads and delivery systems and enabling inspections and data exchanges. Although Russia suspended inspections and halted treaty-mandated data exchanges in 2026, protesting U.S. and NATO support for Ukraine, it promised to maintain treaty limits and has since offered to extend those limits by one year if the United States agrees to do the same. Both sides have expressed interests in further nuclear arms control talks, and since returning to office, U.S. President Donald Trump has repeatedly voiced support for "denuclearization" talks with Russia and China and has said Russia's extension offer "sounds like a good idea." Yet the deadline rapidly approaches with no formal response from his administration.

News -> Shouldn't a new treaty include China with its fast-expanding nuclear arsenal?

A common argument against extending New START is that it does nothing to address China's expanding arsenal. **But this is precisely why the treaty remains essential.**

For the first time, Washington must deter two major nuclear powers whose forces are growing in parallel. China's rapid buildup—including new missile fields, more survivable delivery systems, and increased warhead production—has already forced U.S. planners to rethink long-term deterrence strategy. If New START collapses, the United States would face simultaneous uncertainty about both Russian and Chinese force trajectories, requiring planning for the most demanding potential combinations of expansions on both fronts. This is an exceptionally expensive and destabilizing way to manage nuclear competition. The U.S. nuclear modernization effort is projected to cost more than $1.5 trillion over three decades and is already over budget and behind schedule.

Even if all benchmarks were met, unconstrained competition risks diverting U.S. resources toward perpetual hedging and erodes the predictability that underpins crisis stability. A one-year extension, paired with a restart of on-site inspections or bilateral data exchanges, would reduce uncertainty on several fronts. It would allow Washington to focus analytical and diplomatic resources on understand-ding China's evolving posture while increasing combined U.S. and Russian leverage to incentivize China to join the ranks of responsible nuclear leadership by establishing its own nuclear dialogue. In this sense, extending New START reduces—rather than exacerbates—the difficulty of managing a two-peer nuclear problem.

News -> with Russia suspending inspections, isn't New START already dead?

Another critique of extending New START is practical: If Russia has suspended inspections, ceased data exchanges, and refused certain notifications, what exactly is being extended, and how does it benefit U.S. interests?
The answer is the legal and institutional structure and ongoing mutual restraint that make restored verification possible. Even in suspension, New START anchors the strategic baseline, preserving a structure that steers future talks toward similarly robust treaty mechanisms. Verification regimes do not reappear automatically once they collapse. If New START expires, its mechanisms disappear entirely—along with its definitions, oversight bodies, and channels for resolving compliance issues. While Trump recently claimed that "if it expires, it expires. … We'll just do a better agreement," this process of negotiating an agreement from scratch historically takes years and requires a perfect storm of political conditions that will not exist for the foreseeable future.

Even in its current, strained state, New START's structure gives the Trump administration several useful tools and options for engaging with Russia without having to renegotiate a new treaty and gain approval from the U.S. Senate. They only require political will and execution. The treaty establishes the categories, counting rules, and processes that both sides previously relied on. It also houses the Bilateral Consultative Commission, the body responsible for resolving technical and implementation issues, and codifies the rules and parameters for data exchanges. Even partial transparency would immediately improve the accuracy of U.S. force planning and reduce reliance on costly worst-case assumptions.

News -> Russia’s strategic interest, cost of 3-way arms race, impact on US nuclear modernization program

Russia’s willingness to extend New START is not altruistic. It reflects a clear strategic calculus. With a GDP roughly one-tenth and a defense budget roughly one-sixth that of the United States, Russia faces greater constraints in sustaining long-term nuclear modernization. Moscow has a strong interest in preventing a period of fully unconstrained U.S. expansion, and that asymmetry creates leverage for Washington.

And restraint is in the United States’ strategic interest as well, mitigating the skyrocketing cost of a three-way arms race while shoring up the nuclear order that helped sustain its global dominance for decades. Even narrow, interim transparency directly serves U.S. interests. It would improve U.S. intelligence assessments, reduce pressure for worst-case budgeting, and allow modernization investments to be prioritized more efficiently.

Crucially, the extension also would not constrain U.S. modernization timelines. Instead, it would create a more predictable strategic environment in which modernization could proceed without the pressure to plan simultaneously for every potentially adverse scenario.

News -> impact on international non-proliferation

The state of U.S.-Russian arms control is not merely a bilateral issue.

First, it directly affects allied perceptions of nuclear risk and the credibility of U.S. extended deterrence. When the world's major nuclear powers abandon transparency and limitation structures, allied publics and policymakers naturally question their own adherence to the nuclear order. Russia's nuclear signaling in recent years has revived debates within NATO about forward deployed systems, shared burdens, and the future of nuclear posture in Europe. In East Asia, debates in Japan and South Korea about developing independent nuclear capabilities have become increasingly mainstream.

…

Meanwhile, the broader nonproliferation system is also under acute strain. Iran and North Korea continue to advance their capabilities. The Nuclear Nonproliferation Treaty review process has struggled to produce consensus. States with advanced civilian nuclear programs are increasingly questioning whether the traditional trade-offs underpinning abstinence remain stable. In this environment, the behavior of the established nuclear powers carries outsized influence.

The complete absence of U.S.-Russian limits would further weaken nonproliferation norms and make it harder for the United States to mobilize international support for sanctions, monitoring, and export controls in the future. Even adversarial states closely watch how dominant nuclear powers manage their own arsenals when assessing their commitments.

News -> recommendation: accept, expand cooperation, 3-way talks

Washington should accept the extension and use it to restore the structures that keep nuclear competition stable, predictable, and firmly aligned with U.S. strategic priorities.

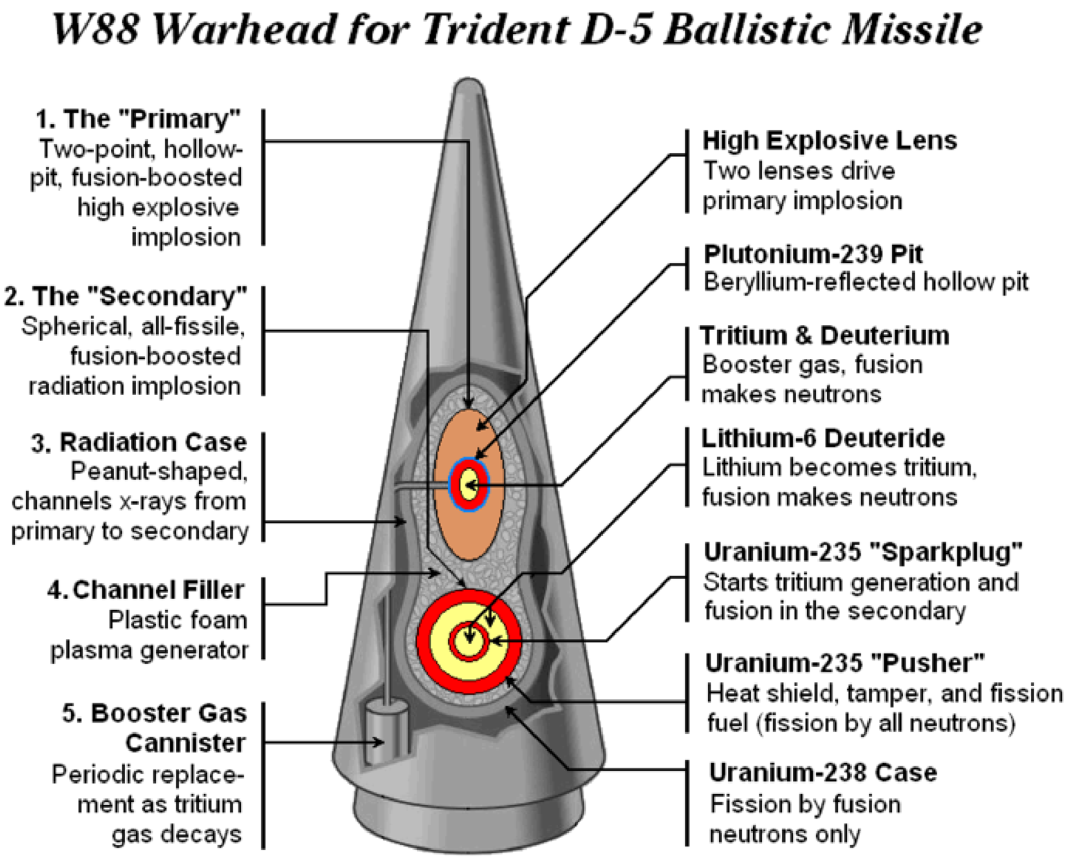
A viable strategy should include three elements: First, accepting the one-year extension as is and then stipulating that further cooperation is contingent on restored transparency. Second, capitalizing on the extension period by reintroducing incremental verification steps, including renewed data exchanges and on-site inspections. And third, treating the extension not as a final solution but as a bridge to longer-term strategic stability discussions with China as well as Russia.

A short extension would not be a concession to Russia. It would preserve a framework that allows the United States to restore oversight mechanisms, manage a period of simultaneous modernization among several nuclear powers, and stabilize a broader nonproliferation system under strain. Even a limited agreement would buy time for U.S. planners to modernize efficiently and reassure allies who increasingly question whether the international order that has constrained nuclear proliferation for five decades is beginning to erode.

Module 2: Nuclear Weapons

Physics of Nuclear Weapons

Why should we 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 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 costs of modernization of nuclear arsenals?
- 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 —

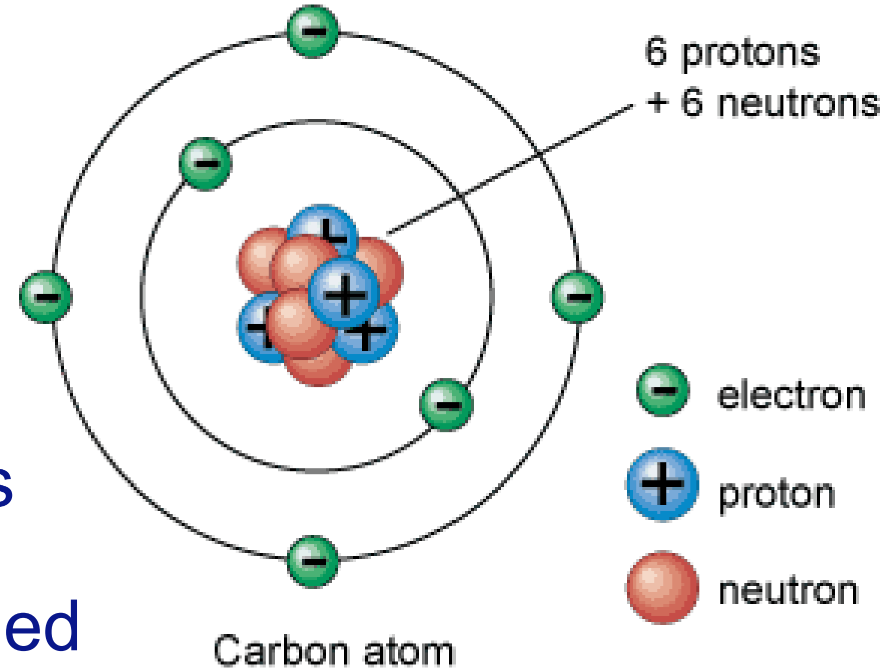
- Atoms and nuclei
- Fission and fusion
- Nuclear reactors and nuclear bombs
- Fission weapons (“A-bombs”)
- Thermonuclear weapons (“H-bombs”)
- Production of nuclear explosive material (NEM)
- Implications for nuclear testing and proliferation

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.

Atoms and Nuclei

Atomic Nature of Matter



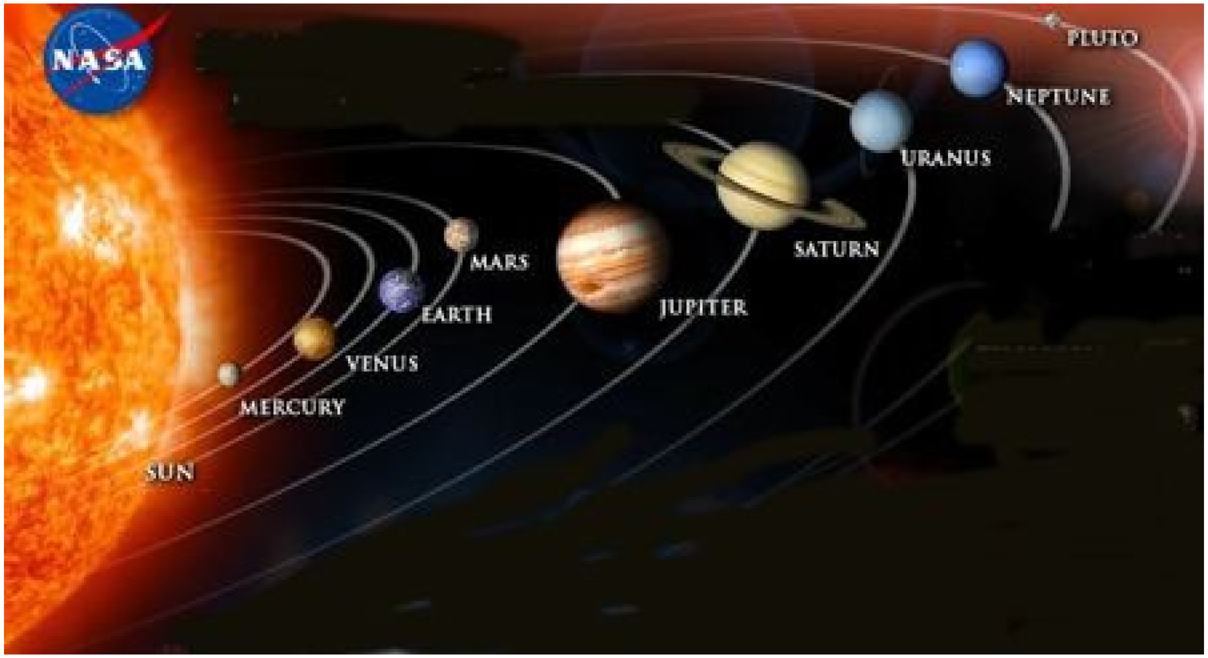
- All matter on earth is made of atoms
- Atoms have a tiny nucleus surrounded by a very much larger electron cloud
- Every nucleus is composed of protons and neutrons; both are called "nucleons"
- Protons and neutrons are made of smaller particles: quarks (this fact is unimportant for nuclear weapons)

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)



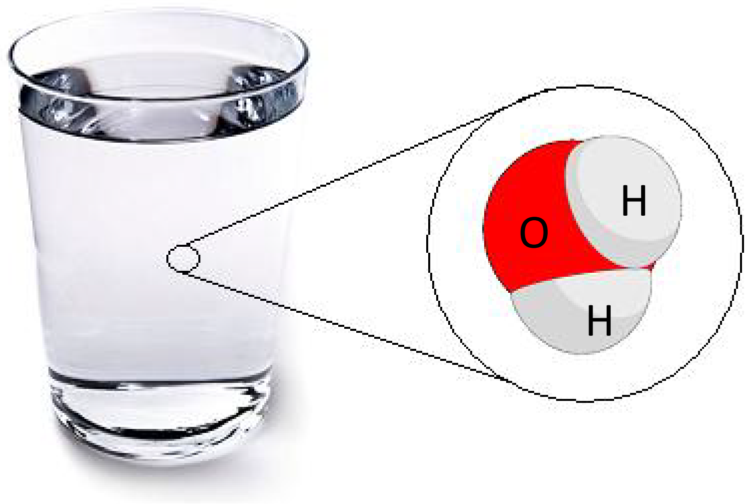
Gravity:
Relative Strength

10^{-41}

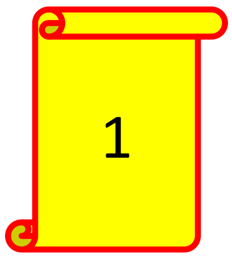
Fundamental Forces of Nature – 2

2. Electromagnetic force (structure of atoms and molecules)

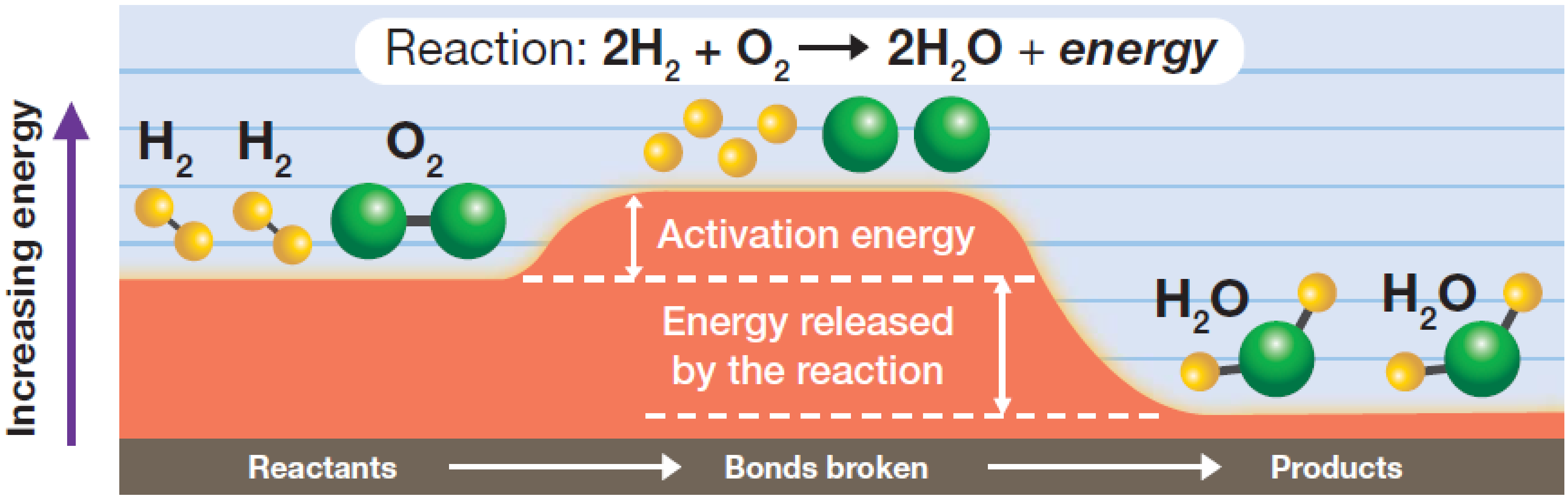
- Can be attractive or repulsive
- Classical electrical force decreases as $1/r^2$ ("long-range")
- Described by the theory of electromagnetism, developed in the late 19th Century
- The quantum theory of electromagnetism is called Quantum Electrodynamics



Electromagnetic Force Relative Strength



Energy Released by Electromagnetic Reactions between Atoms and Molecules



We use electromagnetic energy from chemical bounds frequently:

wood fire
car engine
coal electrical power plant
explosives

Electromagnetic Energy Stored in Chemical Bounds

Lecture Question

Consider that the binding energy of an electron in a hydrogen atom is about 10 eV. How much energy do You estimate can be gained by forming a H_2O molecule ?

A	0.01 eV
B	0.1 eV
C	3 eV
D	100 eV
E	1000 eV

1 eV is a unit for energy: ”electron-volt”. It corresponds to a very small amount of energy: $1 \text{ eV} = 1.6 \times 10^{-19}$ Joule

We will use this energy units “eV” to be able to compare energy released in atomic reactions to energy released in nuclear processes.

eV is a unit suitable to measure energy levels involve in atomic & nuclear reactions

Electromagnetic Energy Stored in Chemical Bounds

Lecture Question Answer

Consider that the binding energy of an electron in a hydrogen atom is about 12 eV. How much energy do You estimate can be gained by forming a H_2O molecule ?

A 0.01 eV

B 0.1 eV

C 3 eV

D 100 eV

E 1000 eV

1 eV is a unit for energy: ”electron-volt”. It corresponds to a very small amount of energy: 1 eV = 1.6 x 10^{-19} Joule

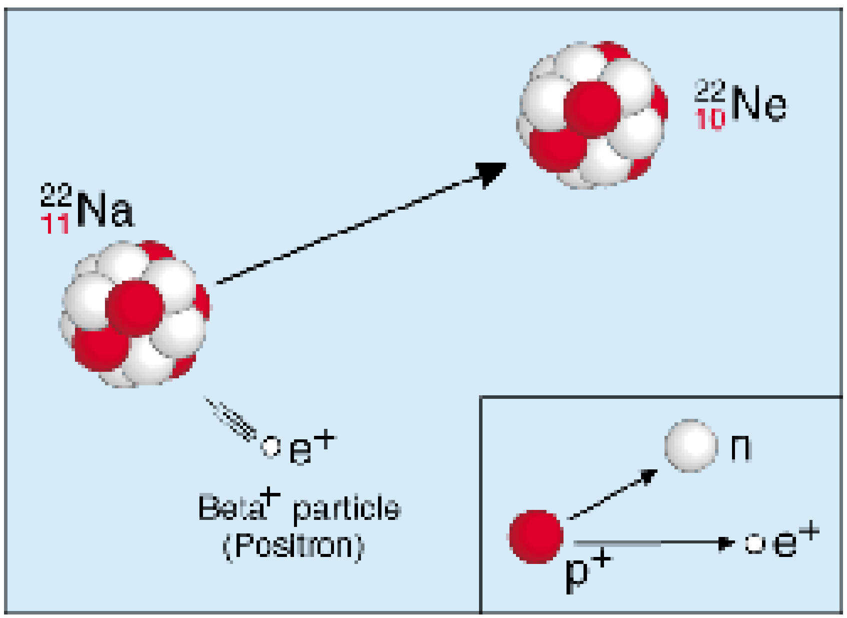
Hydrogen-Oxygen reactions are highly explosive – much energy is released due to the large number of atoms involved!

Fundamental Forces of Nature – 3

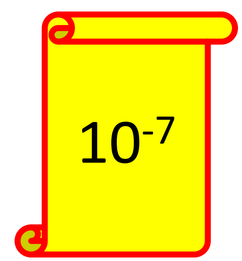
3. Weak nuclear force (radioactivity)

- 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)



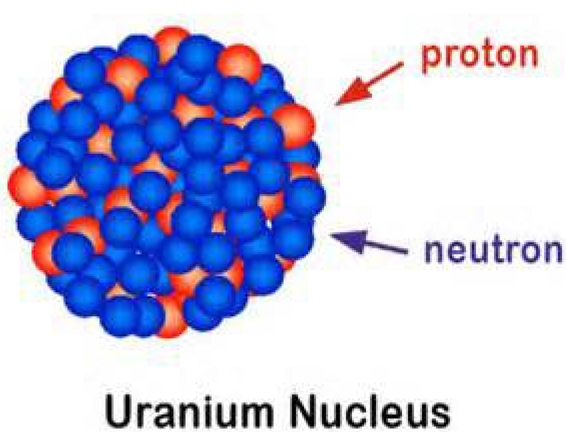
Weak Nuclear Force: Relative Strength



Fundamental Forces of Nature – 4

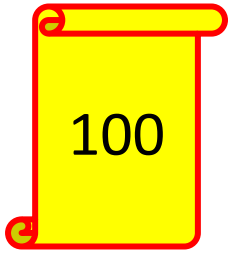
4. Strong nuclear force ("strong force") (structure of nuclei)

- 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



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

Strong Nuclear Force Relative Strength



Nuclear Energy Stored in Nuclei

Lecture Question

The binding energy of each proton and neutron in a Uranium nucleus is about 7.5 MeV (Mega eV = Million eV). There are 235 protons and neutrons in U-235.

After a nuclear fission reaction the binding energy of each proton and neutron in the two fission daughter nuclei is about 8.4 MeV.

How much energy do you estimate can be gained by a nuclear reaction splitting one Uranium nucleus with 235 protons and neutrons into two daughter nuclei?

1MeV = 1,000,000 eV

- A 0.02MeV
- B 0.2 MeV
- C 2 MeV
- D 20 MeV
- E 200 MeV

Nuclear Energy stored in Nuclei

Lecture Question Answer

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A	0.02MeV
B	0.2 MeV
C	2 MeV
D	20 MeV
E	**200 MeV**

1MeV = 1,000,000 eV

Compare energy release from:
1 nuclear fission reaction: 200,000,000 eV
1 atomic reaction: 3 eV

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.

Nuclear Forces and Chemical Reactions

Lecture Question

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

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

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

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

Nuclear Forces and Chemical Reactions

Lecture Question Answer

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Lecture Question

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

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

Lecture Question Answer

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

A 55,000 in 1995

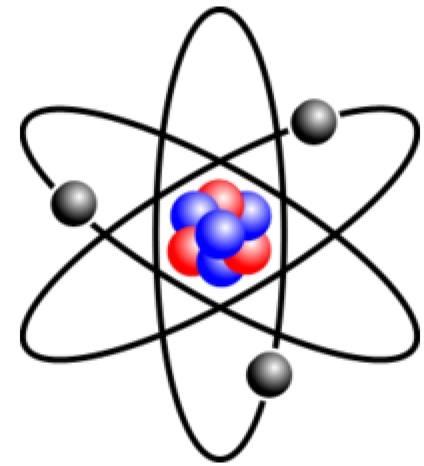
B 70,000 in 1985

C 70,000 in 1980

D 55,000 in 1975

E 90,000 in 1985

Lithium-Atom



Atoms and Nuclei

Sizes of atoms and nuclei

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

$$\text{Size of an Atom: } r_{atom} \approx 10^{-10}\,\text{m} = 0.1\text{ nm}$$

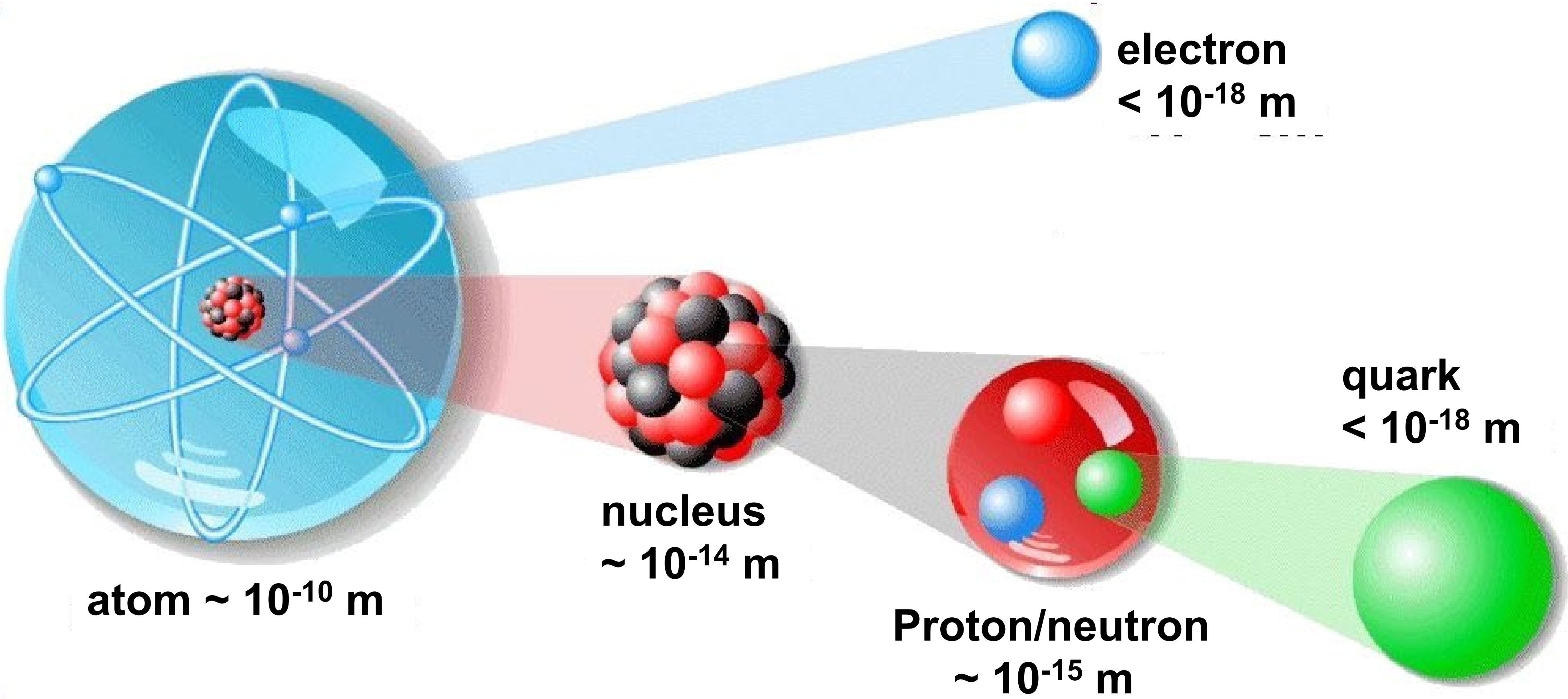
$$\text{Size of a nucleus} : r_{nucleus} \approx 10^{-14}\,\text{m} = 0.0001\text{ nm}\ ,$$

1.0 nm = 1 billionth of a meter

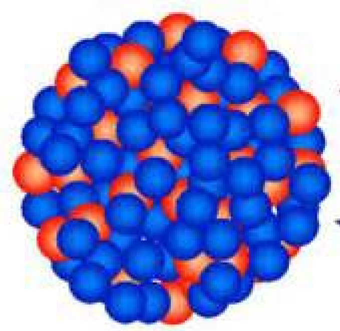
Masses of Protons and Neutrons compared to Electrons

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

Atomic Structure and Length Scales



Atomic Nuclei



- 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: $A = Z + N$

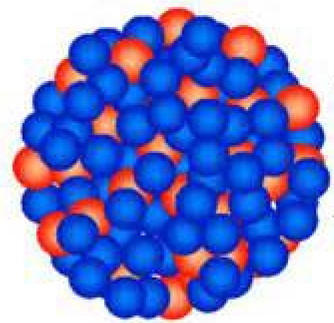
Chemical Properties of Atoms

- 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.

Atoms with Different Nuclei: Isotopes and Isotones



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

Can Pu or U Isotopes be Separated through Chemical Analysis?

Lecture 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

Can Pu or U Isotopes be Separated through Chemical Analysis?

Lecture Question Answer

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?

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

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

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

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Module 2: Nuclear Weapons

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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/sp2026/reading.html

Today: Radioactivity
News
Fission and Fusion

Lecture Question

$^{239}_{94}Pu$ nuclei consist of

A 94 neutrons + 239-94=145 protons

B 94 protons + 239-94=145 neutrons

C 94 protons + 239 neutrons

D 94 neutrons + 239 protons

Lecture Question Answer

$^{239}_{94}Pu$ nuclei consist of

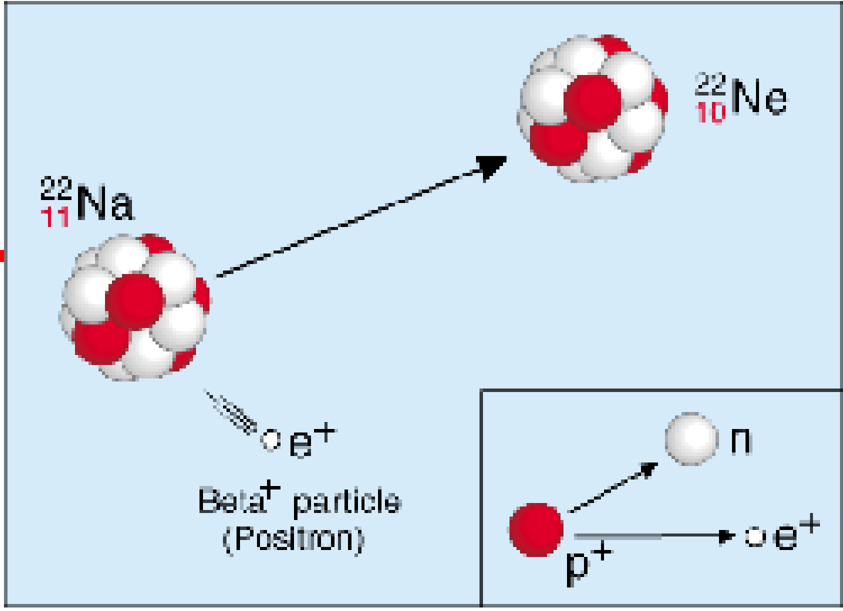
A 94 neutrons + 239-94=145 protons

B 94 protons + 239-94=145 neutrons

C 94 protons + 239 neutrons

D 94 neutrons + 239 protons

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)

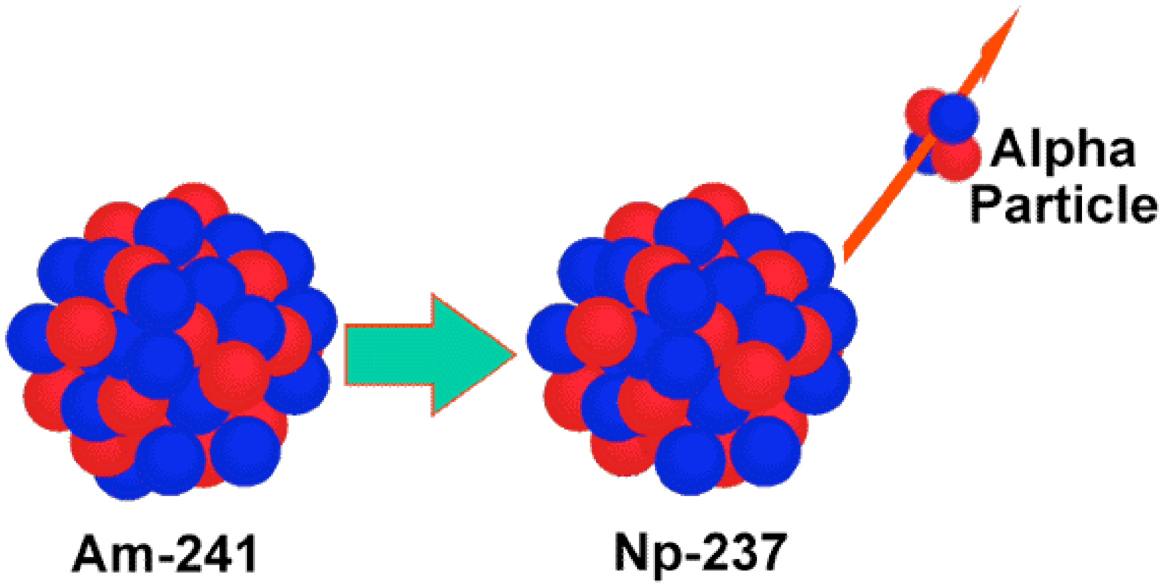
Parent —> Daughter + anti-electron (+ neutrino)

3. Gamma decay

Parent —> Daughter + gamma-ray

4. Spontaneous fission

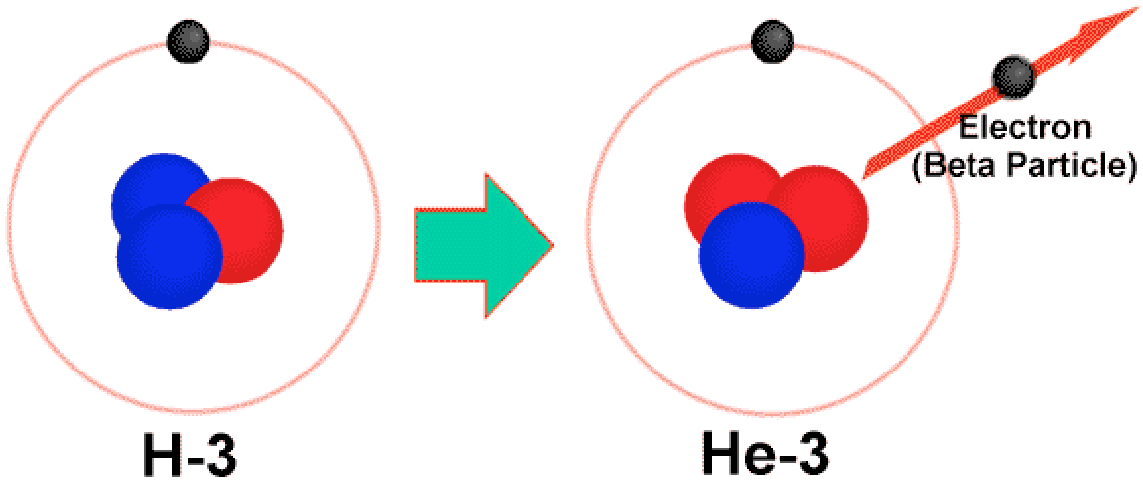
Illustration of Alpha Decay



Americium as 95 protons and 136 neutrons

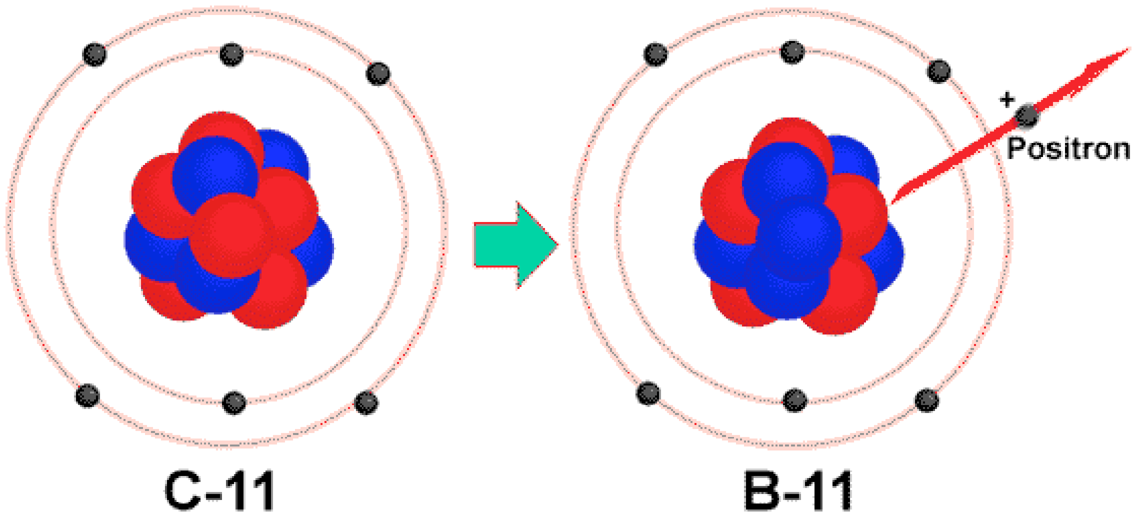
An alpha particle is a helium nucleus and has 2 protons and 2 neutrons

Illustration of Negative Beta Decay (Electron Emission)



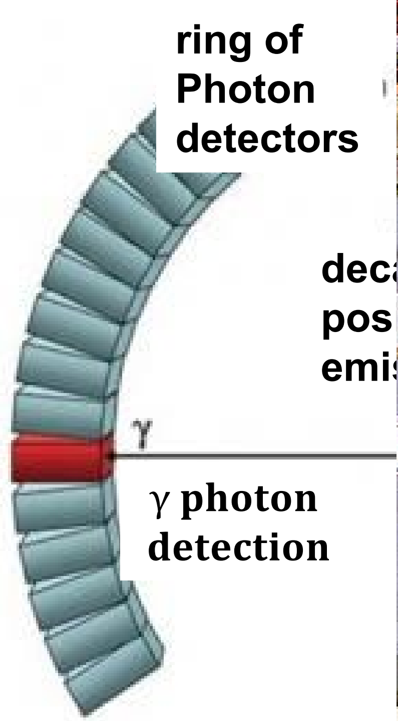
Tritium is a hydrogen isotope and decays into He-3, a helium isotope
Negative Beta Decay increases Z !

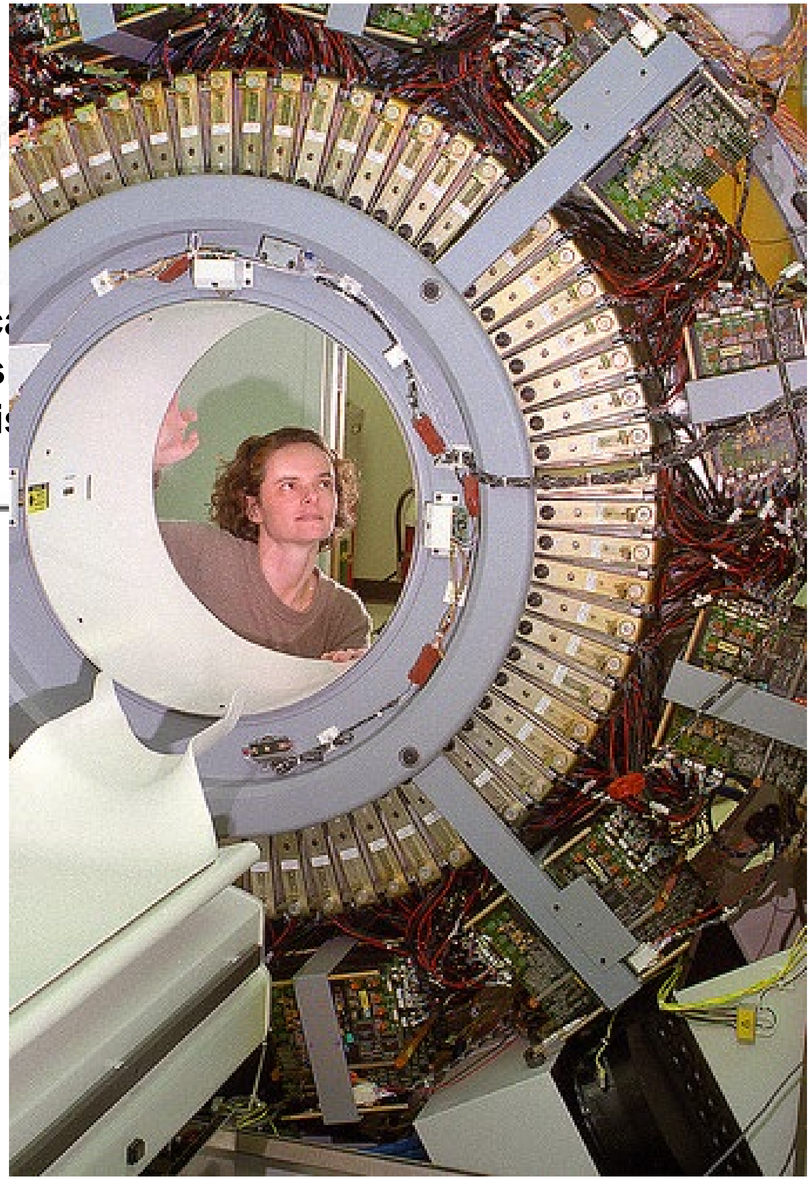
Illustration of Positive Beta Decay (Positron Emission)



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





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

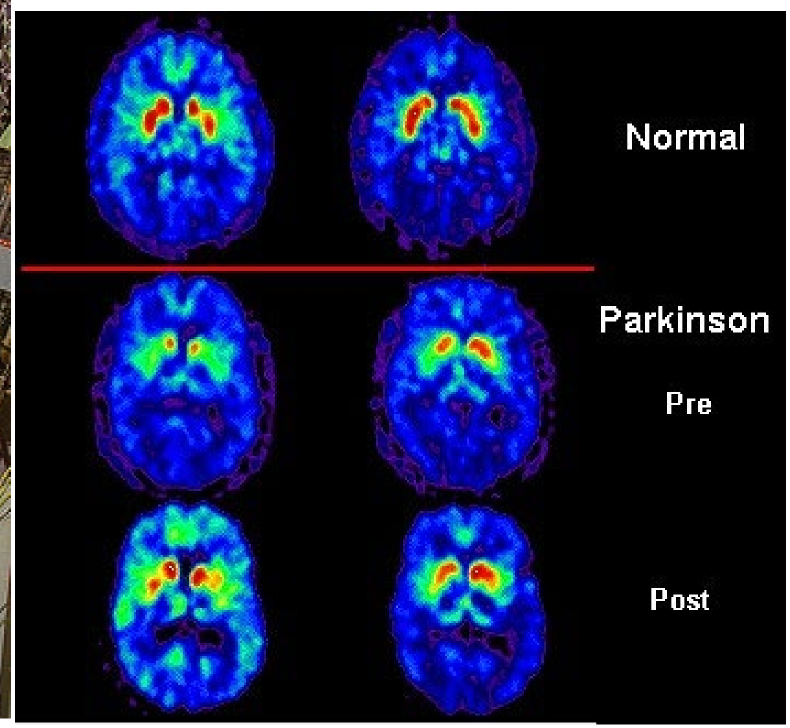
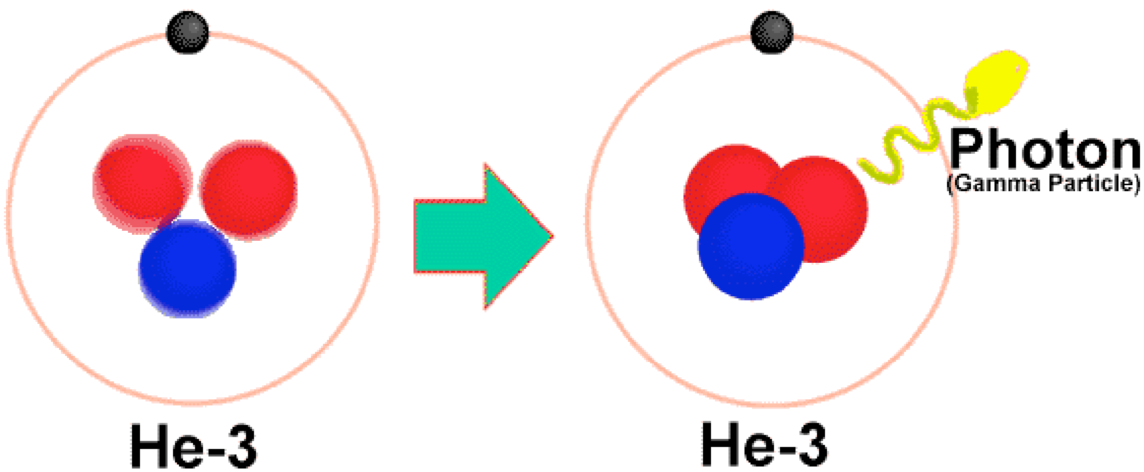
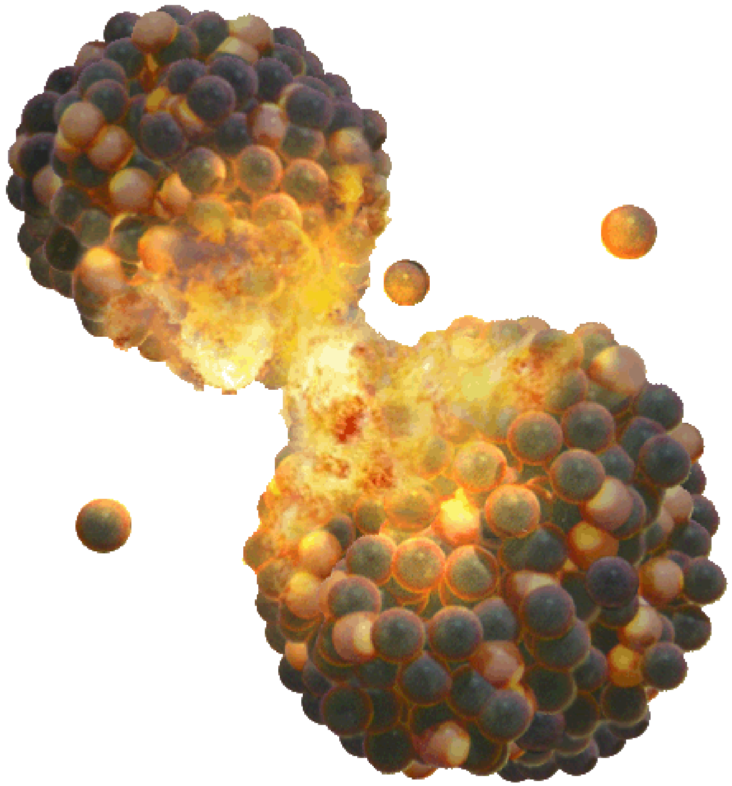


Illustration of Gamma-Ray Emission



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

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.

Lecture 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

Lecture Question 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
B. 10 times more
C. 100 times more
D. 1,000 times more
E. 1,000,000 times more

Lecture Question

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

A. Positive Beta Decay

B. Negative Beta Decay

C. Gamma Decay

D. Spontaneous Fission

Lecture Question Answer

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

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News

Bulletin of the Atomic Scientists

https://thebulletin.org/doomsday-clock/2026-statement/

Bulletin of the Atomic Scientists

Doomsday Clock | Nuclear Risk | Climate Change | Disruptive Technologies | Biosecurity

IT IS 85 SECONDS TO MIDNIGHT

Overview   Current Time   The Clock Setters   FAQ   Timeline

It is now 85 seconds to midnight

2026 Doomsday Clock Statement

Science and Security Board
Bulletin of the Atomic Scientists

Editor, John Mecklin

January 27, 2026

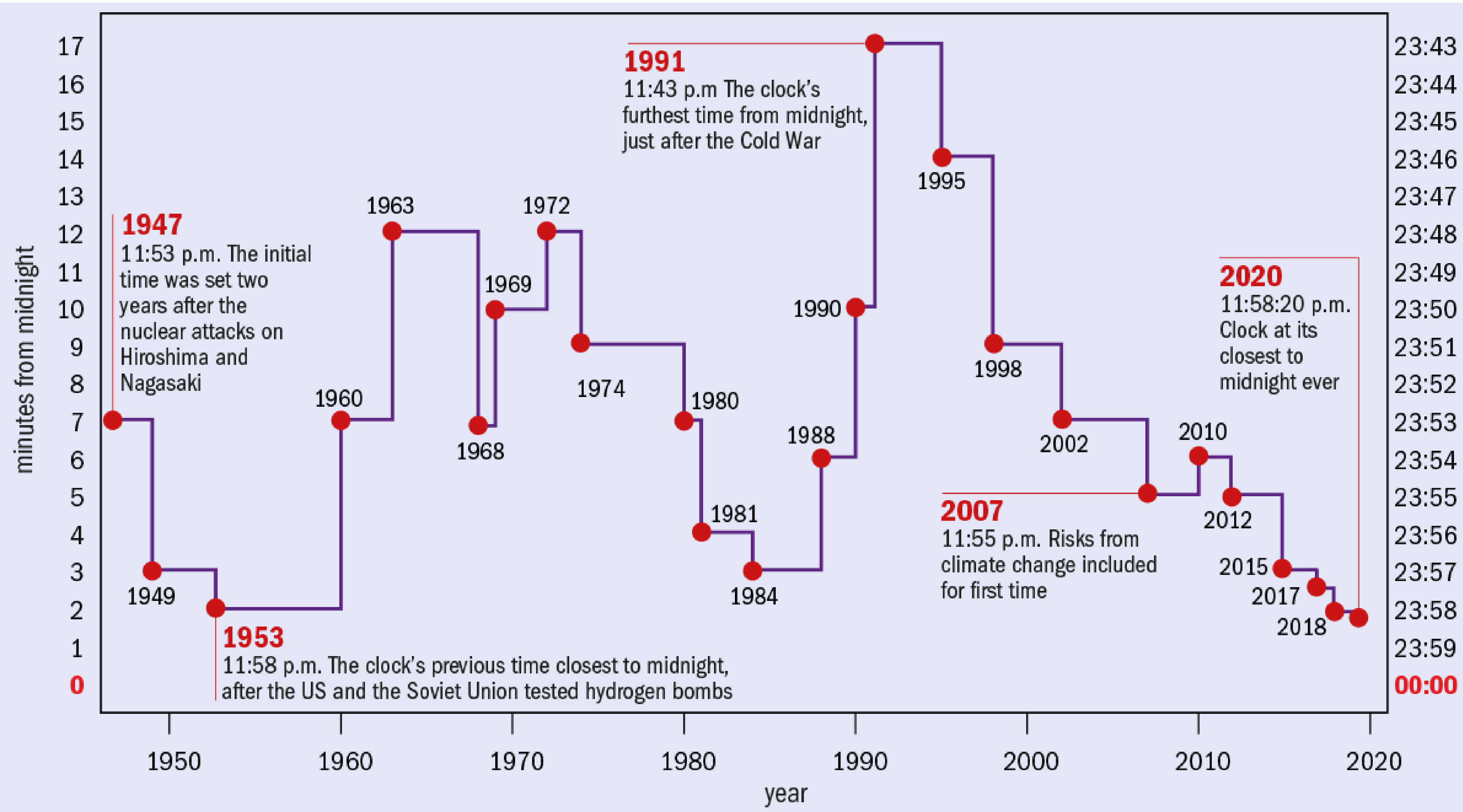
Founded in 1945 by Albert Einstein, J. Robert Oppenheimer, and University of Chicago scientists who helped develop the first atomic weapons in the Manhattan Project, the Bulletin of the Atomic Scientists *created the Doomsday Clock two years later, using the imagery of apocalypse (midnight) and the contemporary idiom of nuclear explosion (countdown to zero) to convey threats to humanity and the planet. The Doomsday Clock is set every year by the* Bulletin's *Science and Security Board in consultation with its Board of Sponsors, which includes eight Nobel laureates. The Clock has become a universally recognized indicator of the world's vulnerability to global catastrophe caused by man-made technologies.*

The Science and Security Board

The *Bulletin*'s Science and Security Board (SASB) is composed of a select group of globally recognized leaders with a specific focus on nuclear risk, climate change, and disruptive technologies. Learn more...

News

Bulletin of the Atomic Scientists



News

Bulletin of the Atomic Scientists

News

Bulletin of the Atomic Scientists

Even as the hands of the Doomsday Clock move closer to midnight, there are many actions that could pull humanity back from the brink:

- The United States and Russia can resume dialogue about limiting their nuclear arsenals. All nuclear-armed states can avoid destabilizing investments in missile defense and observe the existing moratorium on explosive nuclear testing.
- Through both multilateral agreements and national regulations, the international community can take all feasible steps to prevent the creation of mirror life and cooperate on meaningful measures to reduce the prospect that AI be used to create biological threats.
- The United States Congress can repudiate President Trump's war on renewable energy, instead providing incentives and investments that will enable rapid reduction in fossil fuel use.
- The United States, Russia, and China can engage in bilateral and multilateral dialogue on meaningful guidelines regarding the incorporation of artificial intelligence in their militaries, particularly in nuclear command and control systems.

Our current trajectory is unsustainable. National leaders—particularly those in the United States, Russia, and China—must take the lead in finding a path away from the brink. Citizens must insist they do so.

It is 85 seconds to midnight.

Fission and Fusion

The Two Types of Fission

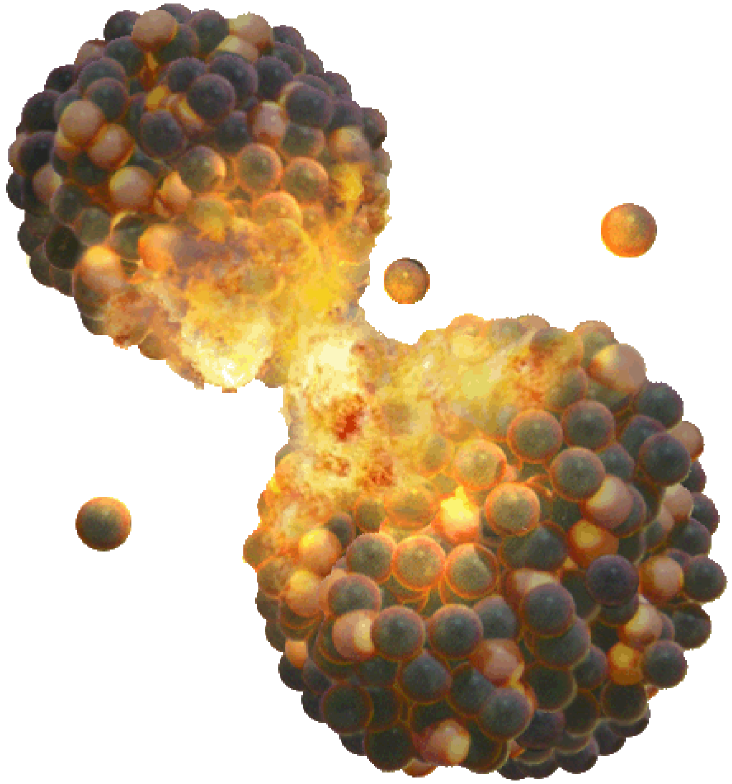
Spontaneous fission —

- 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 —

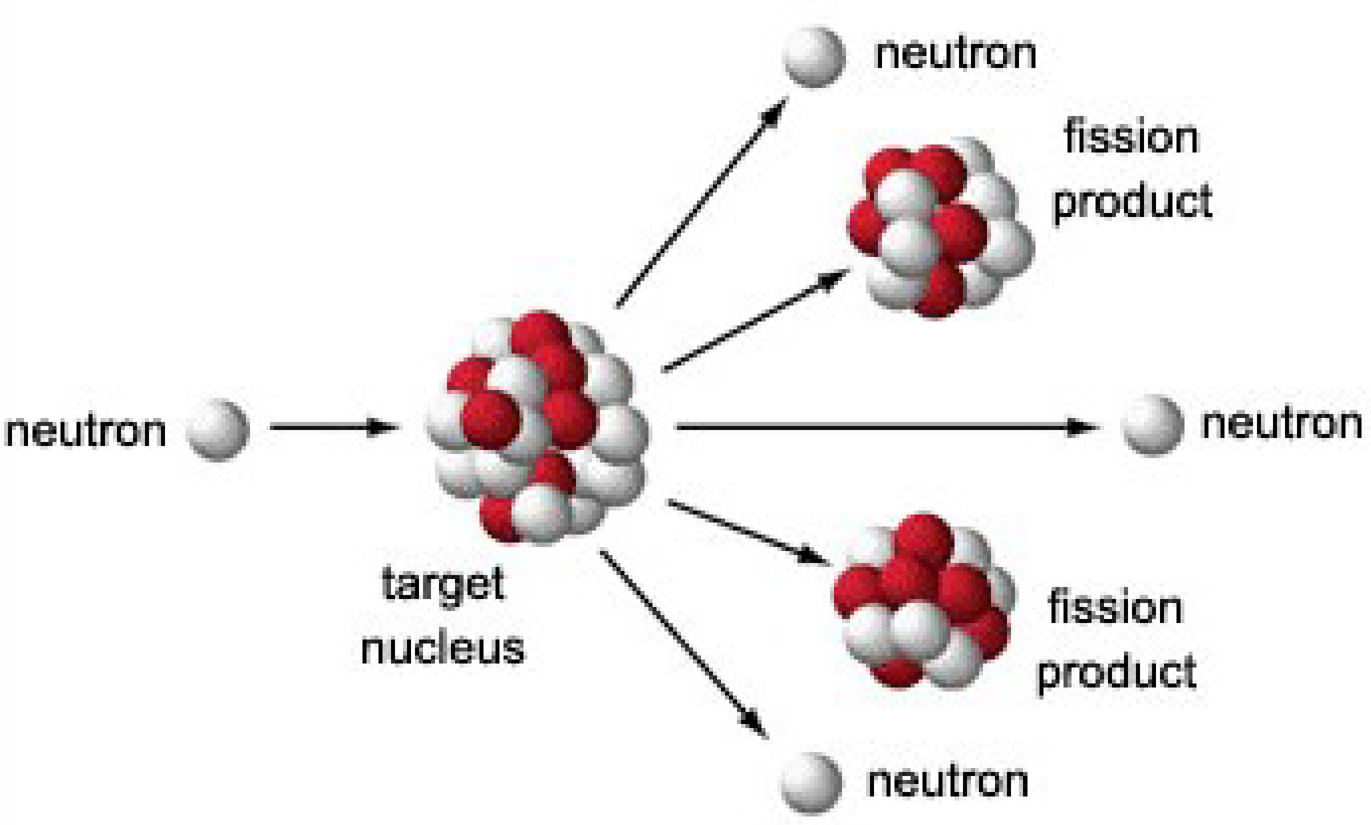
- The process in which capture of a neutron causes a nucleus to become unstable and undergo fission
- The fission fragments are similar to those for spontaneous fission

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

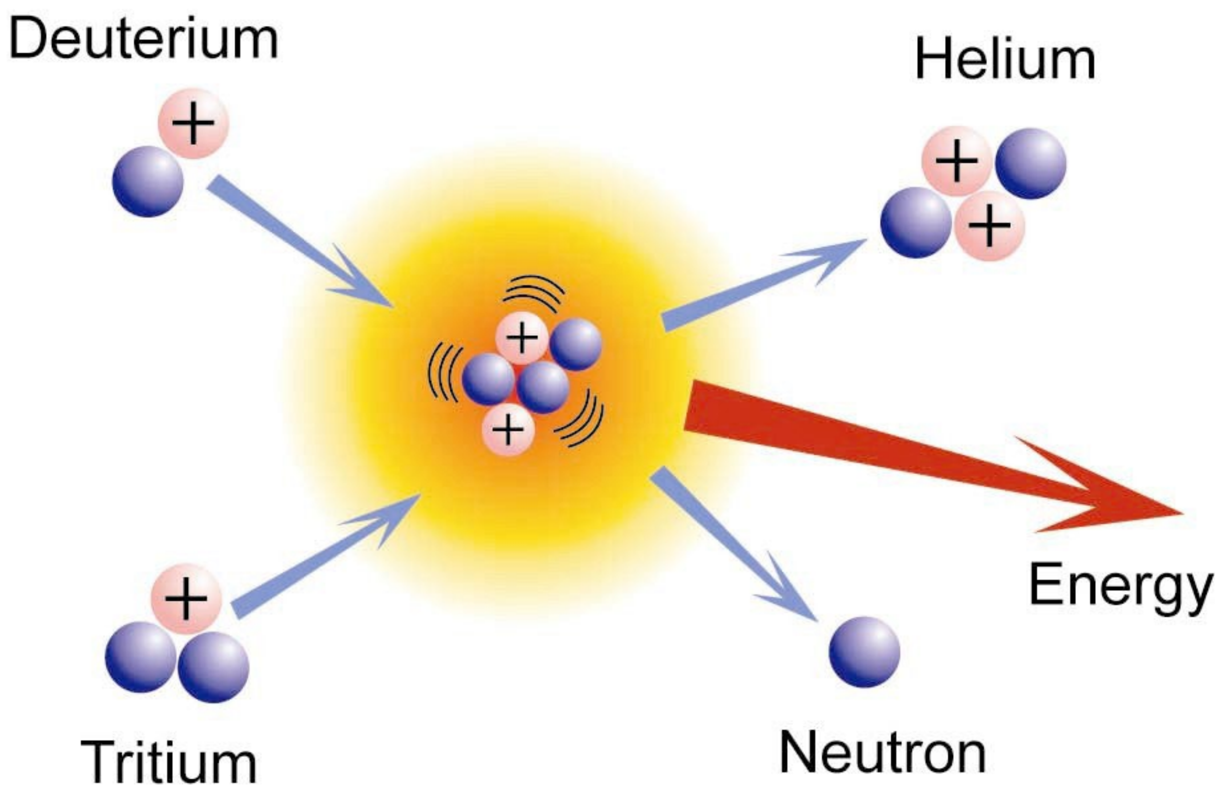


Fission: a large nucleus splits into two daughter nuclei. In the process a small number of neutrons are emitted.

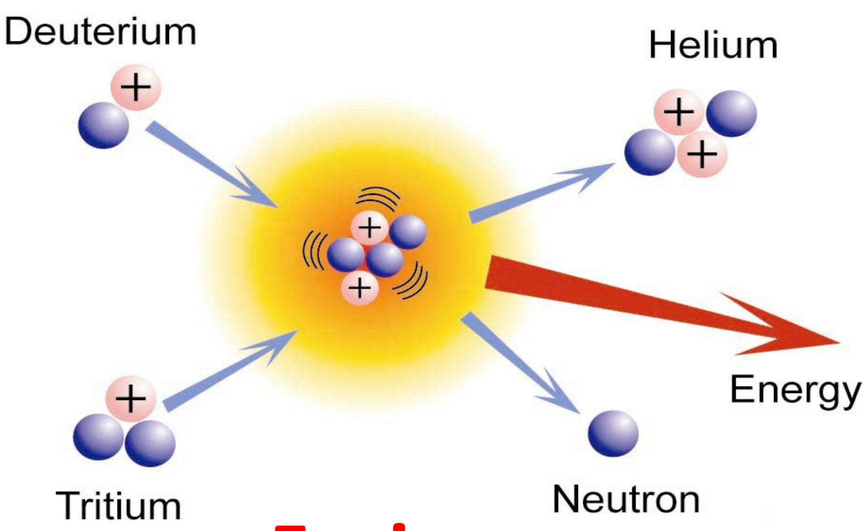
Induced Fission



Fusion

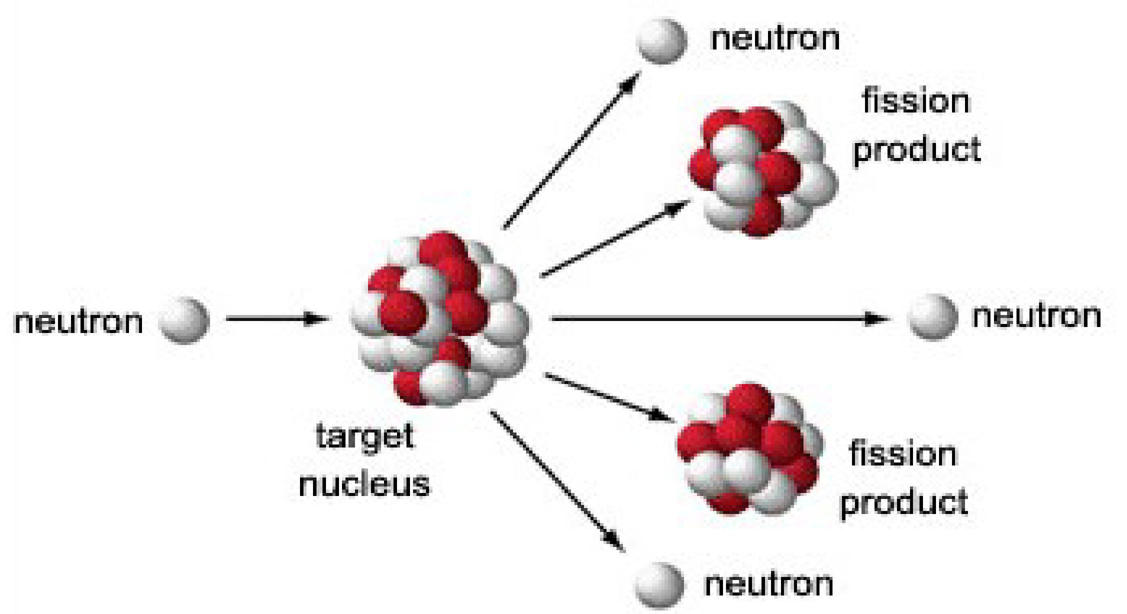


Why can both, Fission and Fusion Reactions Yield Energy ?

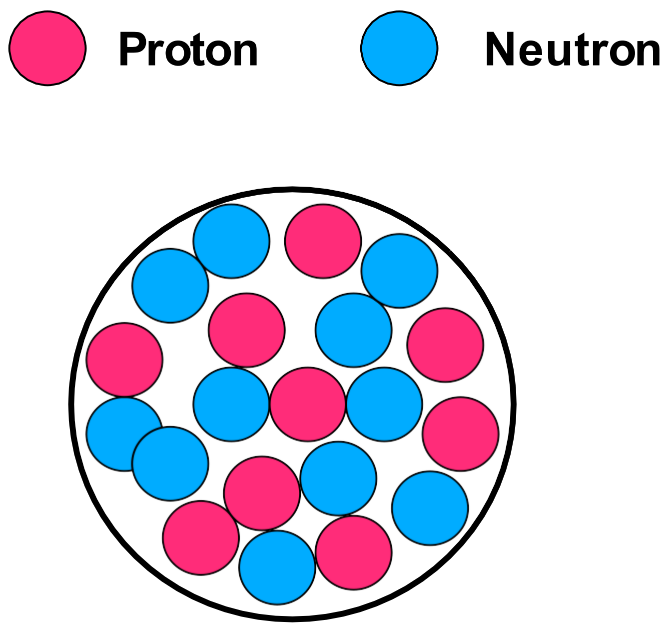


Fusion

Fission



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 !

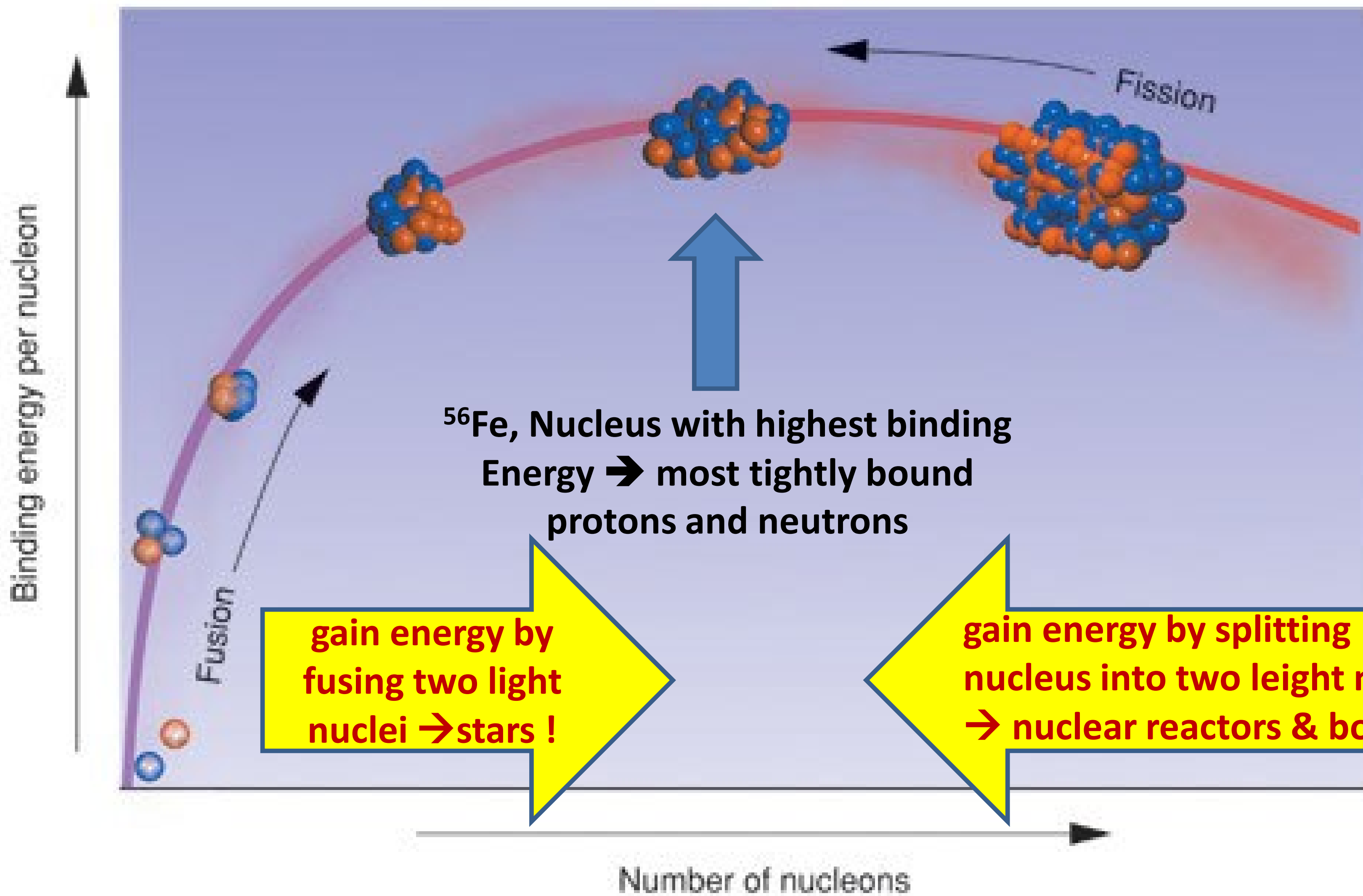
The Binding Energy Per Nucleon

- 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 —

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

- 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)



^{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 !

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)

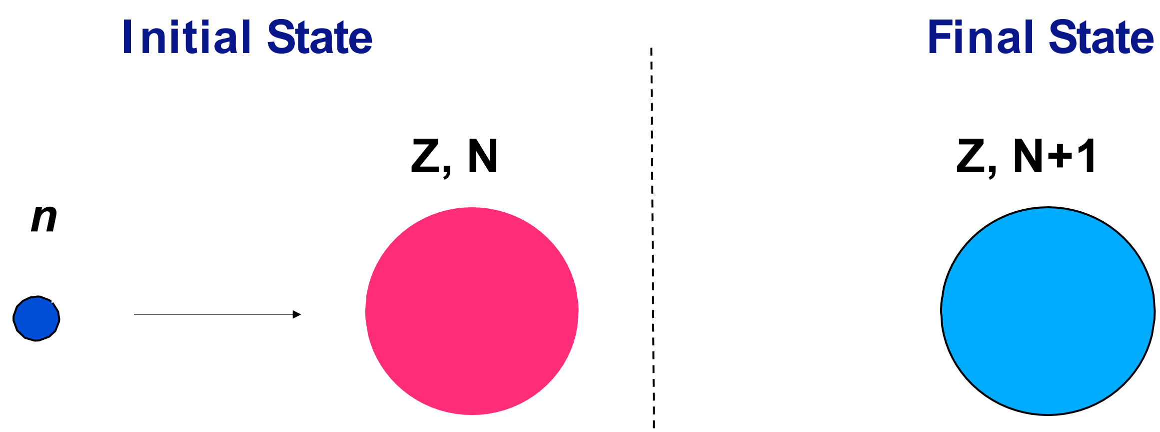
$^{9}_{4}Be$ = Be(9) stable (lighest metal) *

*, **, *** denotes increasing importance

The Neutron – 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



The resulting nucleus may be stable or unstable.

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

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

Lecture Question

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

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

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

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

D. None of the above

Lecture Question Answer

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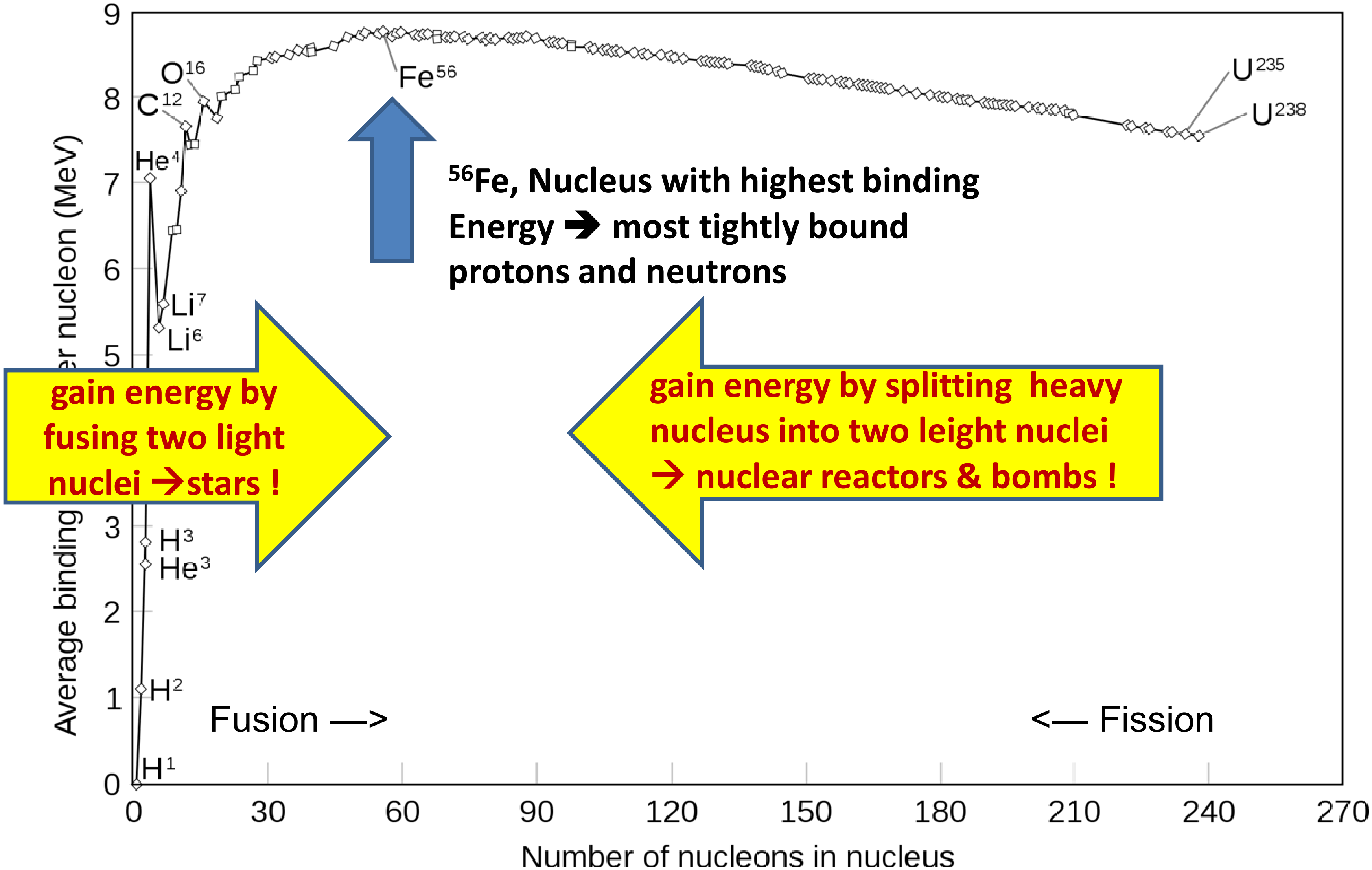
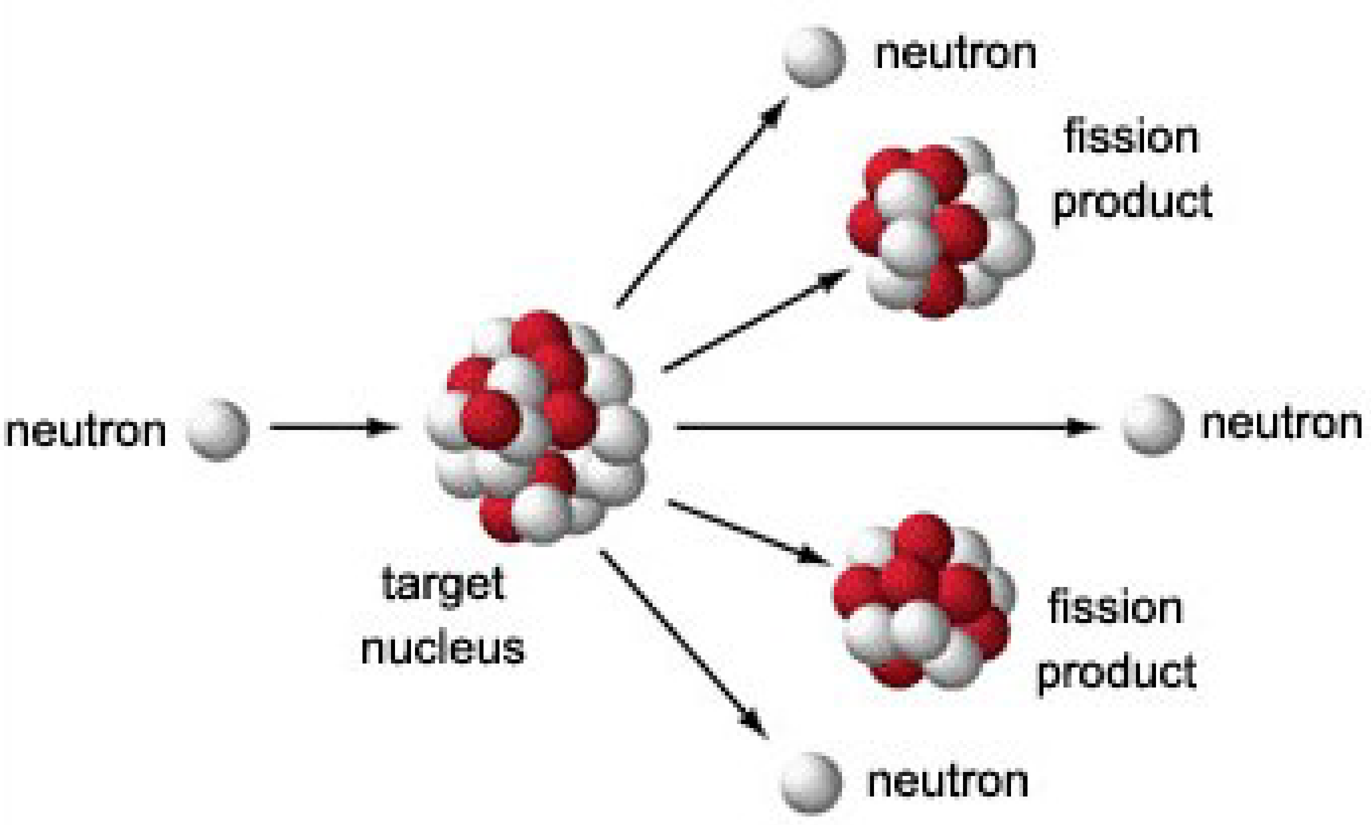
D. None of the above

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

Average Binding Energy [MeV]



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.

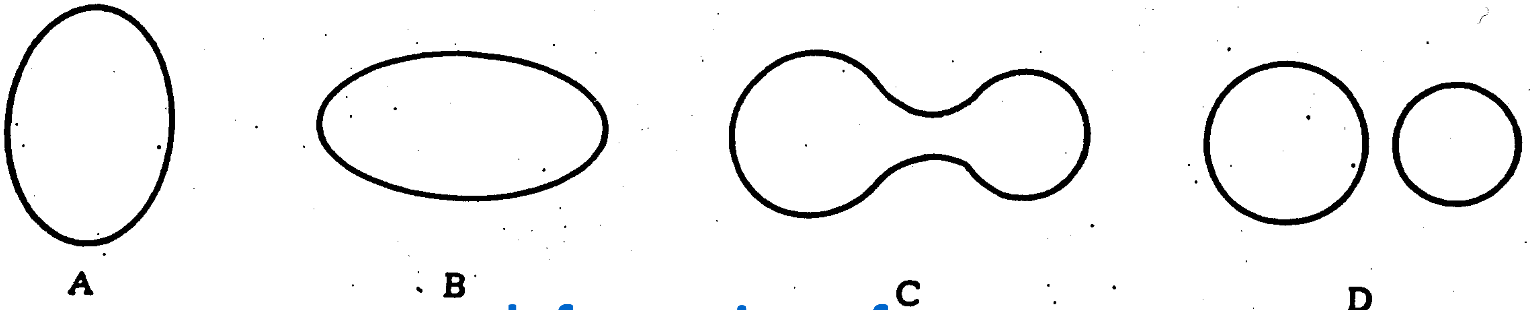
Unfortunately, *she was not included* in the Nobel Prize awarded for the discovery!

Element 109, Meitnerium, is named in her honor.

Lise Meitner's Concept of Fission

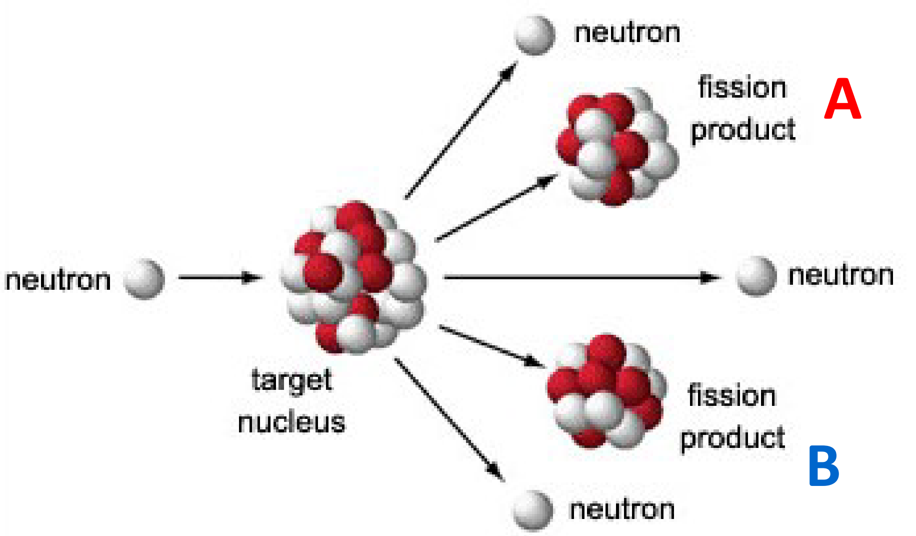
parent nucleus

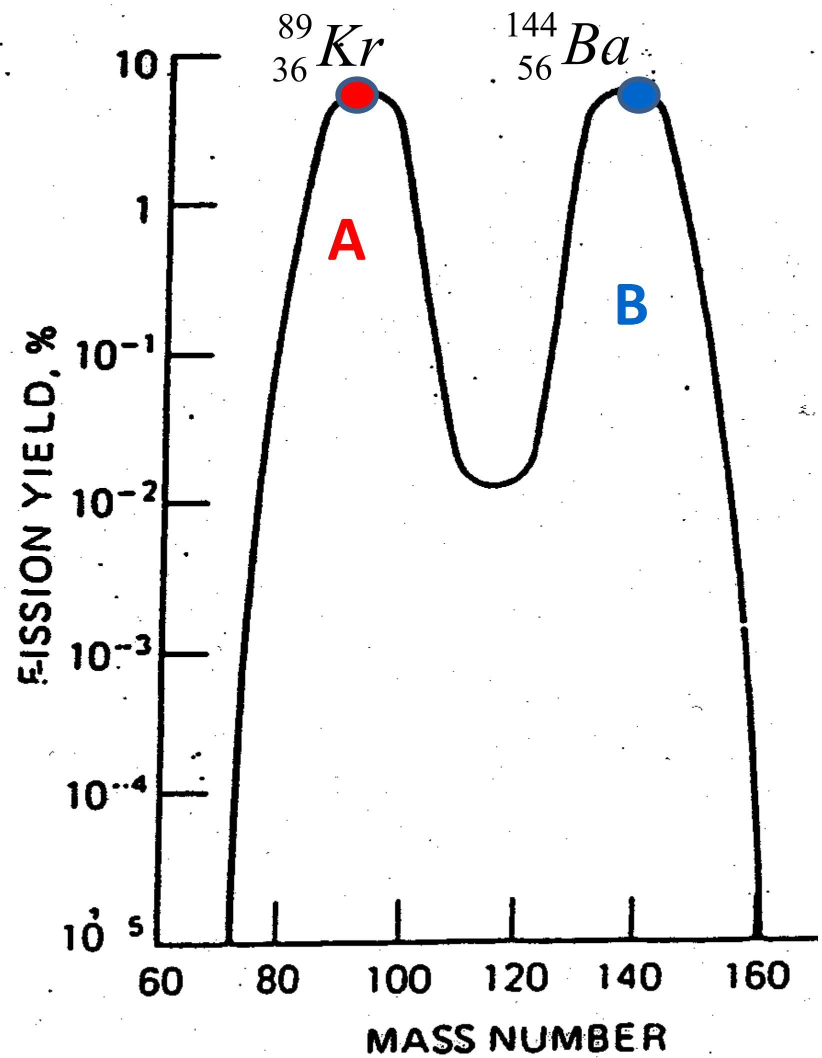
daughter nuclei



deformation of parent nucleus

Distribution of Fission Fragment Masses



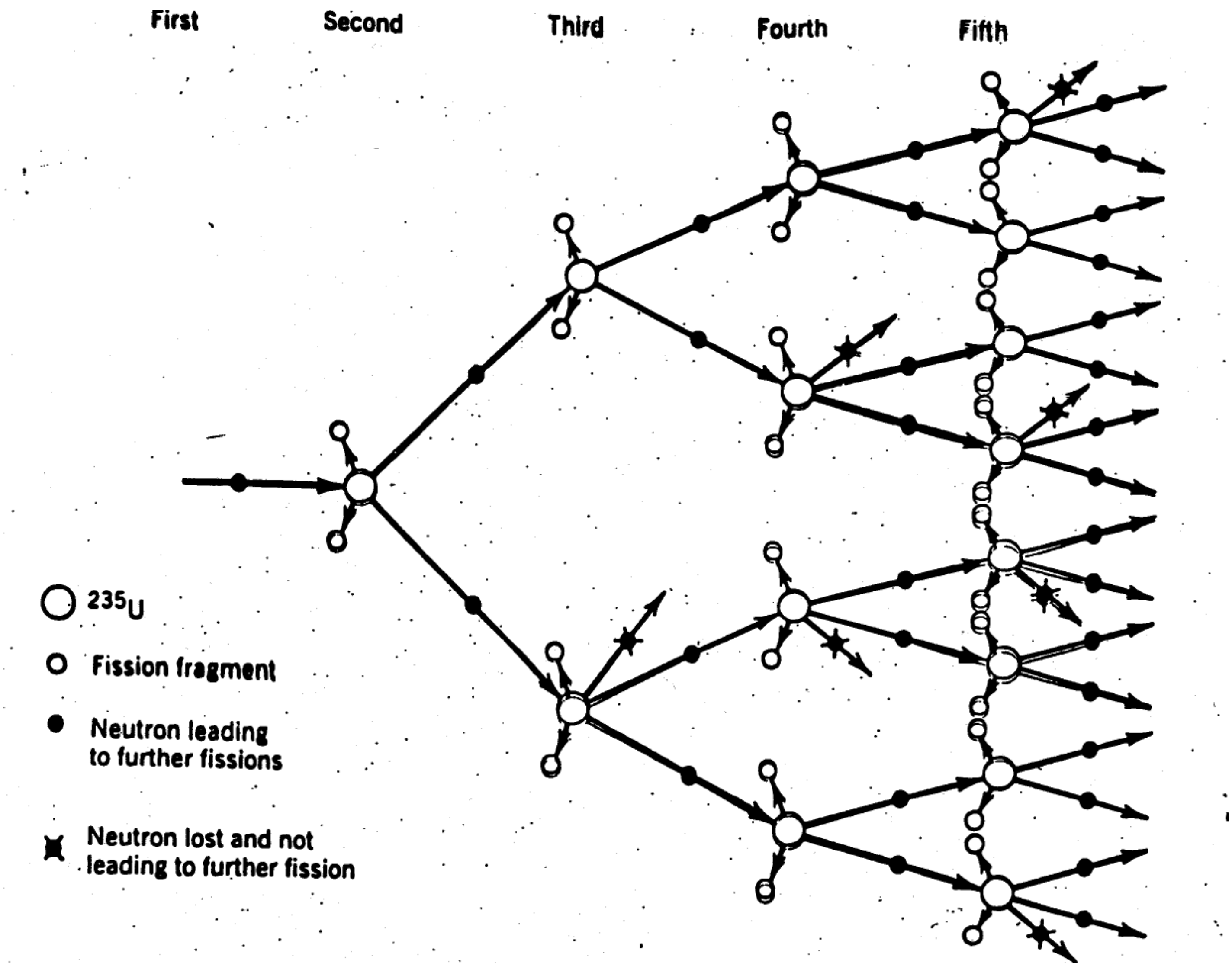


$$^{235}_{92}U \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3n + 177\,MeV$$

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



Lecture Question

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

Lecture Question Answer

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Lecture Question

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

Lecture Question Answer

The symbol "U-238" is sufficient to specify

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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, 2-4

- o Electronic submission (**10pm**)
- o RE2v1 prompt is posted on course web-page

  https://courses.physics.illinois.edu/phys280/sp2026/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/sp2026/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.

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".

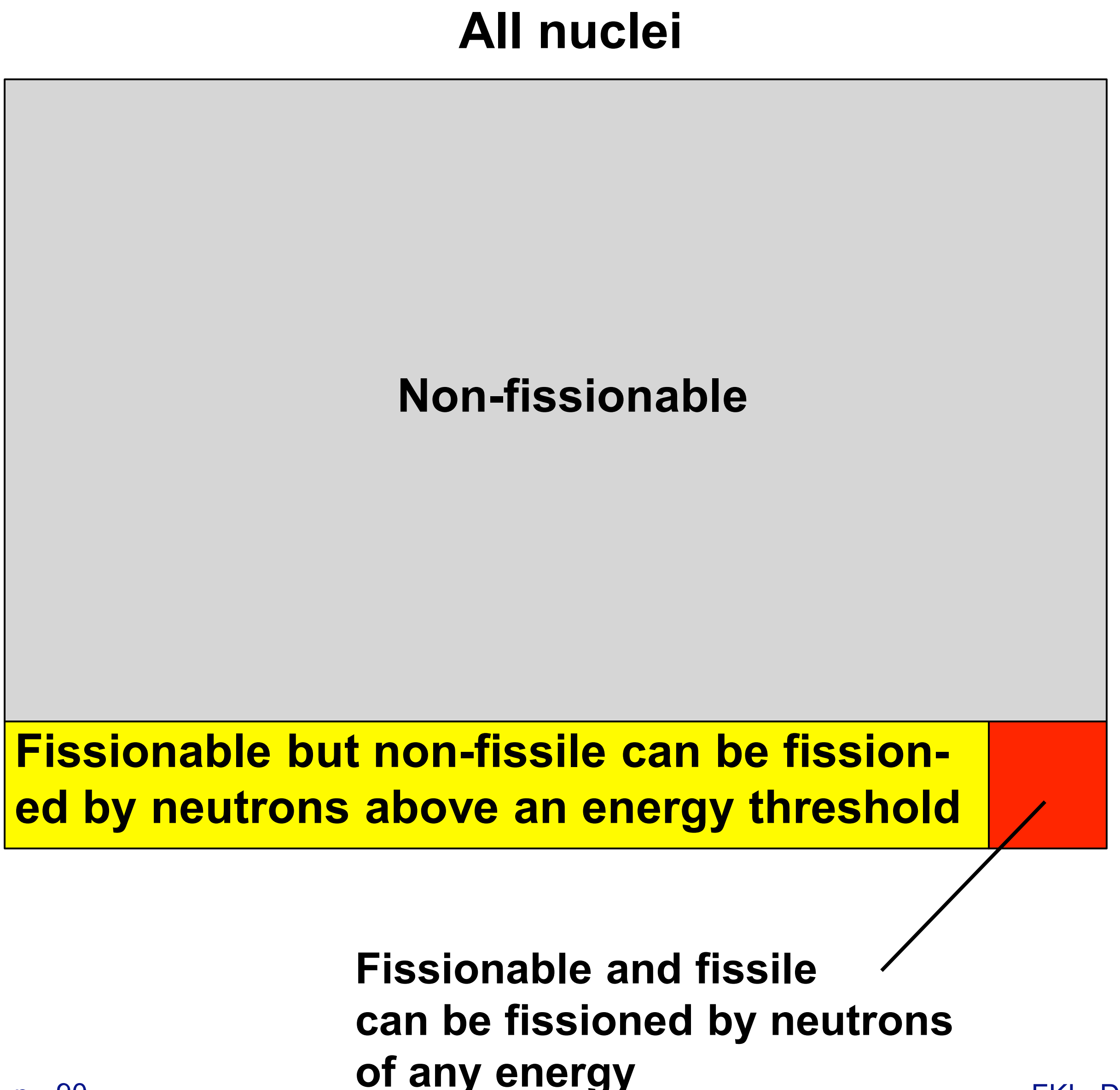
The reason is that in a nuclear reactor, the neutrons emitted by fission events lose most of their kinetic energy (i.e., "slow down") by interacting with surrounding material before inducing a further fission.

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

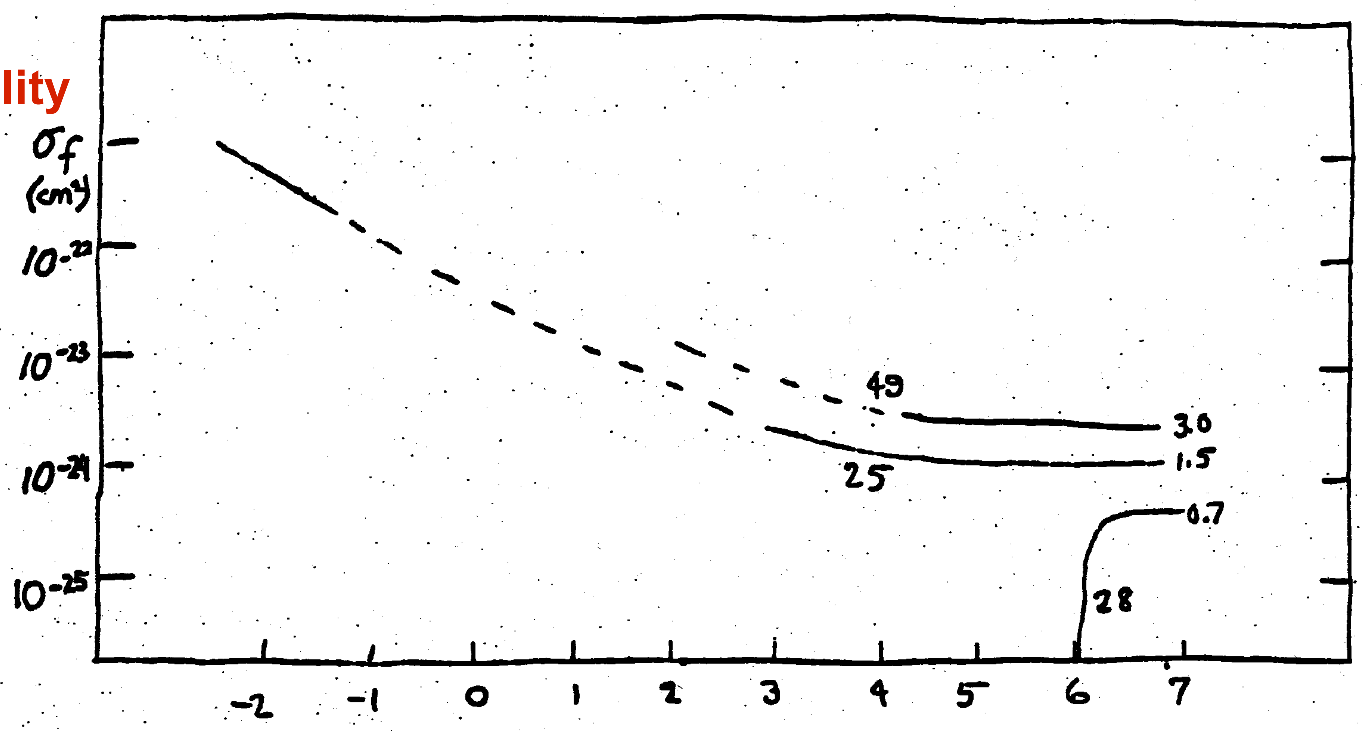


Neutron-Induced Fission Probability As a Function of the Incoming Neutron Energy for Three Important Nuclides

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

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

Fission Probability



(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

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

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

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

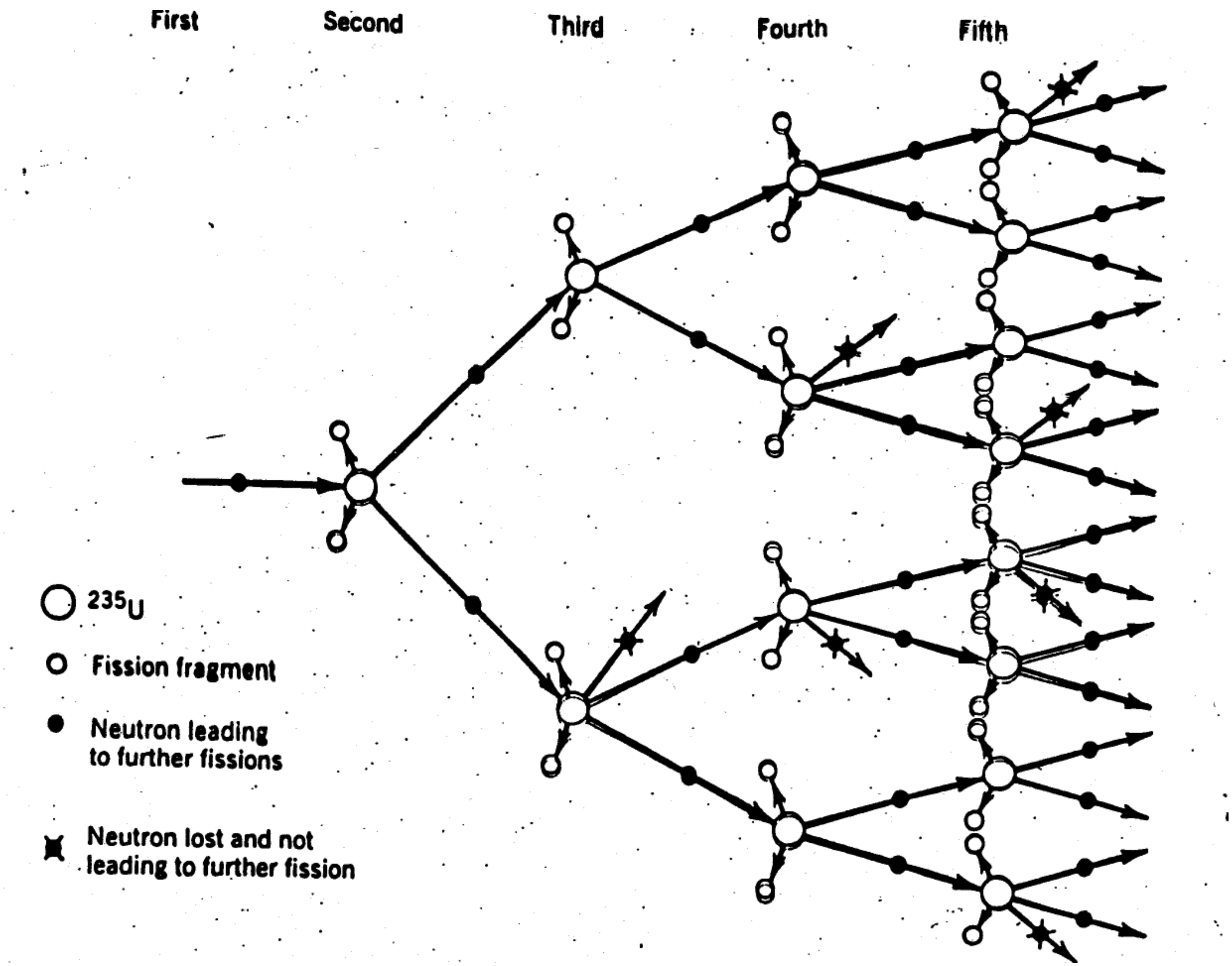
To sustain a fast-neutron chain reaction, on average at least one of the several energetic neutrons released per fission must be "productively" captured, i.e., it must produce another fission following its capture.

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.

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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

88% of total Yield (explosive energy) are released in the 3 final generations of chain reactions!

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.

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

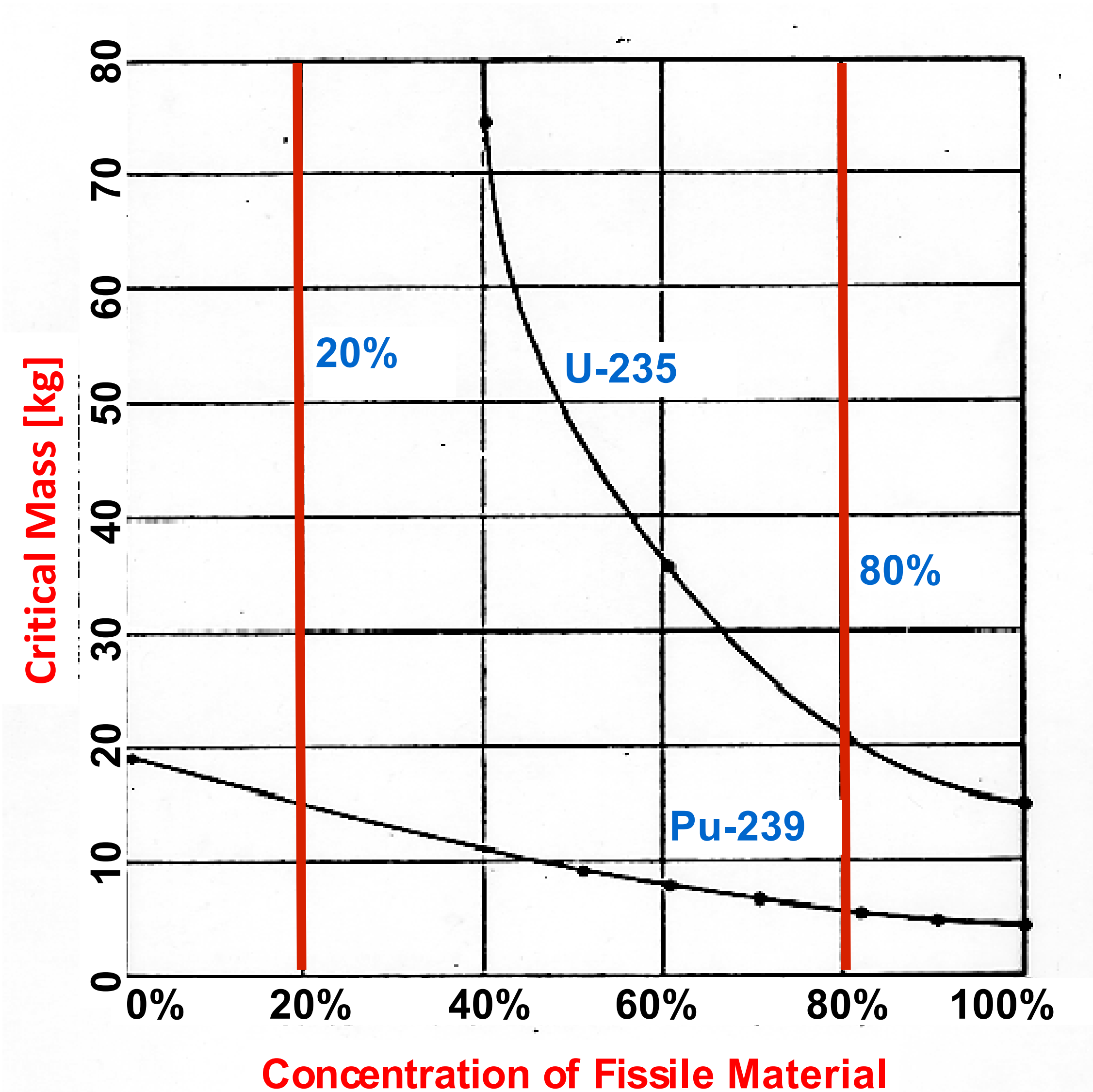
Material	Radioactivity (Ci/g)	Neutron Generation (n/g-sec)	Heat Release (W/kg)	Gamma Dose (rem/hr)
Natural U	0.0000007	0.013	0.000019	0.000012
LEU	0.0000019	0.012	0.000054	0.000057
Weapon-grade HEU	0.0000095	0.0014	0.00026	0.0015
Weapon-Grade Pu	0.22	52	2.5	0.94
Reactor-Grade Pu	6.2	340	14	15

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

Reducing the Fast-Neutron Critical Mass – 1

Critical Mass versus the Concentration of the 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: $\frac{\rho}{\rho_0} = 2, \quad \frac{m_c(\rho)}{m_c(\rho_0)} = \frac{1}{4}$ ⇒ 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 Technical Capability				kg of Highly Enriched U for Technical Capability		
Low	Medium	High	Yield (kt)	Low	Medium	High
3	1.5	1.0	1	8	4	2.5
4	2.5	1.5	5	11	6	3.5
5	3.0	2.0	10	13	7	4.0
6	3.5	3.0	20	16	9	5.0

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

Lecture Question

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

Lecture Question 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

Lecture 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

Lecture Question 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

Important Concepts

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

Fission Weapons ("A-bombs")

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

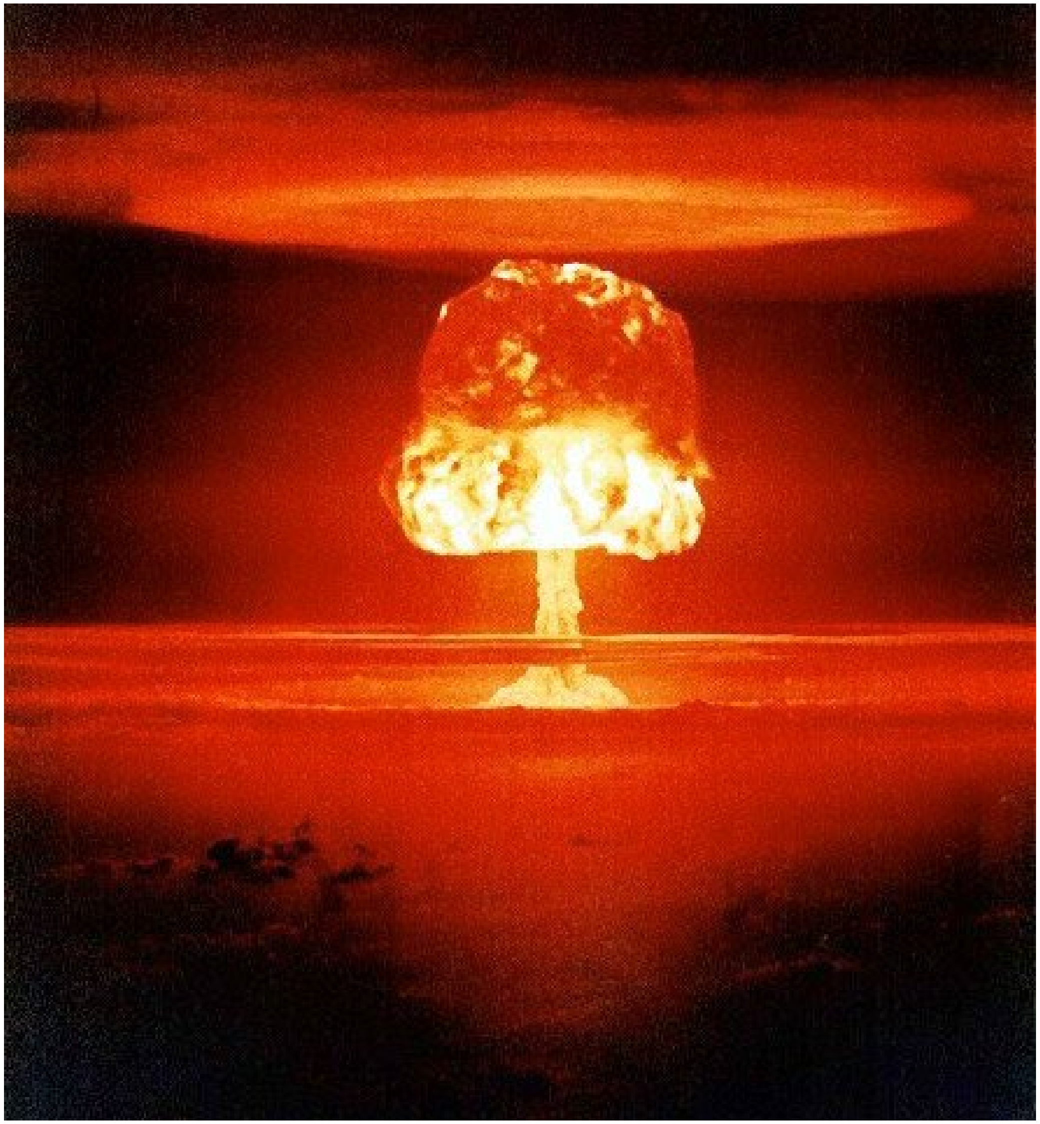
Stages —

- 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”) —

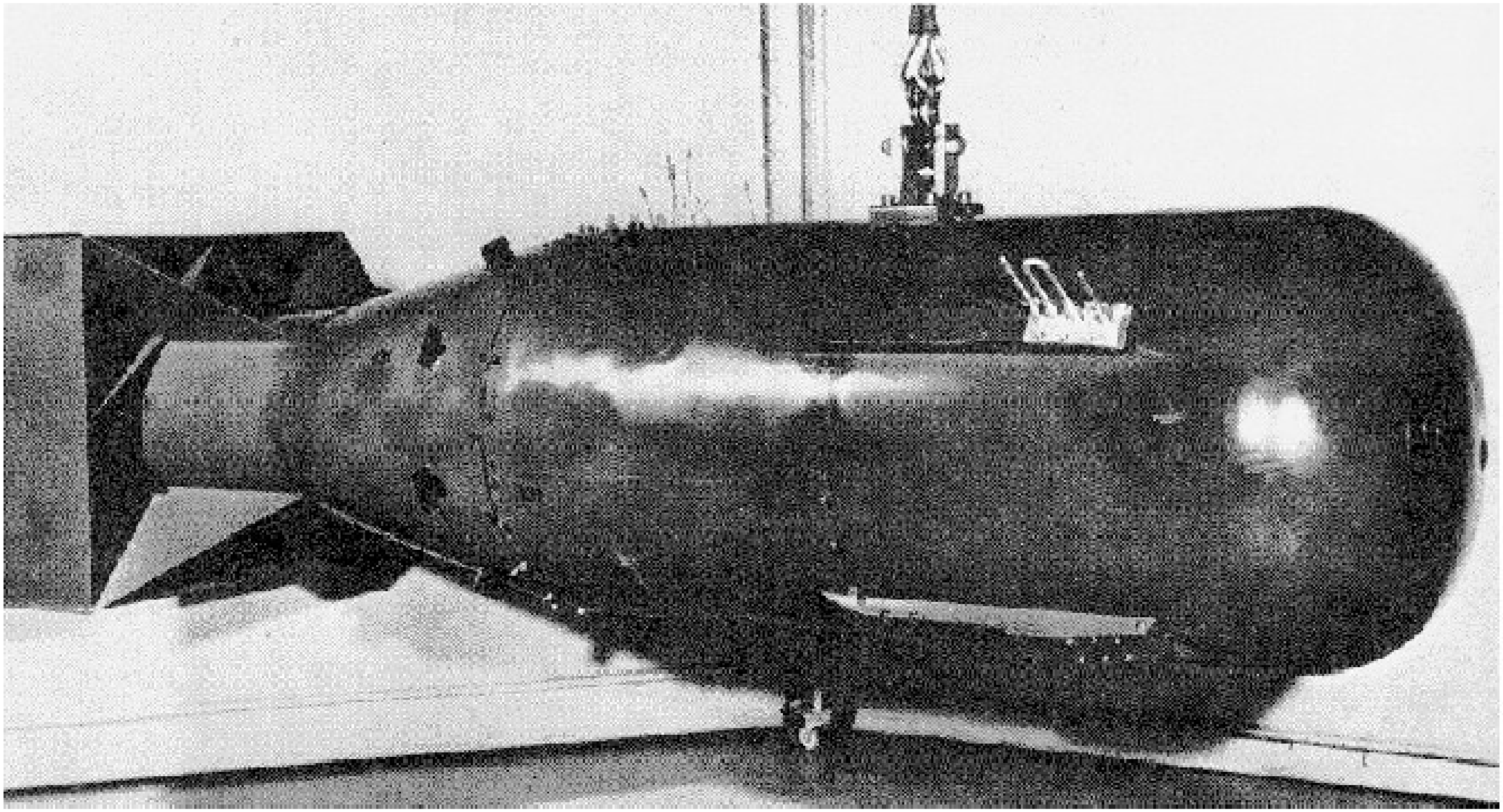
- Theoretical maximum yield-to-weight ratio: 8,000 tons TNT = 8 kt TNT from 1 lb. of NEM (~ 10,000,000 times as much per lb. as TNT)
- Difficult to make weapons larger than few 100 kt (Yields of tested weapons: 1–500 kt)

Thermonuclear weapons (“H-bombs”) —

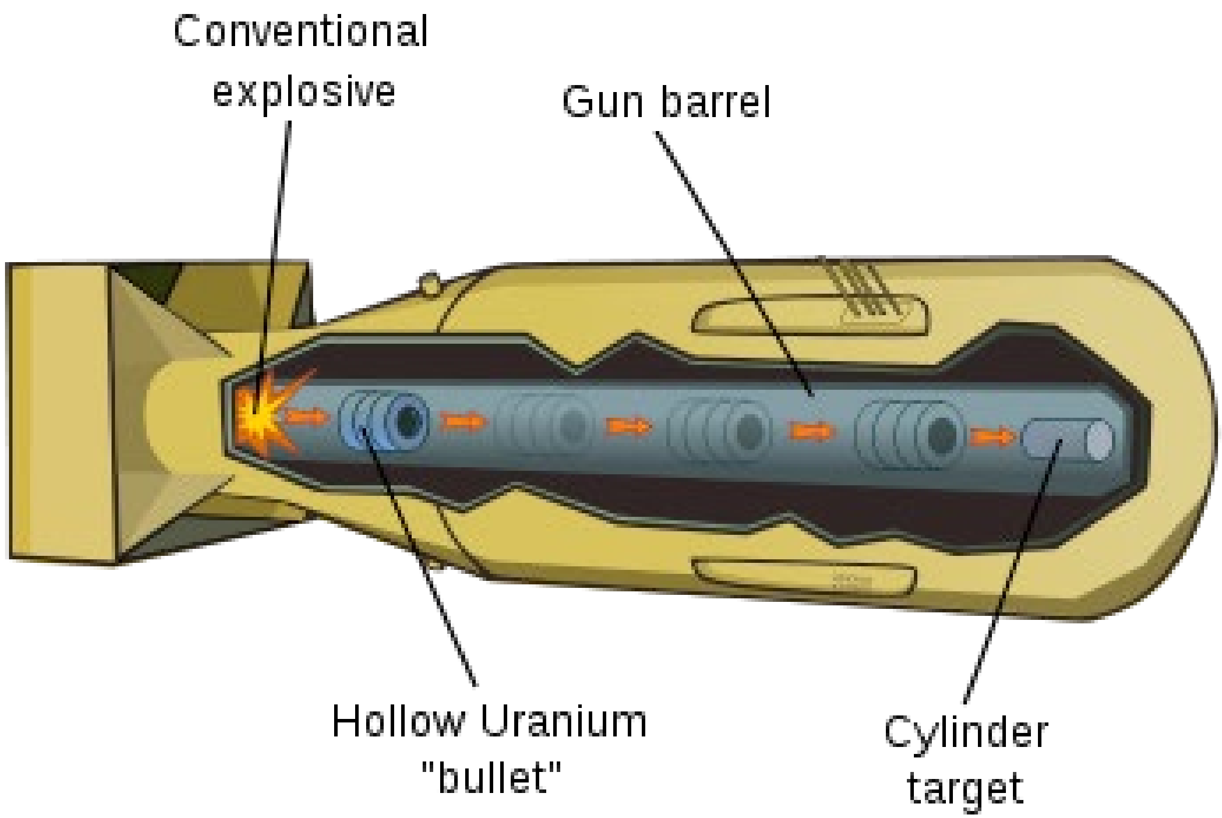
- Theoretical maximum yield-to-weight ratio: 25 kt TNT from 1 lb. of fusion material (~ 3 times as much per lb. as fission weapons)
- There is no fundamental limit to the size of a thermonuclear weapon

Fission Weapons – Gun Type

Little Boy



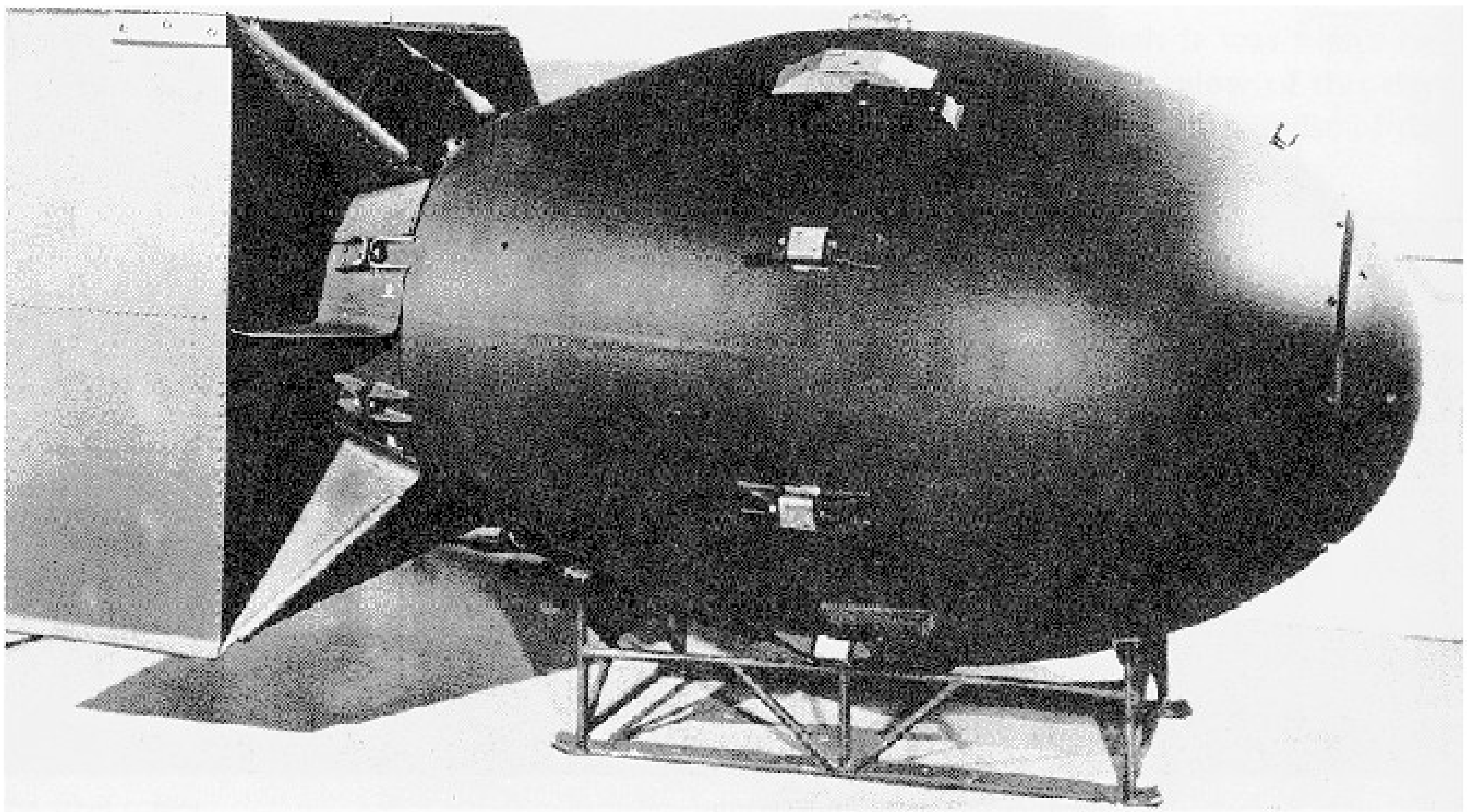
Fission Weapons – Gun Type



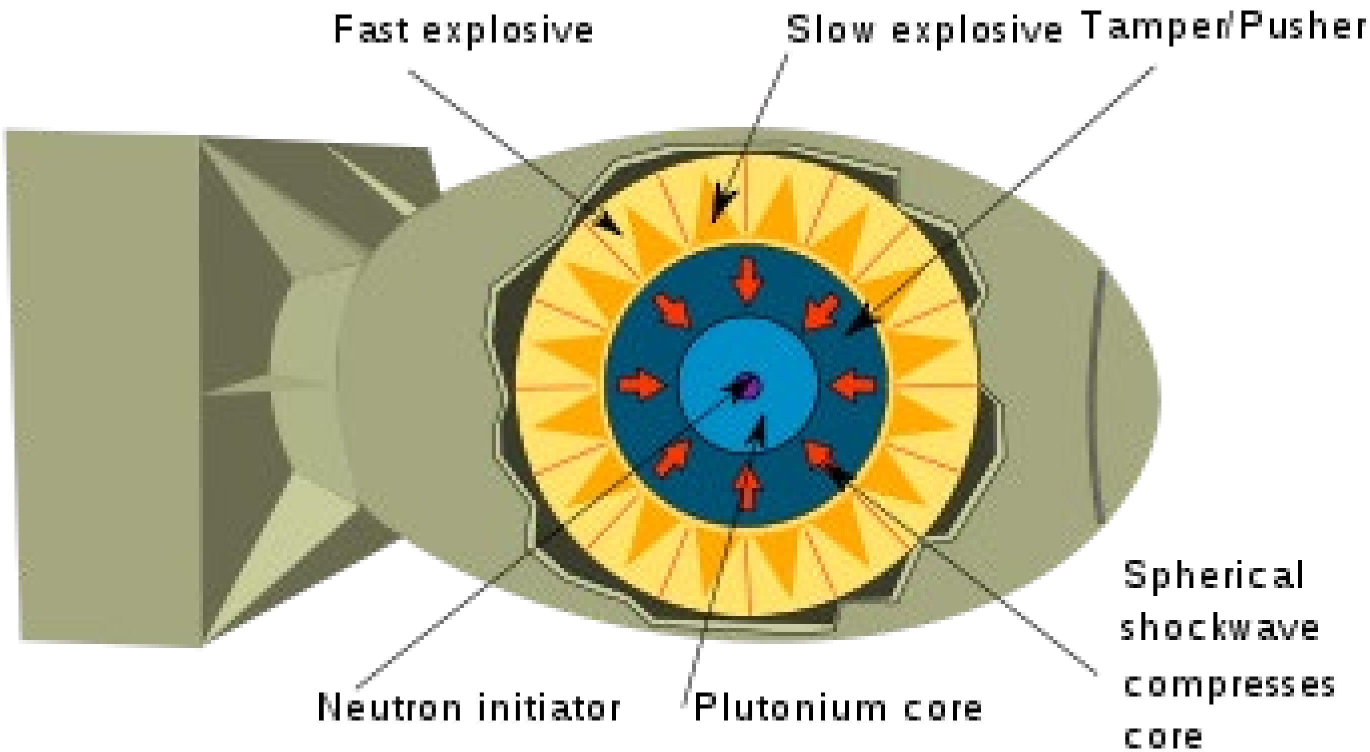
Works only with HEU
(relevant today mostly for non-state groups)

Fission Weapons – Implosion Type

Fat Man

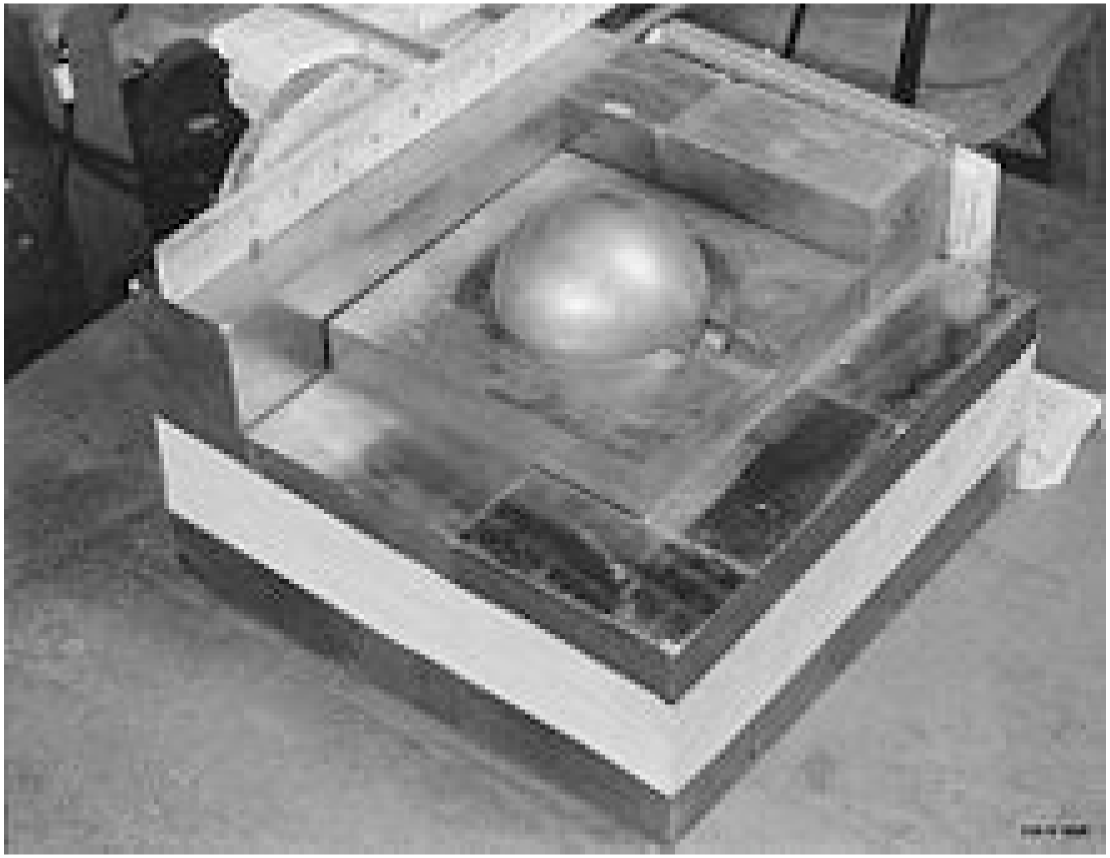


Fission Weapons – Implosion Type



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)

Thermonuclear Weapons ("H-Bombs")

Fusion Nuclear Reactions (Basics)

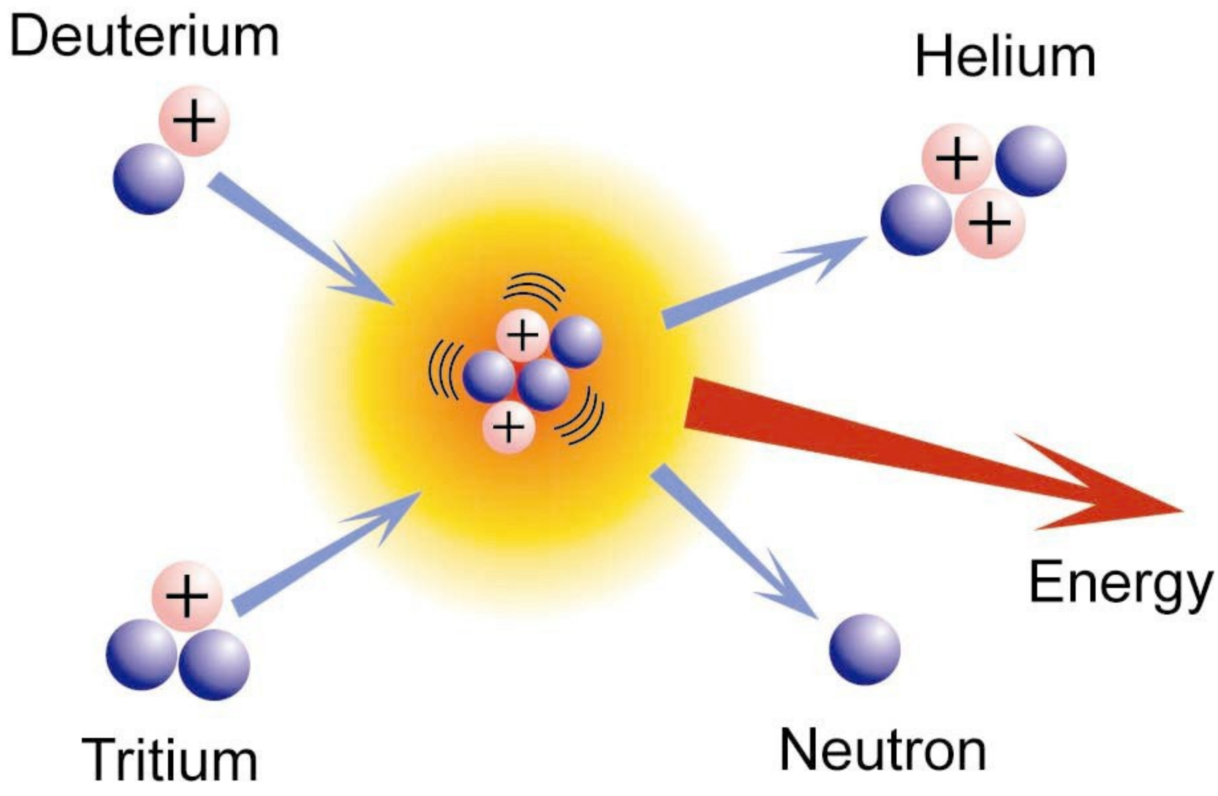
Fusion: a nuclear reaction in which two nuclides combine to form a single nuclide, with emission of energetic particles or electromagnetic radiation —

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

Particles involved:

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

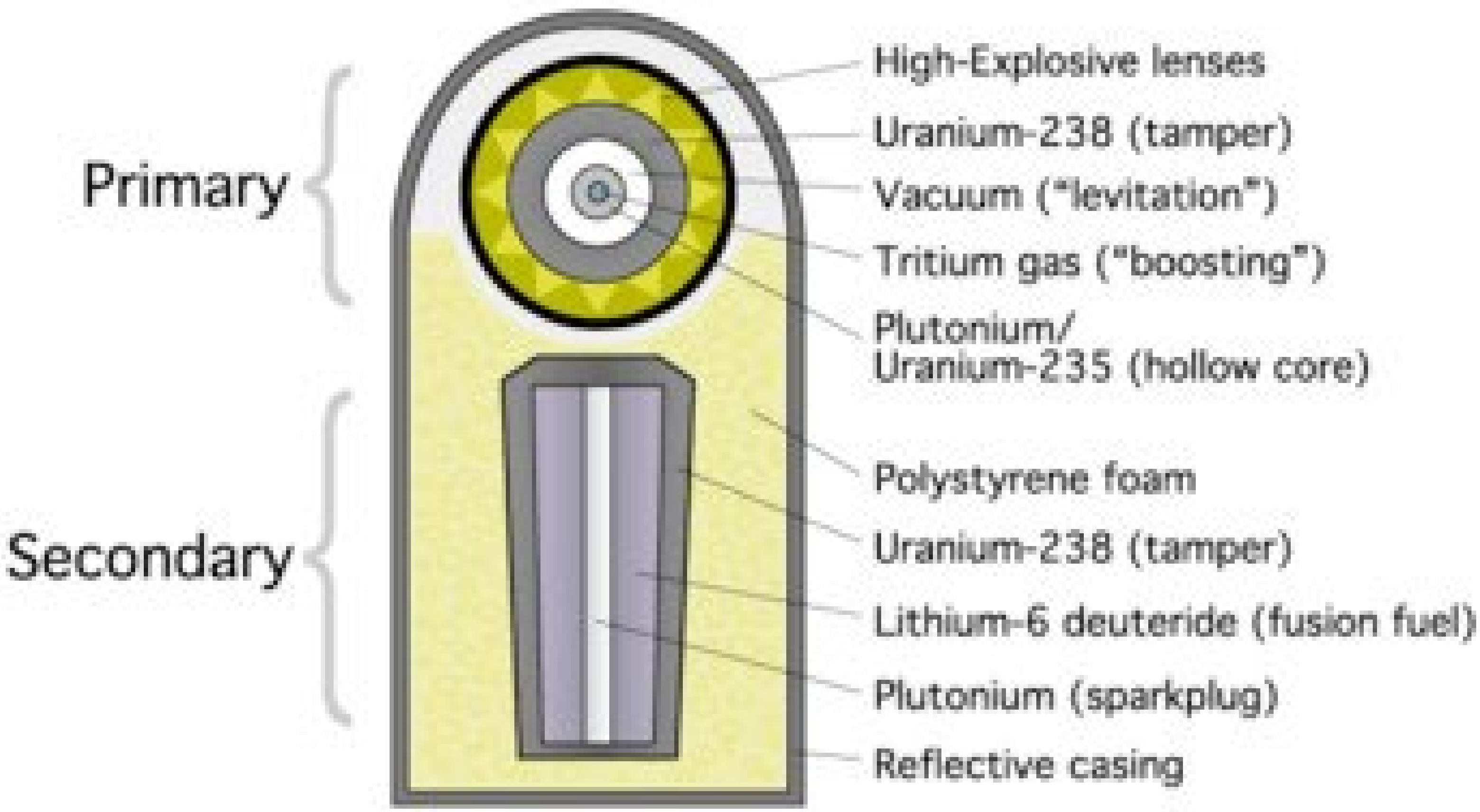
Example Fusion Nuclear Reaction



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

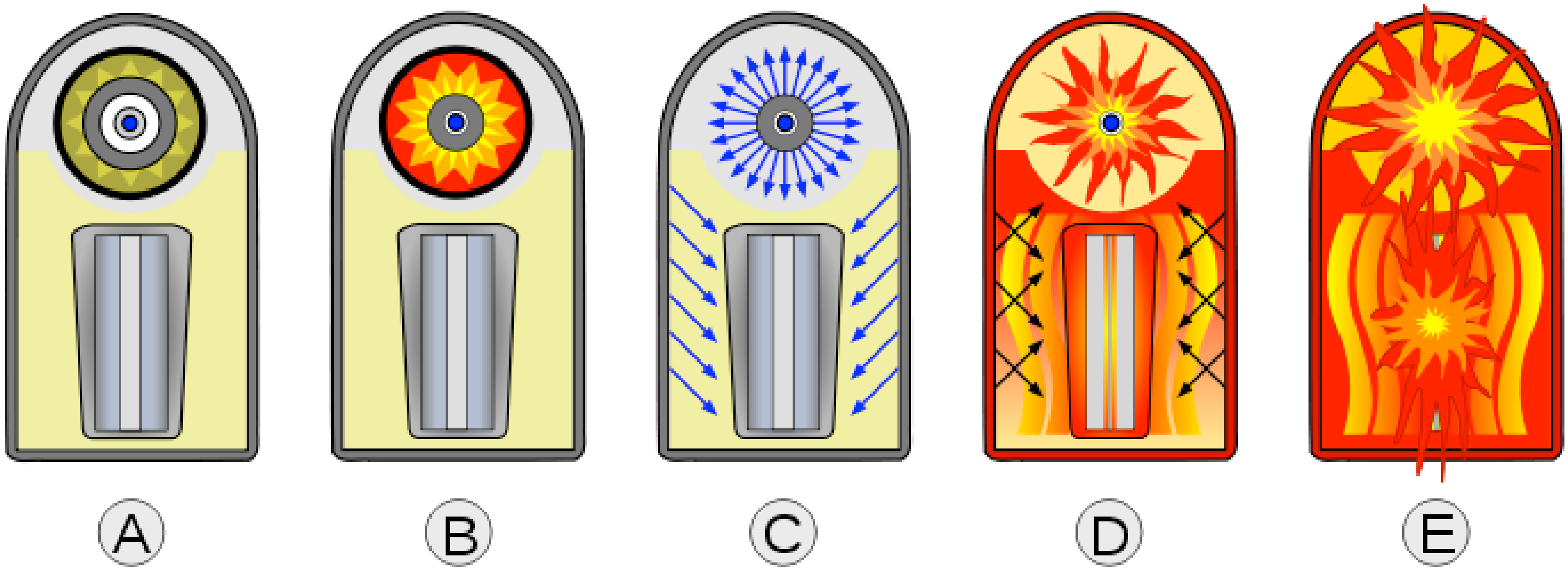
Two-Stage (Thermonuclear) Weapons – 2



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

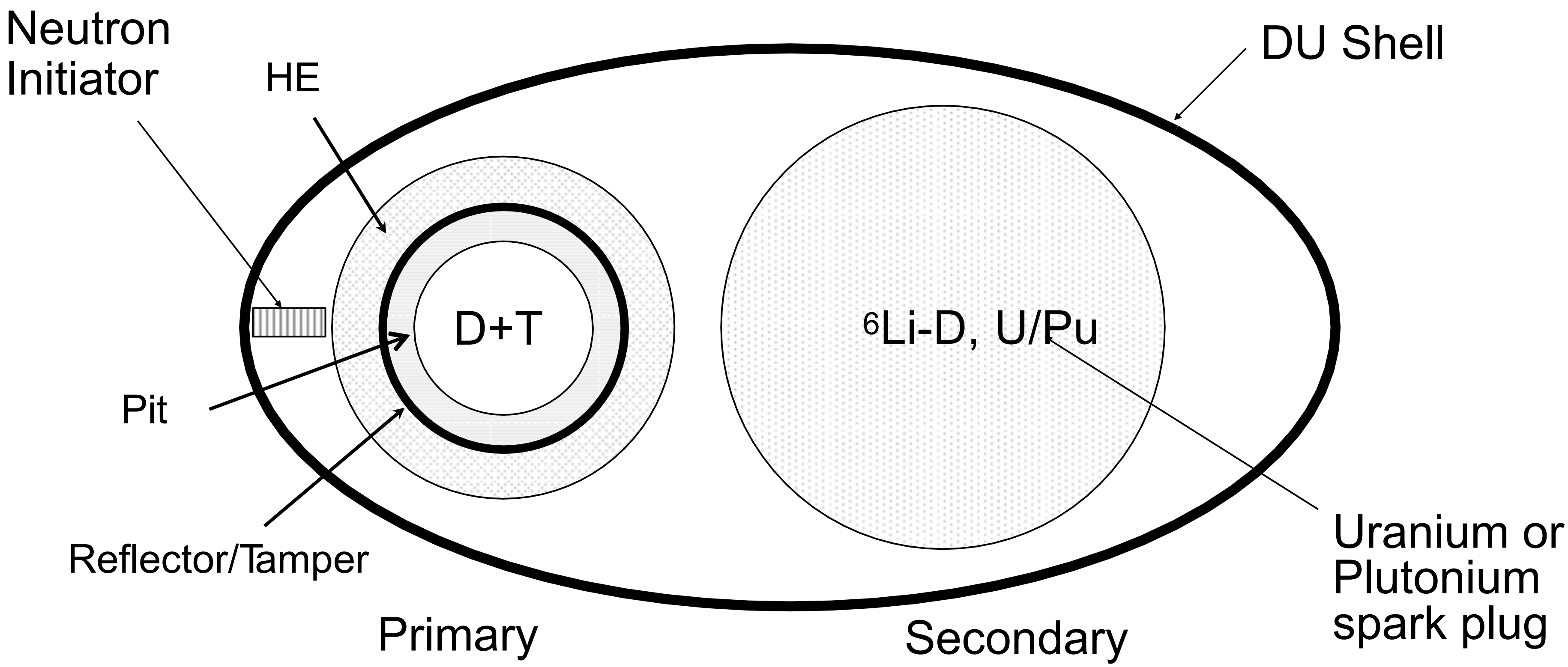
HEU, DU, natural U, or Pu are used to increase the yield —

- 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



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

$$n + {}^{6}_{3}Li \xrightarrow{\text{yields}} {}^{3}_{1}H + {}^{4}_{2}He$$

(I) preparation of fusion fuel

$$ {}^{3}_{1}H + {}^{2}_{1}H \xrightarrow{\text{yields}} n + {}^{4}_{2}He$$

(II) fusion reaction

Plan for This Session

Announcements:

RE2v2 will be due Wednesday at 10pm electronically, Thursday in class as paper copy

Plagiarism – from our course webpage:

Carefully and properly acknowledge others' texts, images, and ideas (when you refer to, summarize, paraphrase, quote directly, or reproduce them in whole or part)--including those you encounter in the course (such as by course slides, class readings, and other students' work) and in your reading and research.

All papers are scanned by plagiarism-detecting software (Turnitin)

Do not use ChatGPT or other AI-based text genertors!

Module 2: Nuclear weapons cont'd

News

Plagiarism in Dissertation Costs German Defense Minister His Job

By Judy Dempsey
March 1, 2011

BERLIN In a bitter political setback for Chancellor Angela Merkel, Germany's defense minister resigned Tuesday under pressure over his admission that he had plagiarized parts of his doctoral dissertation.

One of the country's most popular politicians, the minister, Karl-Theodor zu Guttenberg, 39, had faced mounting criticism from academics and his own conservative party. Resigning was the "most painful step of my life," he told reporters in the Defense Ministry in Berlin. "I was always ready to fight, but have to admit I have reached the limit."

…

The University of Bayreuth, which conferred the doctorate in 2007, revoked Mr. Guttenberg's academic title, saying he had "seriously violated" the institution's standards. Conservatives had hoped that his apology would quell the controversy, but last weekend more than 20,000 scholars from Germany and other parts of Europe sent an open letter to the Chancellery saying that Mrs. Merkel's continuing support of Mr. Guttenberg was a "mockery" of all those who "contribute to scientific advancement in an honest manner."

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 → 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

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

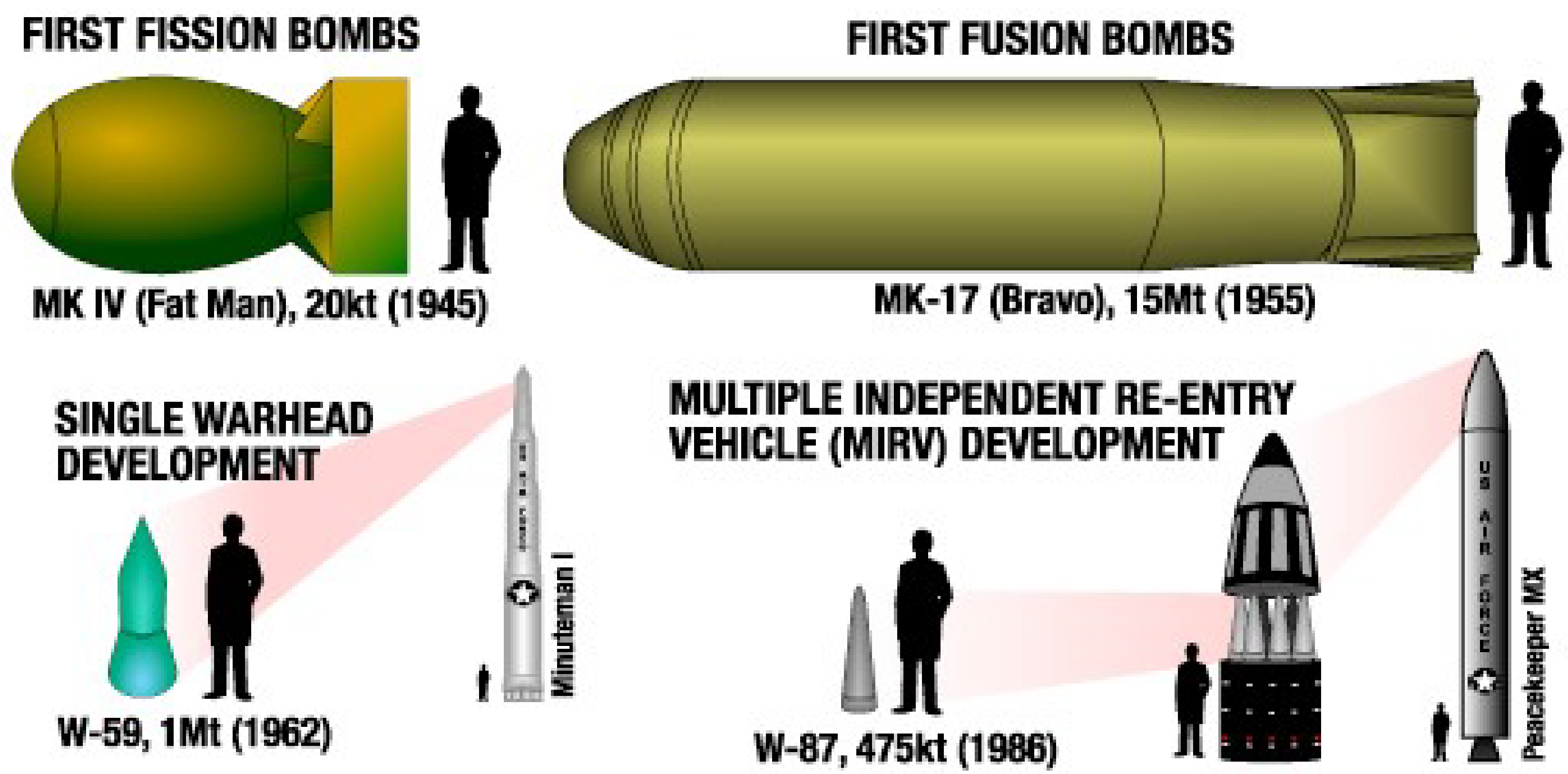
Physics and Engineering Requirements

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

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

Miniaturizing Massive Death and Destruction



Lecture Question

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

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

Lecture Question Answer

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**
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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**

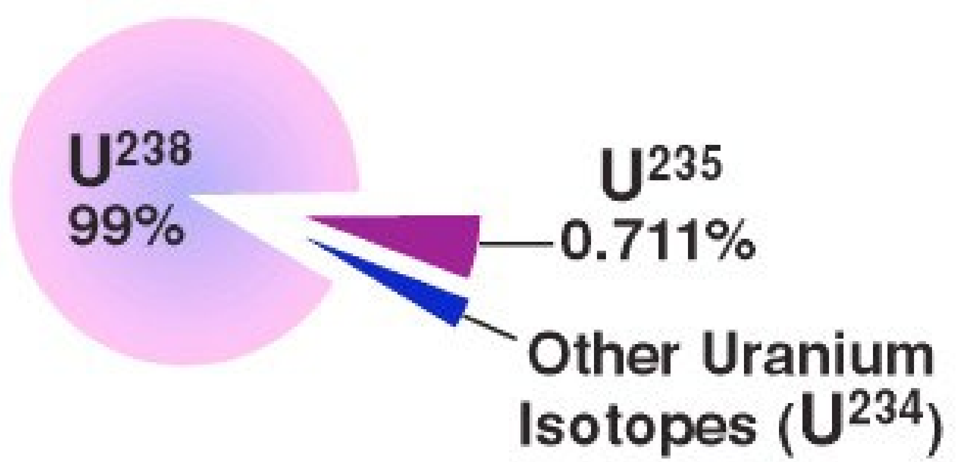
Production of Nuclear Explosive Material

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)



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

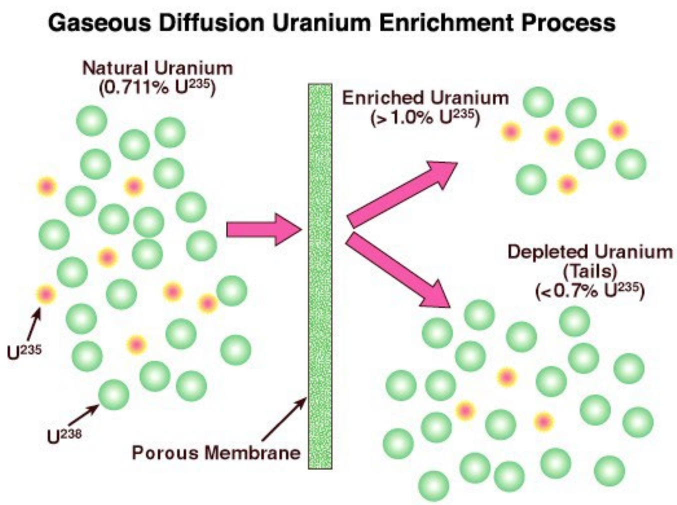
There are 4 main uranium enrichment techniques:

- 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.

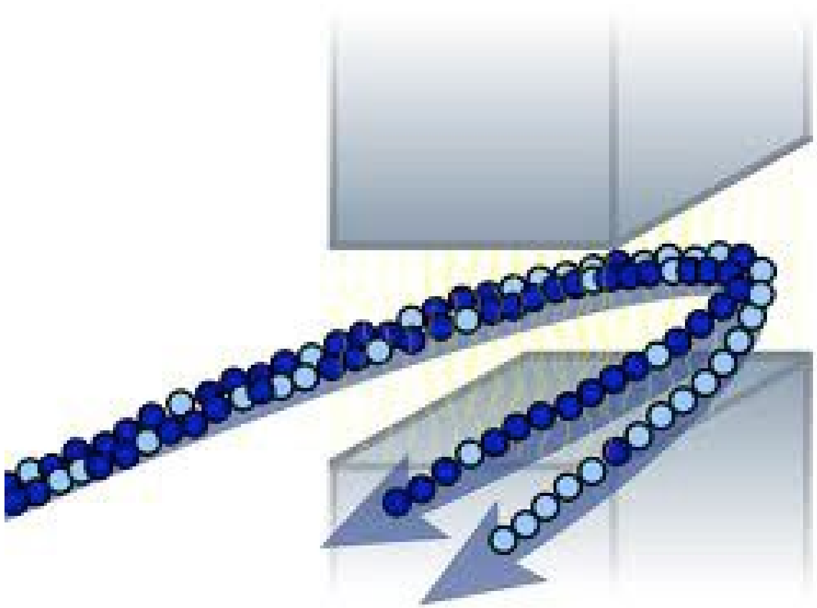
Enriching Uranium – Details 1

- 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



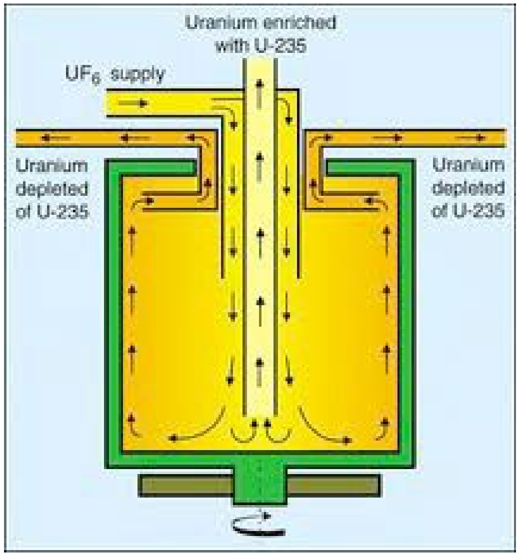
Enriching Uranium – Details 2

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



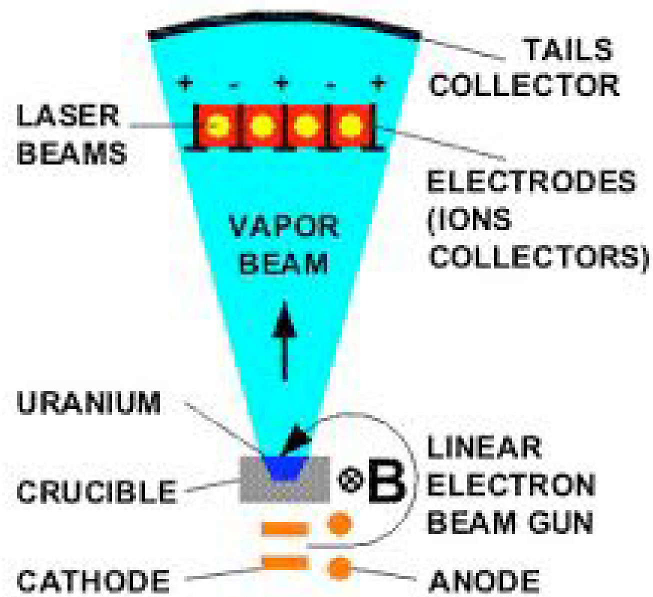
Enriching Uranium – Details 3

- 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)

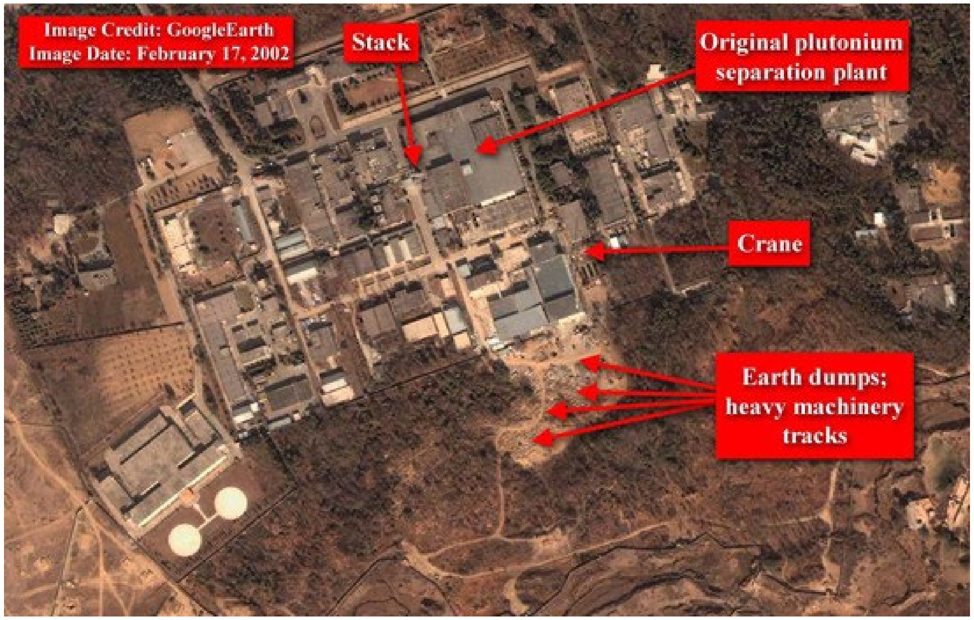
  (non-fissile) (fissile)

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

Plan for This Session

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

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 Monday at 10 am through the assignment upload server and by email to your peer-review partner

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/

Module 2: Nuclear weapons cont'd