Physics 280: Session 4

Extra-Credit Essay Opportunity A
“The Alternatives of Andrei Sakharov”
Tatiana Yankelevich, Harvard University
4:00 – 5:30 p.m. Thursday, February 3, Levis Center

Plan for This Session

Student questions?

Types of armed conflict

Module 2: Nuclear weapons

Types of Armed Conflict

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

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

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

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

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

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

Physics/Global Studies 280

Module 2: Nuclear Weapons

Physics of Nuclear Weapons

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

Physics of Nuclear Weapons

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

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

Physics of Nuclear Weapons

Topics covered in this module —

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

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

It's important to understand this material, but the remainder of the course will *not* be this technical.

Physics of Nuclear Weapons

Introduction

Physics of Nuclear Weapons

Atoms and Nuclei

Atomic Nature of All Matter

- "Everything is made of atoms"
- Atoms have a tiny nucleus surrounded by a very much larger electron cloud
- Every nucleus is composed of protons and neutrons; both are called "nucleons"
- Protons and neutrons are made of smaller particles (this fact is unimportant for nuclear weapon physics)
- All protons (and all neutrons, and all electrons) are *identical* and *indistinguishable*

Fundamental Forces of Nature – 1

Nature has four basic forces (three at the fundamental level) —

1. Gravitational force

- Always attractive, weakest but first to be discovered
- Strength decreases as $1/r^2$ ("long-range")

2. Electromagnetic force

- Can be attractive or repulsive
- Classical electrical force decreases as $1/r^2$ ("long-range")
- Magnetic force between bar magnets decreases as $1/r^3$
- Both are described by the theory of electromagnetism, which was developed in the latter part of the 19th Century
- The quantum theory of electromagnetism is called Quantum Electrodynamics

Fundamental Forces of Nature – 2

3. Weak nuclear force

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

“electroweak” theory describes
electromagnetic + weak forces in a unified way

4. Strong nuclear force (“strong force”)

- 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

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Atoms and Nuclei

Sizes of atoms and nuclei —

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

$$a_B \approx 10^{-8}\,\text{cm} = 10^{-10}\,\text{m} \;=\; 0.1\ \text{nm}$$

$$r_o \approx 10^{-12}\,\text{cm} = 10^{-14}\,\text{m} \;=\; 10\ \text{fm}$$

Masses of subatomic particles —

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

Atomic Nuclei

- A distinct atomic nucleus (“nuclide”) is specified by
  - —its number of protons (denoted Z – always an integer) and
  - —its number of neutrons (denoted N – always an integer)
- Protons and neutrons are both called “nucleons”.
- Z is called the “proton number” or “atomic number”.
- N is called the “neutron number”.
- The total number $N+Z$ of nucleons in the nucleus is denoted A and is called the “atomic weight” of the nucleus.

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 (always an integer) in its electron cloud.

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

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

Isotopes and Isotones

Several notations are in common use for nuclides –

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

Here X is the chemical symbol

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

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

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

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

Naturally Occurring Chemical Elements

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

Radioactivity

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

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

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

There are Four Types of Radioactive Decay

1. Alpha decay

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

2. Beta decay

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

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

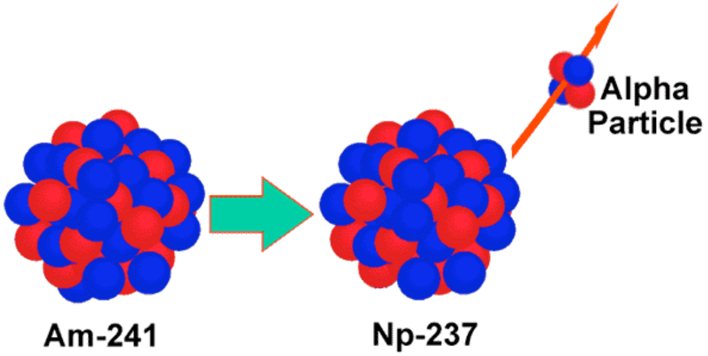
3. Gamma decay

Parent —> Daughter + gamma-ray

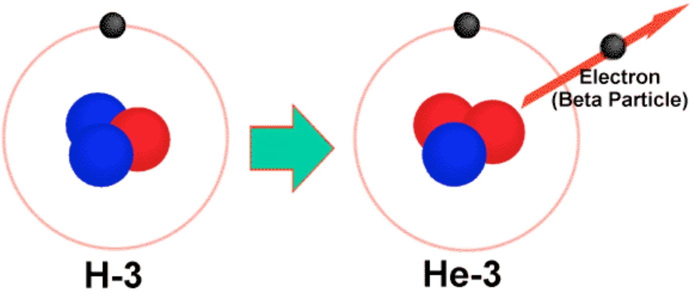
4. Spontaneous fission

Parent —> Fragment 1 + Fragment 2 + neutrons

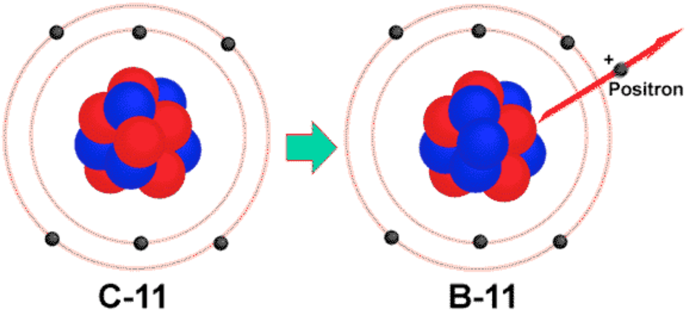
Example of Alpha Decay



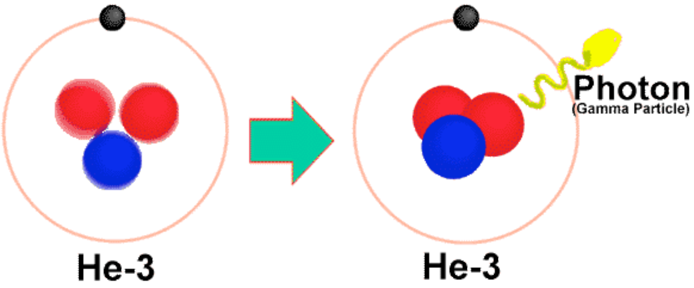
Example of Beta Decay (Electron Emission)



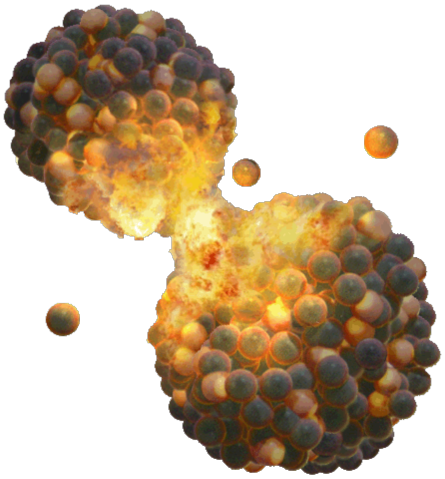
Example of Beta Decay (Positron Emission)



Example of Gamma-Ray Emission



Example of Spontaneous Fission



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iClicker Question (Use Channel C-C)

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

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

iClicker Answer

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iClicker Question (Use Channel C-C)

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

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

iClicker Answer

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iClicker Question (Use Channel C-C)

Which of the following is **not** permissible under International Law?

A. Attacking a country that is blockading your territory
B. Attacking a country to prevent it from launching an attack at some time in the future
C. Attacking a country to disrupt an attack on your own territory that is already underway or is imminent
D. Attacking a country that is allowing pirates from its territory to attack ships in international waters
E. All of the actions listed above are permissible

iClicker Answer

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E. All of the actions listed above are permissible

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iClicker Question (Use Channel C-C)

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

A. About the same

B. 10 times more

C. 100 times more

D. 1,000 times more

E. 1,000,000 times more

iClicker Answer

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

A. About the same

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D. 1,000 times more

E. **1,000,000 times more**

Physics of Nuclear Weapons

Fission and Fusion

The Two Types of Fission

Spontaneous fission —

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

Induced fission —

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

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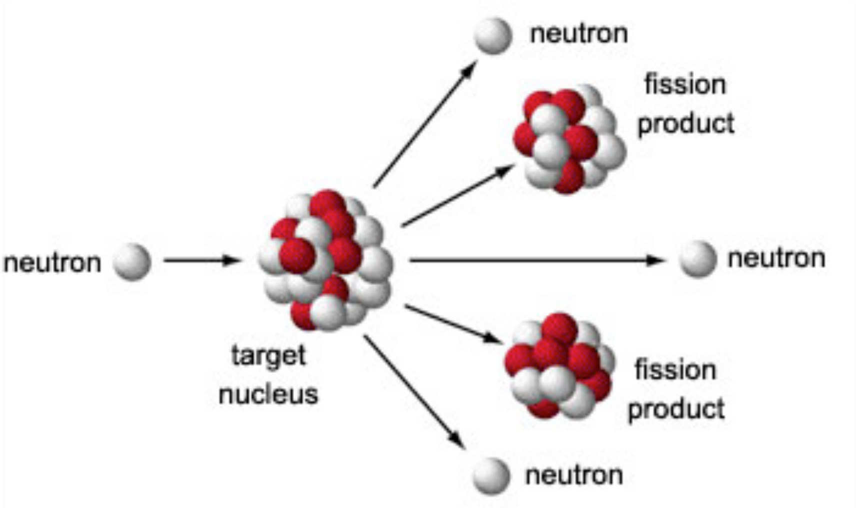
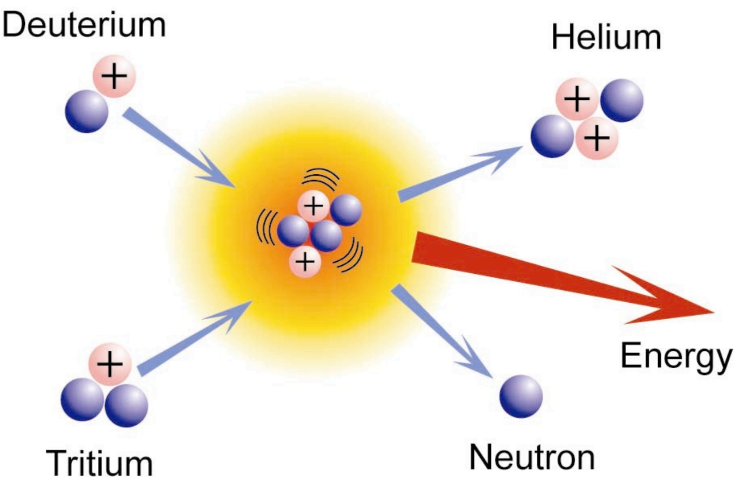
Induced Fission



Fusion



Deuterium

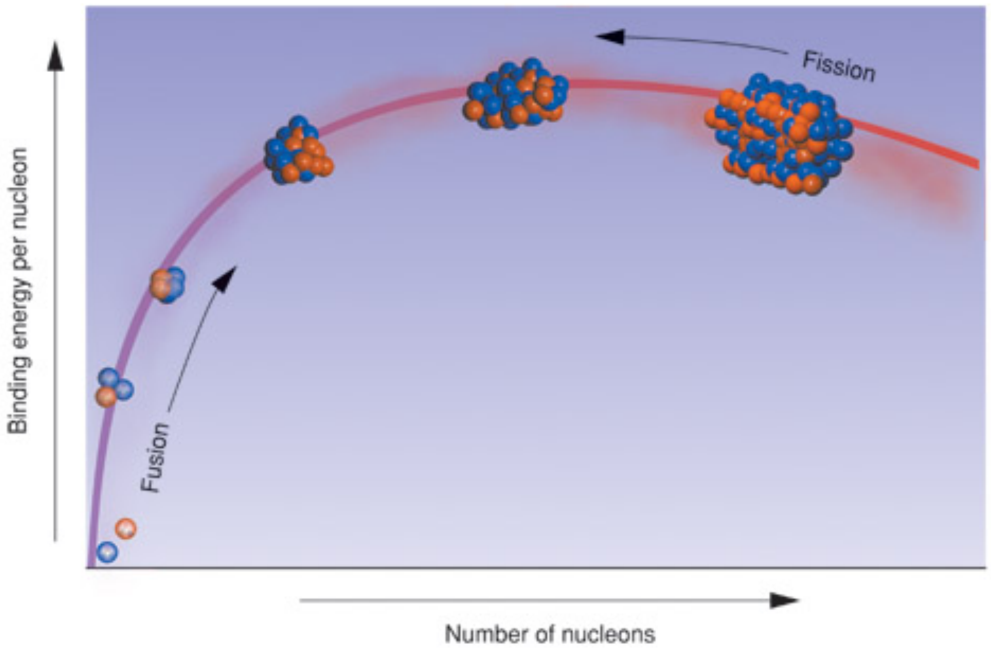
Helium

Energy

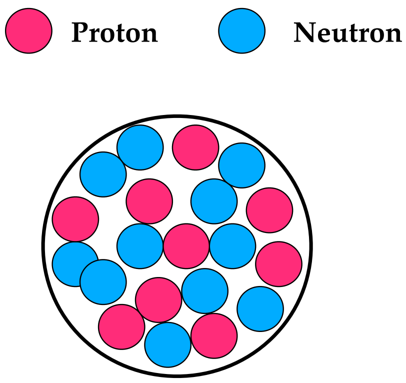
Tritium

Neutron

The Curve of Binding Energy



Explanation of the Curve of Binding Energy



Nucleus: ***N, Z***

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

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

Competition between (1) and (2) determine nuclear mass *M* and total binding energy B_T:

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

$$B_T = \underbrace{\text{const} \times (N + Z)}_{\text{Nuclear Term}} - \underbrace{\text{const} \times Z^2}_{\text{Electrical Term}}$$

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

Eventually repulsion exceeds attraction: $B_T < 0$.

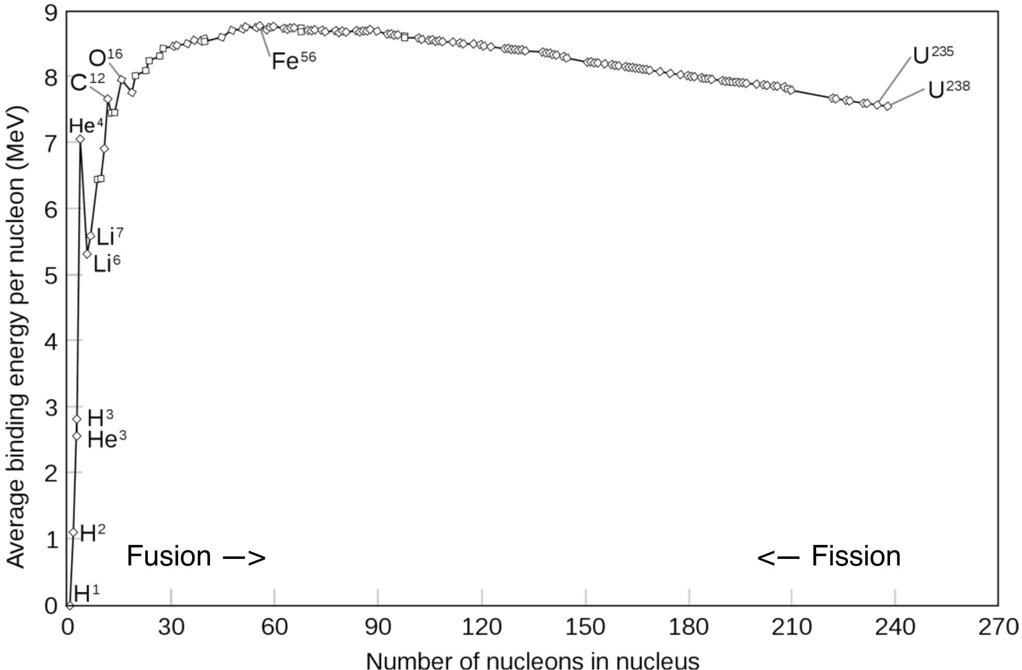
The Binding Energy Per Nucleon

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

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

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

Detailed Curve of Binding Energy



Nuclides Important for Fission Bombs

Heavy elements (high Z) —

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

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

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

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

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

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

*, **, *** denotes increasing importance

Nuclides Important for Fusion Bombs

Light elements (low Z) —

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

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

$^{3}_{1}\mathrm{H} \;=\; \mathrm{T}$ (tritium), unstable * * *

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

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

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

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

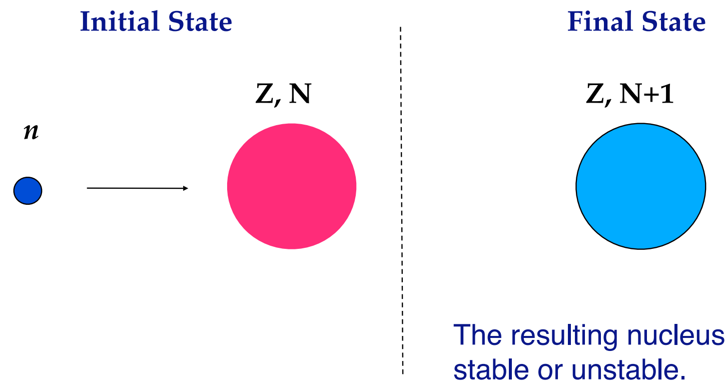
$^{9}_{4}\mathrm{Be} = \mathrm{Be}(9)$ stable (lighest metal) *

*, **, *** denotes increasing importance

The Neutron

- The discovery of the neutron in 1932 was the single most important discovery in nuclear physics after the discovery of the nucleus itself.
- Until the neutron was discovered, physicists could not understand nuclei, in particular how A could be greater than Z.
- The discovery of the neutron made it possible to understand for the first time how $A = Z + N$ could 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.

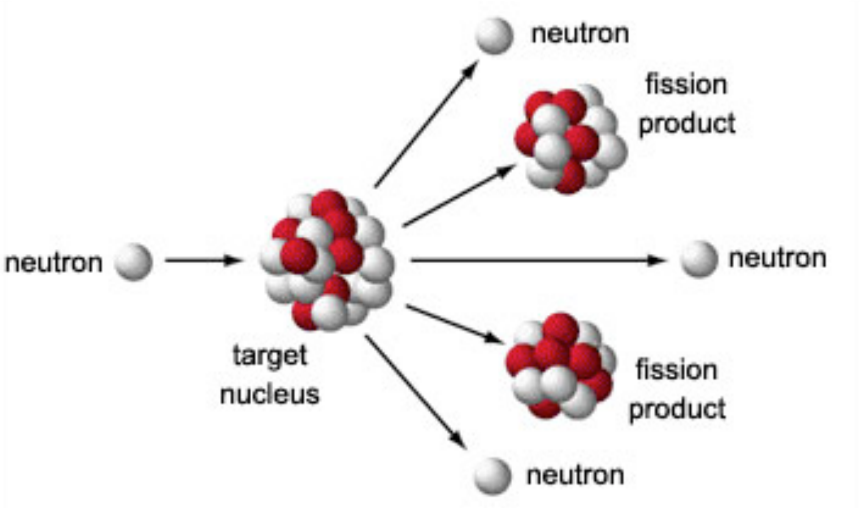
Consequences of Neutron Capture



The resulting nucleus may be stable or unstable.

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

Induced Fission



Physics 280: Session 5

CANCELLED
Extra-Credit Essay Opportunity A
“The Alternatives of Andrei Sakharov”
Tatiana Yankelevich, Harvard University
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CANCELLED

i>clicker issues

Plan for This Session

Student questions?

News

Module 2: Nuclear weapons (cont’d)

News

Global Security Newswire by National Journal Group — Daily news on nuclear, biological and chemical weapons, terrorism and related issues.

Arizona Senator's Support Sought for New START Pact

Tuesday, April 20, 2010

The Obama administration has placed top priority on winning the endorsement of Senator Jon Kyl (R-Ariz.) for ratification of a new nuclear arms control pact with Russia, the *Wall Street Journal* reported today (see ***GSN***, April 14).

U.S. President Barack Obama and Russian President Dmitry Medvedev signed the replacement to the 1991 Strategic Arms Reduction Treaty earlier this month. The pact would obligate the two former Cold War adversaries to both lower their respective strategic arsenals to 1,550 fielded warheads and to limit their deployed nuclear delivery vehicles -- missiles, submarines and bombers -- to 700, with another 100 permitted in reserve. Under a 2002 pact, Moscow and Washington had until 2012 to reduce their deployed strategic stockpiles to a maximum of 2,200 weapons each.

News

Global Security Newswire
by National Journal Group

Daily news on nuclear, biological and chemical weapons, terrorism and related issues.

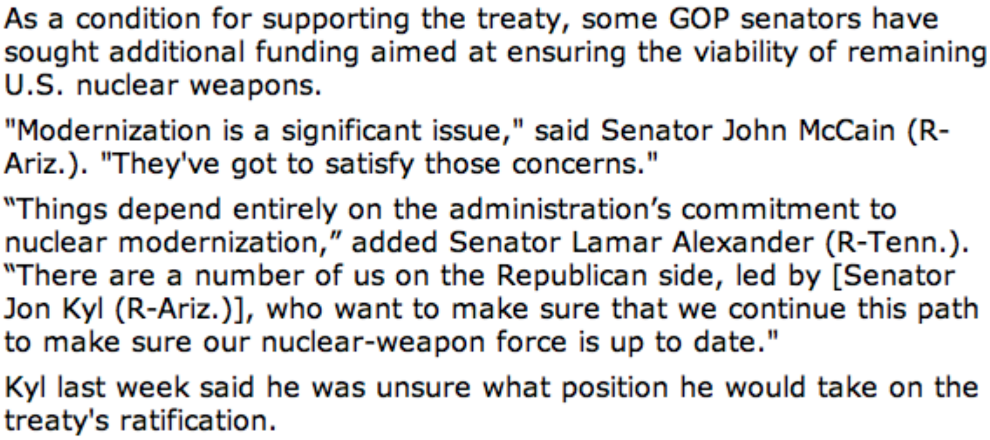
"New START" Approval Not Secured, GOP Senators Warn

Tuesday, Oct. 5, 2010

The White House must take additional steps to secure sufficient Senate backing for ratification of a new U.S. nuclear arms control treaty with Russia, Republicans warned last week (see ***GSN***, Oct. 1).

The lawmakers said it remained far from certain how "New START" would fare on the Senate floor, despite the Foreign Relations Committee's bipartisan endorsement of the pact last month, *The Hill* reported yesterday. The 67 votes required for ratification must include at least eight Republicans in this Congress.

News



As a condition for supporting the treaty, some GOP senators have sought additional funding aimed at ensuring the viability of remaining U.S. nuclear weapons.

"Modernization is a significant issue," said Senator John McCain (R-Ariz.). "They've got to satisfy those concerns."

"Things depend entirely on the administration's commitment to nuclear modernization," added Senator Lamar Alexander (R-Tenn.). "There are a number of us on the Republican side, led by [Senator Jon Kyl (R-Ariz.)], who want to make sure that we continue this path to make sure our nuclear-weapon force is up to date."

Kyl last week said he was unsure what position he would take on the treaty's ratification.

News

New START Ratification Anticipated Today

Wednesday, Dec. 22, 2010

By Megan Scully
National Journal

WASHINGTON -- After months of wrangling on Capitol Hill, the Senate today is expected to deliver President Obama a decisive political win and approve the New START arms-reduction treaty with Russia (see ***GSN***, Dec. 21).

Treaty supporters are now confident they have more than the 67 votes required for approval despite lingering concerns among some Republicans that the accord could hamstring missile defense efforts or otherwise hurt the United States' strategic posture.

News

U.S. Senate Ratifies New START in 71-26 Vote, Despite Top GOP Opposition

Wednesday, Dec. 22, 2010

By Elaine M. Grossman
Global Security Newswire

WASHINGTON -- More than a dozen Republican lawmakers today defied their party leadership to vote in favor of ratifying a U.S.-Russian nuclear arms control treaty, which the Senate approved at just before 3 p.m. local time in a 71-26 **vote** (***GSN***, Dec. 22).

News

Global Security Newswire
by National Journal Group
Daily news on nuclear, biological and chemical weapons, terrorism and related issues.

Medvedev Inks New START Ratification Text

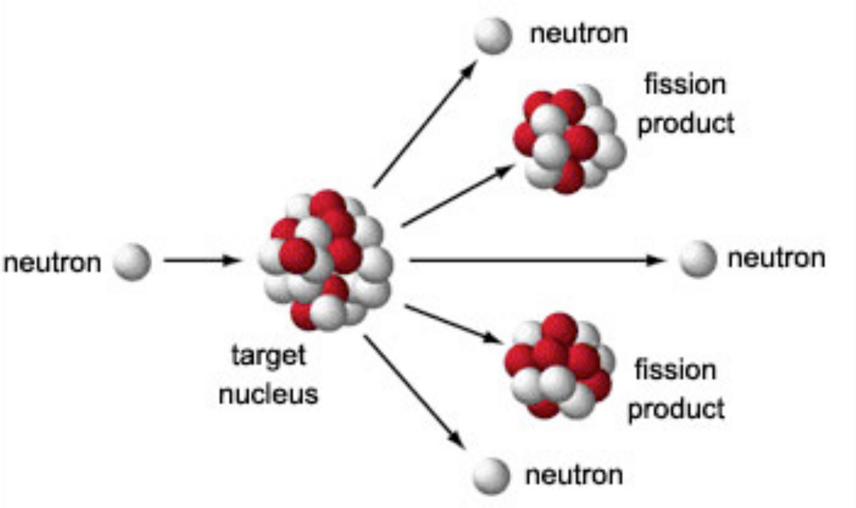
Friday, Jan. 28, 2011

Russian President Dmitry Medvedev today announced he had inked his country's ratification document for a new nuclear arms control treaty with the United States, Russia Today reported (see ***GSN***, Jan. 27).

"Today I signed the ratification bill on the New START treaty. This is a very important event for our entire country, considering the understandings that Russia has with the U.S.," Medvedev said.

Russian Foreign Minister Sergei Lavrov and U.S. Secretary of State Hillary Clinton are expected to exchange ratification instruments for the treaty early next month, formally bringing the agreement into force.

Induced Fission – 1



Induced Fission – 2

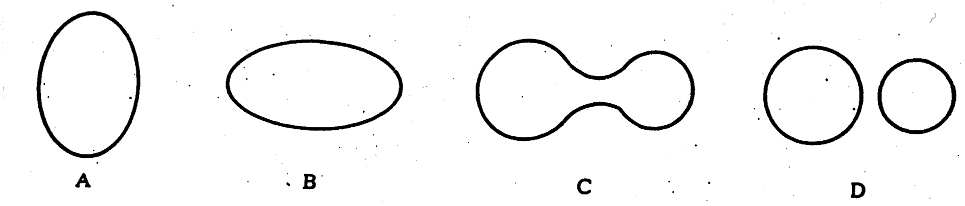
The discovery of induced fission was a great surprise!

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

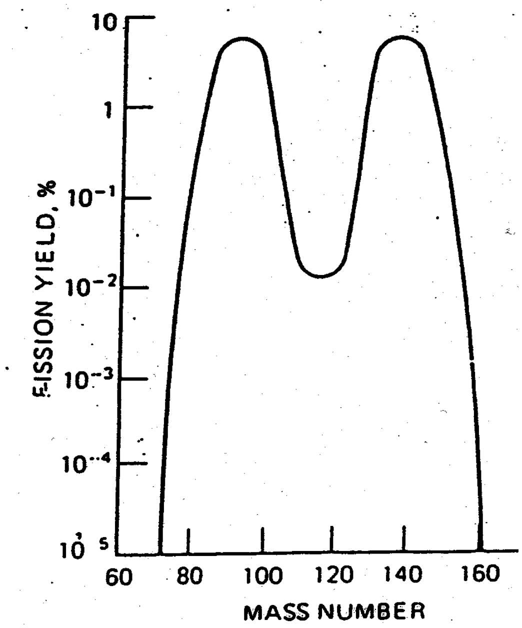
Lise Meitner, a brilliant Jewish scientist who had fled from Germany to Copenhagen in 1933, was the first person to understand what was happening in the experiments.

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

Lisa Meitner’s Concept of Fission



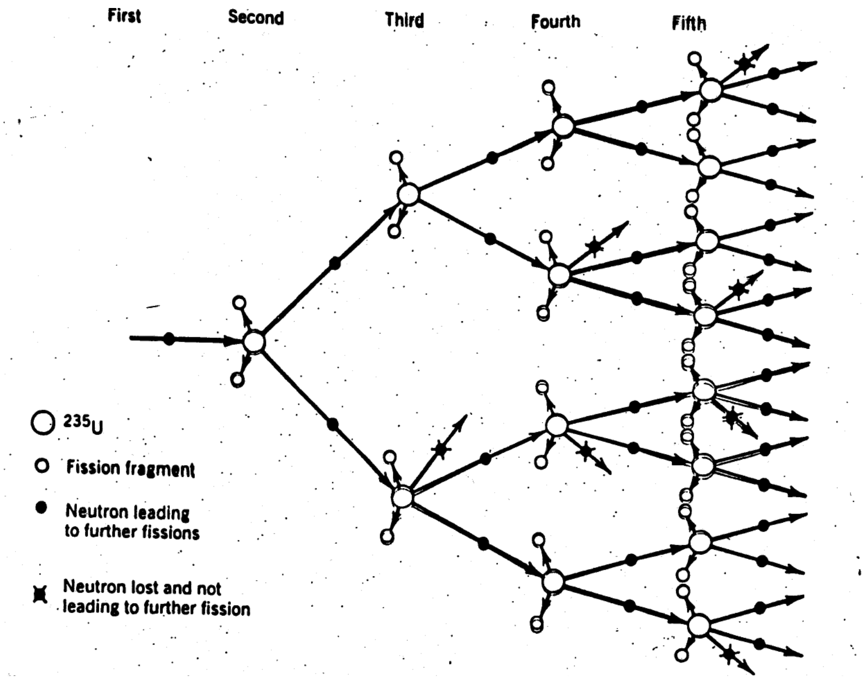
Distribution of Fission Fragment Masses



Induced Fission – 3

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

Chain Reaction



Physics of Nuclear Weapons

Nuclear Reactors and Nuclear Bombs

Definition of 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 nuclear material needed 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 configuration (the geometry, surroundings, etc.).

The Neutron Multiplication Factor

The number of neutrons released by each fission that cause a subsequent fission 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 generation $n + 1$ to the number present in generation n is called *the neutron multiplication factor*.

If $R < 1$, the configuration has *a subcritical mass* and hence fissions in it will die out (usually quickly) as time passes. Such a configuration is of little use.

If $R = 1$, the configuration has *the critical mass* and hence fissions in it will continue at the same rate as time passes. Such configurations are used in nuclear reactors.

If $R > 1$, the configuration has *a supercritical mass* and hence fissions in it grow in number (usually quickly) as time passes. Such configurations are used in nuclear bombs.

Nuclides Useful for Nuclear Reactors Versus for Fission Bombs

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

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

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

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

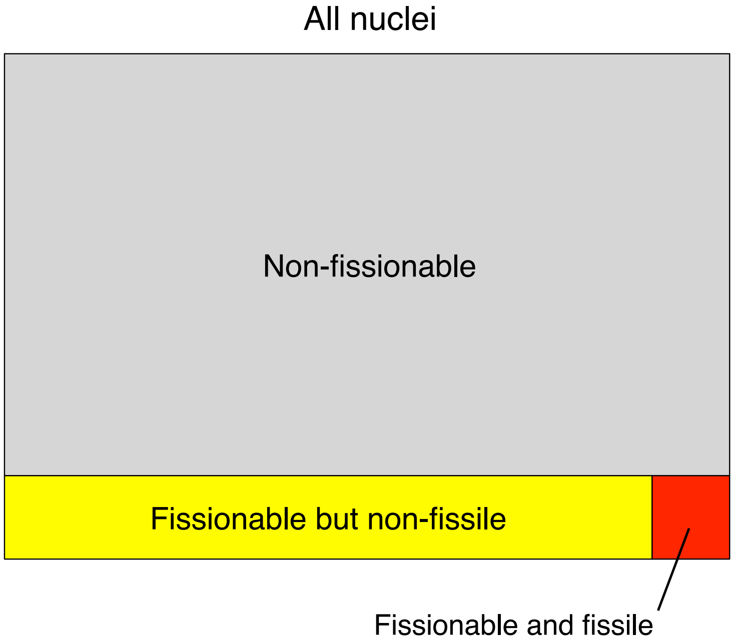
Fissionable but not fissile nuclides cannot be used in a nuclear reactor but some can be used in nuclear bombs.

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

All nuclides (fissionable and non-fissionable)

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

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



All nuclei

Non-fissionable

Fissionable but non-fissile

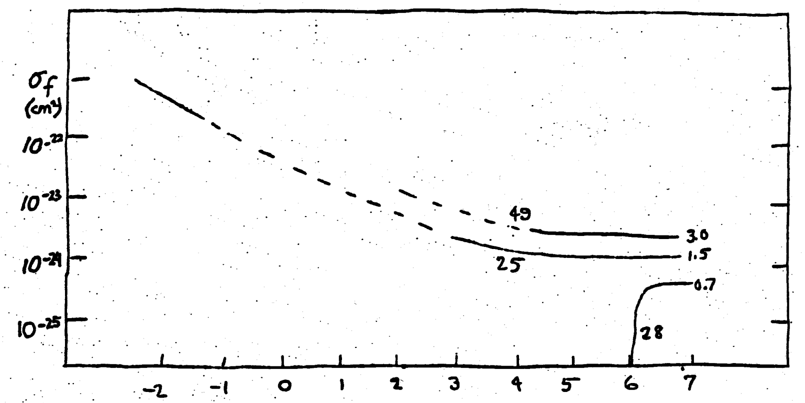
Fissionable and fissile

Neutron-Induced Fission Probability for Three Important Fissile and Non-fissile 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

Physics of Nuclear Weapons – 1

Nuclear weapons require nuclides that can support an explosive (exponentially growing) chain reaction of fissions induced by “fast” neutrons (with a suitable quantity, purity, and geometry).

Such nuclides are called “nuclear-explosive nuclides”.

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

However, the underlying physics is such that —

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

Physics of Nuclear Weapons – 2

Any *mixture of nuclear-explosive nuclides and other nuclides* that can support a fast-neutron chain reaction (with a suitable quantity, purity, and geometry) is called *nuclear-explosive material.*

Fissionable but non-fissile nuclides cannot be used in a nuclear reactor, but some can be used in nuclear bombs.

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

The Principle of a Nuclear Weapon

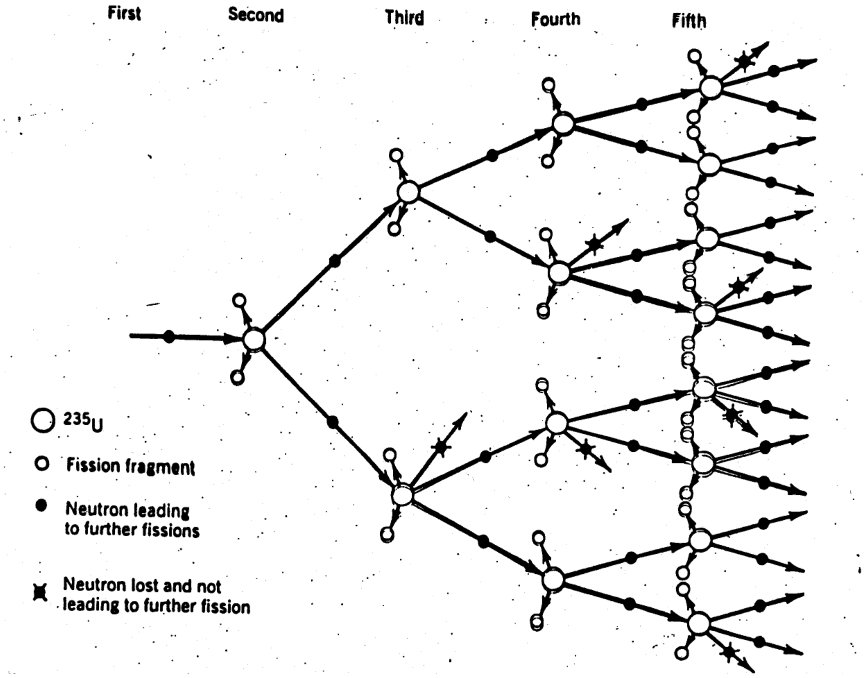
A nuclear explosion is achieved by the rapid assembly, in a suitable geometry, of NEM with sufficient nuclear reactivity to initiate and sustain a chain reaction driven by *fast* neutrons.

For this to happen, on average at least one of the several energetic neutrons released per fission in the NEM must be “productively” captured, i.e., it must produce another fission following its capture.

The neutron must be productively captured before it is unproductively captured, loses too much energy, or escapes from the configuration.

In order to produce an explosion, the fast neutrons from each fission must produce *more* fast neutrons in each successive “generation”, i.e., the neutron multiplication factor R must be > 1. Such a configuration is said to be “prompt supercritical”.

Explosive Chain Reaction



Definitions of Fission and Nuclear Materials (Summary)

- 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, protons, or other particles.
- 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.

---

iClicker Question (Use Channel C-C)

France first tested a nuclear device in what year?

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

iClicker Answer

France first tested a nuclear device in what year?

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

---

iClicker Question (Use Channel C-C)

Which of the following is **not** permissible under International Law?

A. Attacking a country that is blockading your territory
B. Attacking a country to prevent it from launching an attack at some time in the future
C. Attacking a country to disrupt an attack on your own territory that is already underway or is imminent
D. Attacking a country that is allowing pirates from its territory to attack ships in international waters
E. All of the actions listed above are permissible

iClicker Answer

Which of the following is **not** permissible under International Law?

A. Attacking a country that is blockading your territory

B. **Attacking a country to prevent it from launching an attack at some time in the future**

C. Attacking a country to disrupt an attack on your own territory that is already underway or is imminent

D. Attacking a country that is allowing pirates from its territory to attack ships in international waters

E. All of the actions listed above are permissible

---

iClicker Question (Use Channel C-C)

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

A. About the same

B. 10 times more

C. 100 times more

D. 1,000 times more

E. 1,000,000 times more

iClicker Answer

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

A. About the same

B. 10 times more

C. 100 times more

D. 1,000 times more

E. **1,000,000 times more**

---

iClicker Question (Use Channel C-C)

Which of the following is an example of radioactive decay?

A. Alpha decay

B. Beta decay

C. Gamma decay

D. Spontaneous fission

E. All of the above

Physics 280: Session 5

iClicker Answer

Which process is an example of radioactive decay?

A. Alpha decay

B. Beta decay

C. Gamma decay

D. Spontaneous fission

E. All of the above

Properties of Nuclear Explosive Nuclides

Reactivity, Critical Mass, and Explosive Yield

TABLE A-1 Properties of Nuclear-Explosive Nuclides

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

Properties of Nuclear Explosive Materials

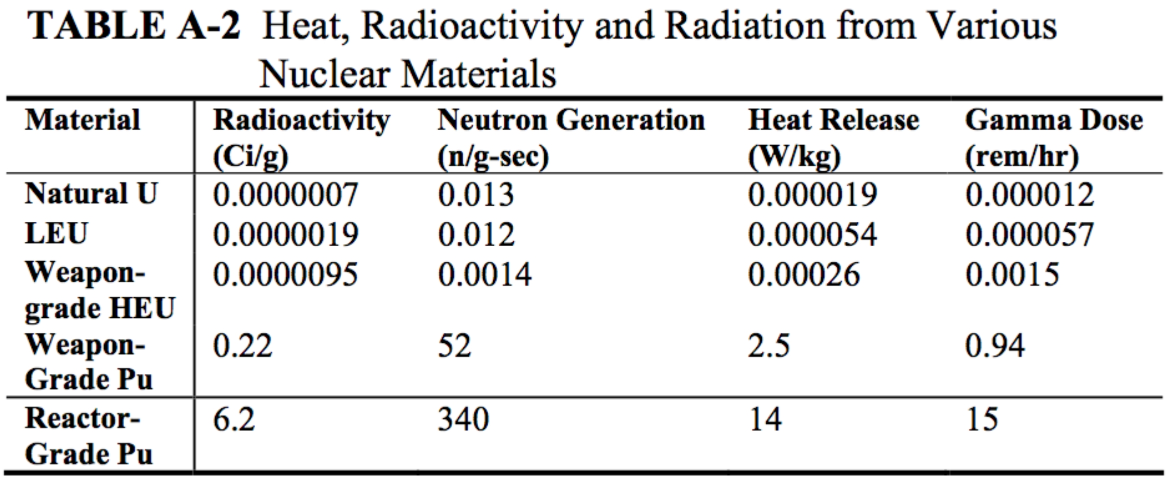
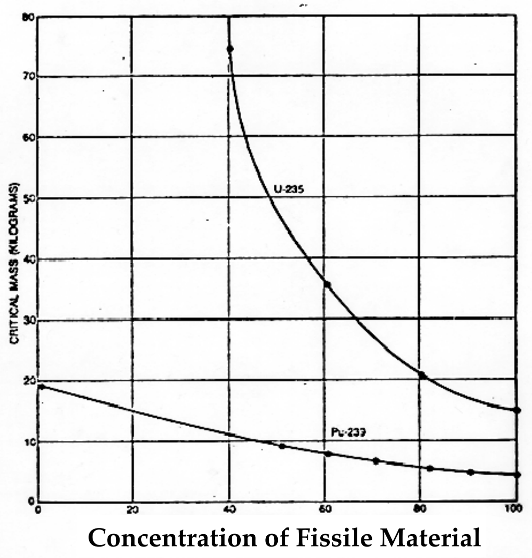


TABLE A-2 Heat, Radioactivity and Radiation from Various Nuclear Materials

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

Reducing the Fast-Neutron Critical Mass – 1

Dependence on the Concentration of the Fissile Material



Reducing the Fast-Neutron Critical Mass – 2

Dependence on the Density ρ of the Fissile Material

Let m_c be the critical mass. Then

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

where ρ_0 is normal density and ρ is actual density

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

Reducing the Fast-Neutron Critical Mass – 3

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

Mass Required for a Given Technology

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

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

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

U-235 and Pu-239 are *fissile*

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

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

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

Physics 280: Session 6

President Obama signed the New START articles of ratification yesterday at the White House.

U.S. Secretary of State Clinton will exchange the articles with Russian Foreign Minister Sergei Lavrov on Saturday (Feb. 5) in Munich, after which the treaty will be in force.

Plan for This Session

Student questions

Module 2: Nuclear weapons (cont'd)

Physics of Nuclear Weapons

Fission Weapons ("A-bombs")

Review of Important Concepts

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

How to Make a Chemical Explosion – 1

Explosive —

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

Packaging —

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

Ignition —

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

How to Make a Chemical Explosion – 2

Stages —

- Explosive is ignited
- Fuel and oxidizer burn (chemically), releasing ~ 10 eV per molecule
- Hot burned gases have high pressure, break bomb case and expand

Energy released goes into —

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

How to Make a Nuclear Explosion

Key steps in making a fission bomb —

- 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

Added steps required to make a two-stage bomb —

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

Energy Released By a Single Fission (Details)

n + (fissile nucleus) → (fission frags) + (2 or 3 n's)

Energy Distribution (MeV)	
Kinetic energy 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 = 8 kt TNT from 1 lb. of NEM
  (~ 10,000,000 times as much per lb. as TNT)
- Difficult to make weapons larger than few 100 kt
  (Yields of tested weapons: 1–500 kt)

Thermonuclear weapons (“H-bombs”) —

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

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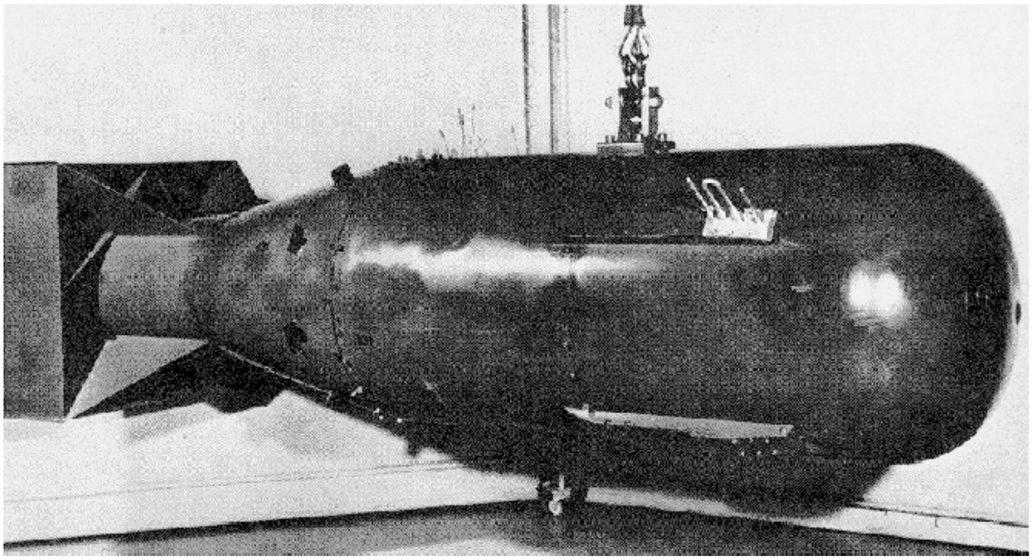
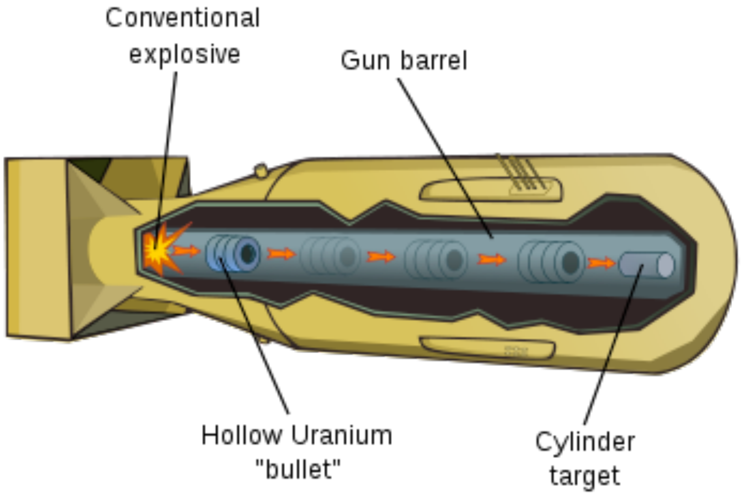
Fission Weapons – Gun Type

Little Boy



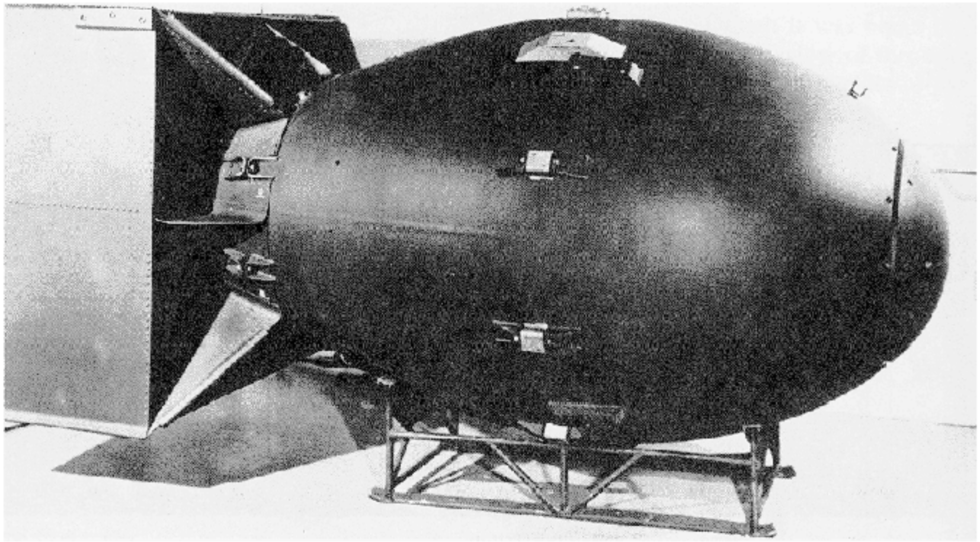
Fission Weapons – Gun Type



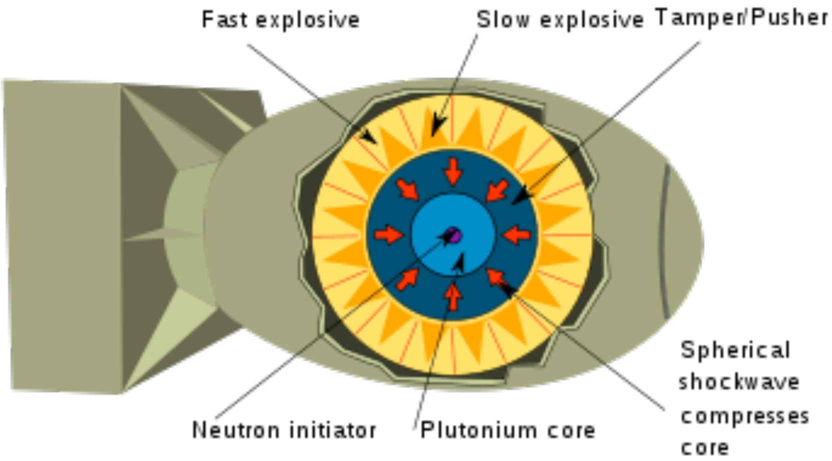
Works only with HEU
(relevant today mostly for terrorists or non-state groups)

Fission Weapons – Implosion Type

Fat Man

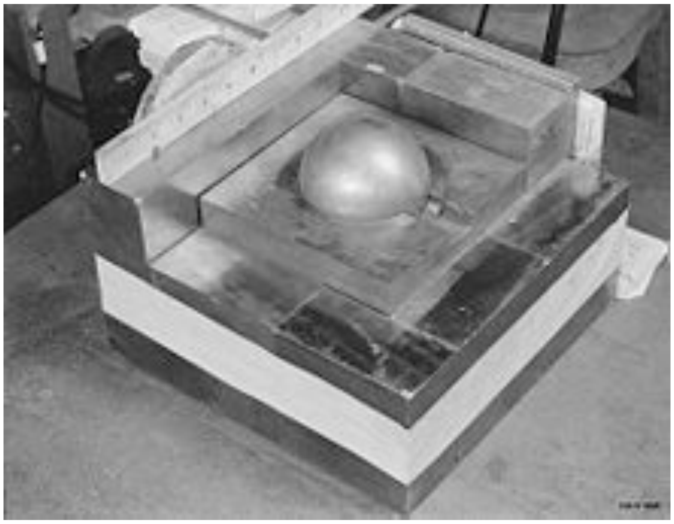


Fission Weapons – Implosion Type



Fission Weapons – Implosion Type

Plutonium Sphere ("Pit")



Initiating a Fission Explosion – 1

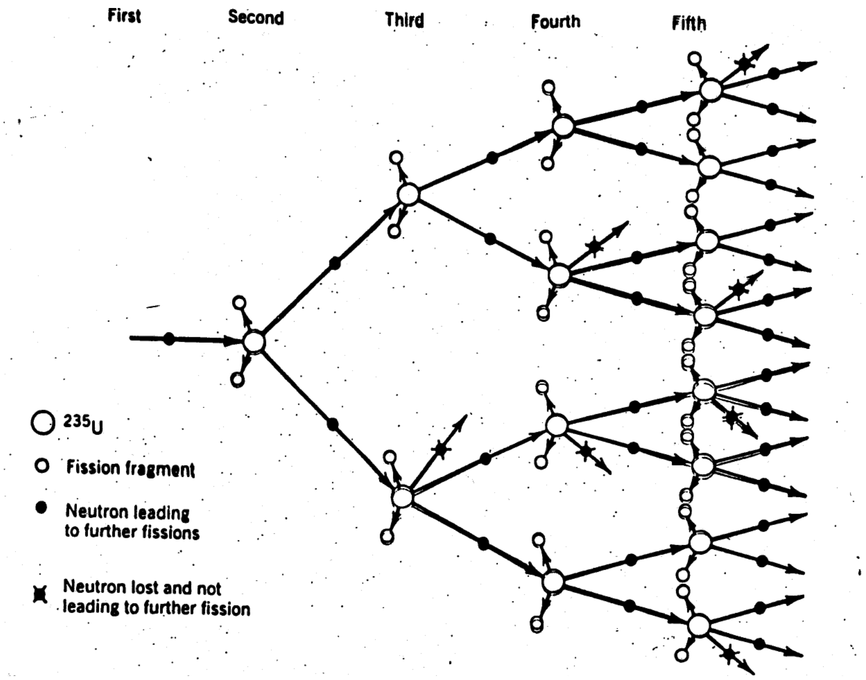
- Quickly assemble a *supercritical* configuration of nuclear-explosive material and, at the instant of maximum compression (maximum density)…
- Introduce *millions* of neutrons to initiate millions of chain reactions
- Chain reactions will continue until the increasingly hot nuclear-explosive material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

Explosive Chain Reaction



[Mousetrap Demonstration]

Requirements for Making a Fission Bomb

1. Know the nuclear physics of fission
2. Have needed data on the physical and chemical properties of weapon materials
3. Build technical facilities to fabricate and test devices and components of the chosen design

All these requirements are now met in any significantly industrialized country

4. Obtain the needed nuclear-explosive material
5. Allocate the necessary resources

iClicker Question (Use Channel C-C)

The symbol "U-238" is sufficient to specify

A. The chemical element to which this nucleus corresponds

B. The number of neutrons in this nucleus

C. The number of protons in this nucleus

D. The number of neutrons and protons in its nucleus

E. All of the above

Blank

iClicker Answer

The symbol “U-238” is sufficient to specify

A. The chemical element to which this nucleus corresponds

B. The number of neutrons in this nucleus

C. The number of protons in this nucleus

D. The number of neutrons and protons in its nucleus

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---

iClicker Question (Use Channel C-C)

Which one of the following statements is true?

A. A non-fissionable nuclide can sometimes be fissioned

B. A fissile nuclide cannot be fissioned

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

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

E. None of the above statements are true

Blank

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iClicker Answer

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E. None of the above statements are true

iClicker Question (Use Channel C-C)

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

A. Radioactivity

B. Spontaneous fission

C. Induced fission

D. Neutron activation

E. All of the above

Blank

iClicker Answer

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

A. Radioactivity

B. Spontaneous fission

C. **Induced fission**

D. Neutron activation

E. All of the above

---

iClicker Question (Use Channel C-C)

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

A = a marble

B = a softball

C = a basketball

D = a large beach ball

Blank

---

iClicker Answer

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

B = a softball

iClicker Question (Use Channel C-C)

China first tested a nuclear device in what year?

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

Blank

iClicker Answer

China first tested a nuclear device in what year?

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

Physics of Nuclear Weapons

Thermonuclear Weapons (“H-Bombs”)

Fusion Nuclear Reactions (Basics)

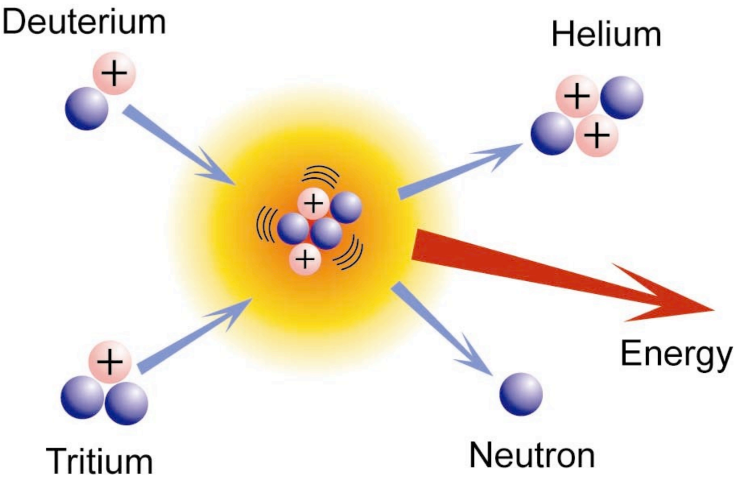
Fusion: a nuclear reaction in which two nuclides combine to form a single nuclide, with emission of energetic particles or electromagnetic radiation —

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

Particles involved:

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

Fusion Nuclear Reactions (Basics)



Two-Stage Nuclear Weapons – 1

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

---

Two-Stage Nuclear Weapons – 2

- Modern thermonuclear weapons have two stages:
  - the primary (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 Nuclear Weapons – 3

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

---

Two-Stage Nuclear Weapons – 4

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

Two-Stage Nuclear Weapons – 5

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

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

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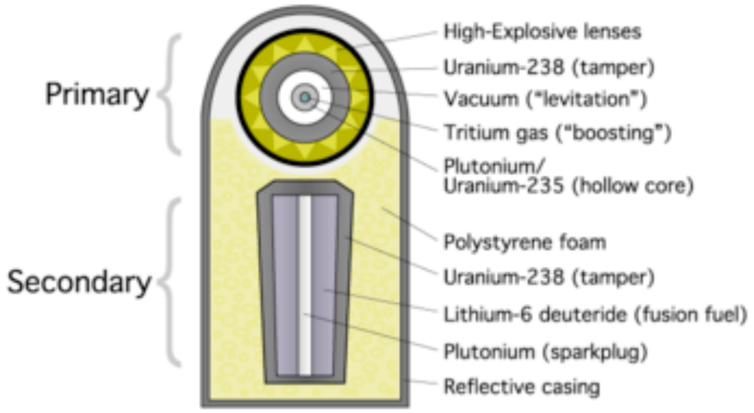
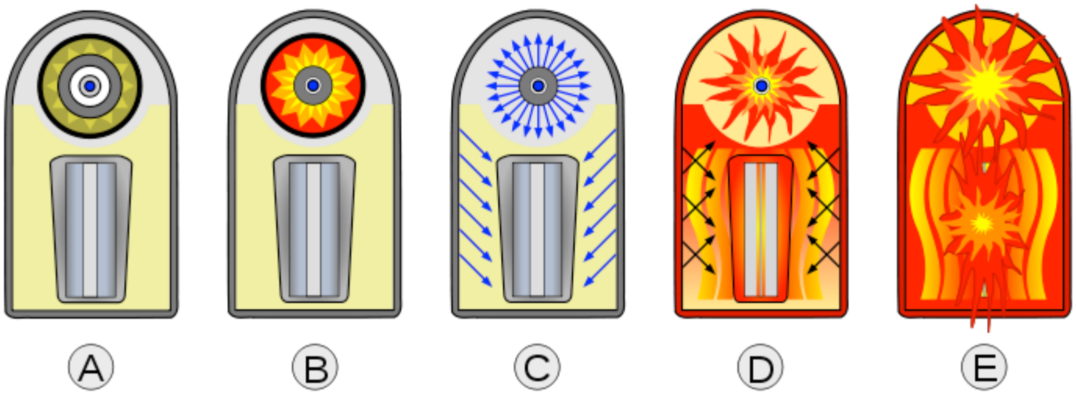
Two-Stage Nuclear Weapons – 6

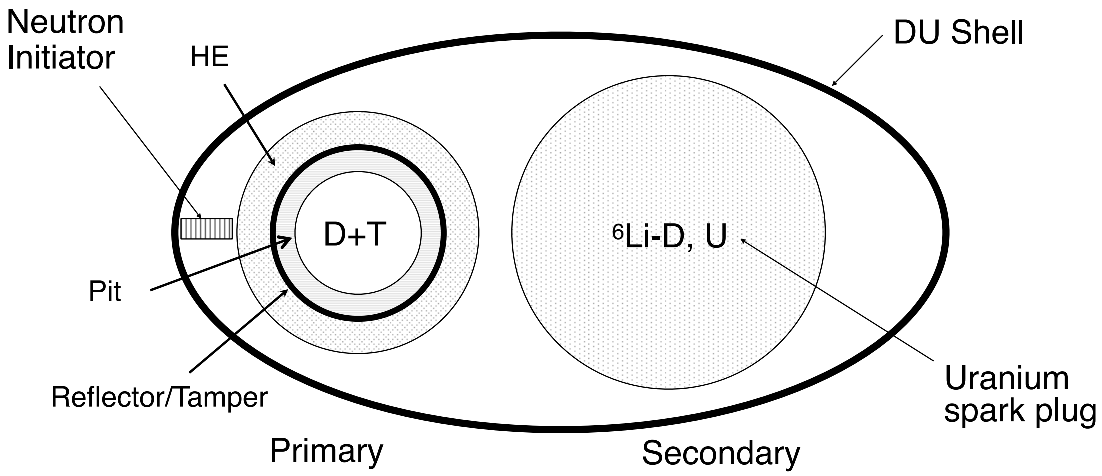


Two-Stage Nuclear Weapons – 7

Sequence of events —



Two-Stage Nuclear Weapon (“P280 Design”)



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

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 (a spherical shape is *not* required!)
- Compression and ignition of the ‘secondary’ is described by *radiation-hydrodynamics* —
  - Electromagnetic radiation moves at the speed of light
  - A uniform distribution of radiant energy is quickly achieved
  - All the matter behaves as a fluid at the high temperatures and pressures involved and hence is described by hydrodynamics
  - Large, fast computers are required to simulate the explosion accurately

---

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

Fission trigger —

- HE lenses + tamper + fissile core

Fusion fuel packet —

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

Uranium components —

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

“Weaponizing” a Nuclear Device

Technologies needed to make a nuclear *weapon* —

- Technology to produce nuclear-explosive material (NEM)

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

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

B-61 Bomb

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

Physics and Engineering Requirements

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

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

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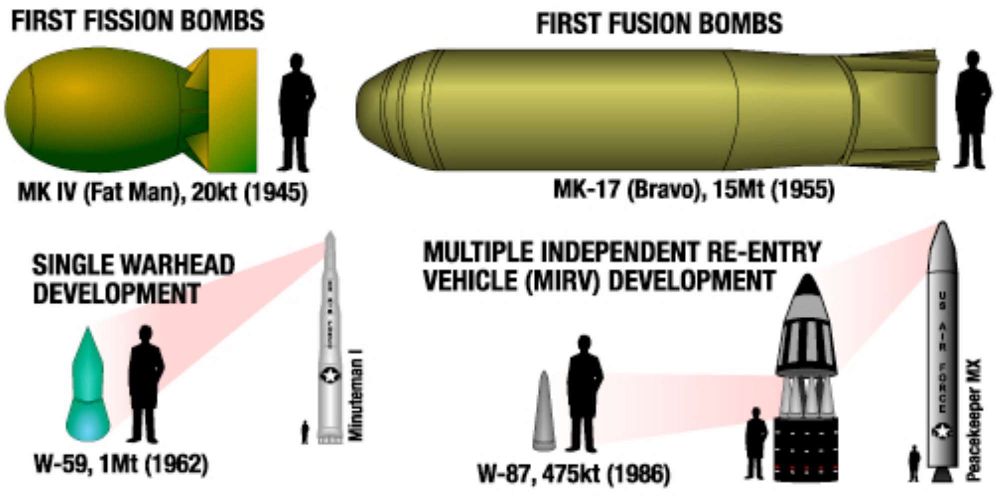
Making a Nuclear Warhead That Can Be Delivered By a Missile – 2

Miniaturizing Massive Death and Destruction



Physics 280: Session 7

Extra-Credit Essay Opportunity A
“The Mushroom Cloud & the Cinematic Imaginary”
Video and Panel Discussion
7:00 p.m. Tuesday, February 15
805 W. Pennsylvania Ave.

Plan for This Session

Student questions

News and discussion

Module 2: Nuclear weapons (cont’d)

News and Discussion

New START entered into force last Saturday, February 5th, when U.S. Secretary of State Hillary Clinton and Russian Foreign Minister Sergei Lavrov exchanged copies of the articles of ratification in Munich.

Previous Strategic Nuclear Arms Agreements

- 1972 : Nixon — Strategic Arms Limitation Treaty (SALT) and Anti-Ballistic Missile Treaty (ABMT), approved
- *1979 : Carter — Second Strategic Arms Limitation Treaty (SALT II), withdrawn*
- 1987 : Reagan — Intermediate-Range Nuclear Forces Treaty (INF), approved
- 1991: Reagan & Bush I — Strategic Arms Reduction Treaty (START I), approved
- 1992 : Bush I — Lisbon Accord, approved
- *1993 : Bush I & Clinton — Strategic Arms Reduction Treaty II (START II), Senate did not consent*
- *1996 : Clinton — Comprehensive Test Ban Treaty (CTBT), Senate did not consent*
- 2002 : Bush II — Strategic Offensive Reductions Treaty (SORT), approved

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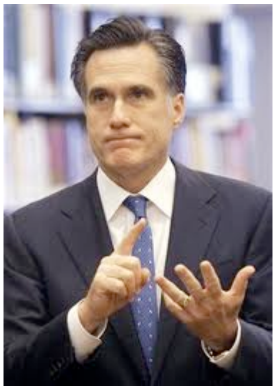
Key Provisions of New START

- Restricts the United States and Russia to no more than 700 deployed ICBMs, SLBMs, and nuclear-capable heavy bombers, and no more than 100 additional, nondeployed launchers
- Restricts the United States and Russia to 1,550 or fewer strategic nuclear warheads, down from 2,200 currently, including land-mobile missiles
- Allows the United States and Russia to resume inspection of each other’s strategic nuclear forces
- Establishes information exchanges, unique identifiers, notifications, and enhanced on-site inspections that provide high confidence that both countries are complying with the restrictions
- Russia must notify the United States 48 hours before a new intercontinental ballistic missile or submarine-launched ballistic missile leaves Votkinsk and when it arrives at its destination

What Were the Objections to New START?



Mitt Romney's objections to New START —

- *"New-START impedes missile defense, our protection from nuclear-proliferation rogue states such as Iran and North Korea. Its preamble links strategic defense with strategic arsenal [sic]."*

- *"[New START] explicitly forbids the United States from converting intercontinental ballistic missile (ICBM) silos into missile defense sites."*
- *"Russia has expressly reserved the right to walk away from the treaty..."*

What Were the Objections to New START?

- *"The treaty empowers a Bilateral Consultative Commission with broad latitude to amend the treaty with specific reference to missile defense."*
- *"The treaty also gives far more to the Russians than to the United States. As drafted, it lets Russia escape the limit on its number of strategic nuclear warheads."*

In fact, both Russia and the United States are restricted to 1,550 warheads each. Russia, which currently has 2,787 warheads, will have to cut back more than the United States, which currently has 2,252.

Both Russia and the United States are restricted to 700 launchers. Russia is already down to 600; the United States will have to go from 850 to 700.

What Were the Objections to New START?

- *“rail-based ICBMs and launchers are not mentioned”*

1. Neither Russia nor the United States has any rail-based ICBMs or launchers and neither has plans to build any.

2. Article III, Section 5b says that an ICBM is counted under the treaty's limits the moment it leaves the production facility (which other sections of the treaty place under constant monitoring). It doesn't matter whether the missile is later put in a silo, on a railroad car, or in a truck, it's still counted as an ICBM. So while rail-based missiles are not mentioned by name in the treaty, they are most definitely included.

What Were the Objections to New START?

- *“Similarly, multiple nuclear warheads that are mounted on bombers are effectively not counted. Unlike past treaty restrictions, ICBMs are not prohibited from bombers. This means that Russia is free to mount a nearly unlimited number of ICBMs on bombers—including MIRVs (multiple independently targetable reentry vehicles) or multiple warheads—without tripping the treaty's limits.”*

ICBMs are not now and never have been “mounted on” or loaded inside bombers. Nor are MIRV missile warheads mounted on bombers. Bombers carry bombs.

This counting rule is to the United States’ advantage, not Russia’s: the U.S. has 113 heavy bombers; Russia 77.

The Importance of New START

- The Russian strategic nuclear force could obliterate the United States any day. It is the only immediate threat to the existence of the United States. It is a relic of an insane military competition that ended more than 20 years ago.
- In my view, New START is a small but significant further step toward a rational nuclear policy.
- It is impossible to pressure other countries to give up or refrain from developing nuclear weapons if by its actions the United States shows that it thinks nuclear weapons are important and usable. The reduction of U.S. and Russian nuclear arsenals was supposed to counter this impression.
- Unfortunately, the nearly $200 billion increase in funds for manufacturing nuclear weapons extracted by the opponents of New START has seriously undercut this goal.

Types of Official Secrets

- Security secrets
  - Example: thermonuclear weapon designs
- Diplomatic secrets
  - Example: locations of certain overseas facilities
- Thoughtless secrets
  - Example: information classified because it’s easy to do
- Political secrets
  - Example: information that would undercut official policies or lies
- Embarrassing secrets
  - Example: political or technical mistakes
- Silly secrets
  - Example: well-known laws of physics

Nuclear Weapon Secrets

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

There were 3 important secrets —

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

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

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

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Physics of Nuclear Weapons

Production of Nuclear-Explosive Material

Enrichment of U-235

Separation of Pu-239

Enrichment of Uranium Required to Make Nuclear Bombs

- Natural uranium is
  - 99.3% U-238 (which is fissionable but not fissile)
  - 0.7% U-235 (which is fissile)
- Natural uranium must be *enriched* in U-235 to make a nuclear explosion (but not for 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

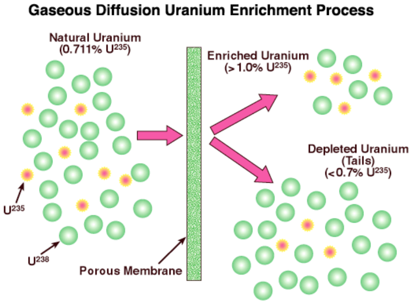
There are 4 main
uranium enrichment techniques:

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

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

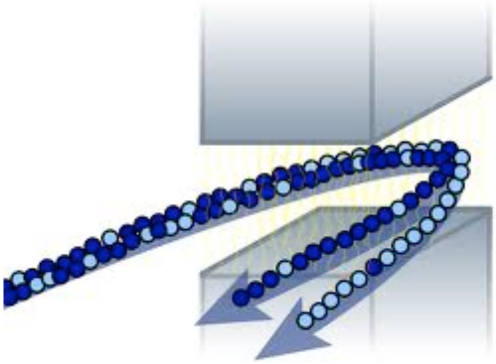
Enriching Uranium – Details 1

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



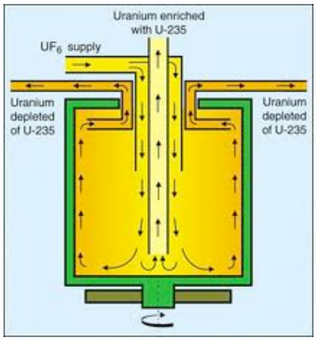
Enriching Uranium – Details 2

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



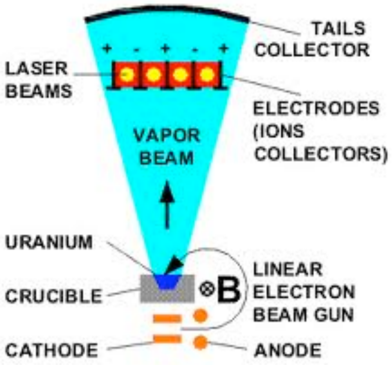
Enriching Uranium – Details 3

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



Enriching Uranium – Details 4

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



Making Plutonium

Plutonium can be produced by bombarding *uranium* or *thorium* in a *nuclear reactor*—

- U-238 + n → Pu-239 (two step process)
- Th-232 + n → U-233 (two-step β-decay process)

(non-fissile) (fissile)

Heavier plutonium isotopes are produced the longer the uranium (or thorium) is exposed to neutron bombardment in the reactor —

- Pu-239 → Pu-240 → Pu-241 → Pu-242, etc.
- Pu-240 undergoes spontaneous fission
- Heavier Pu isotopes are highly radioactive

Producing a Nuclear Explosion Using Plutonium (Overview)

Producing a nuclear explosion is more difficult with “high burn-up” (reactor-grade) plutonium —

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

It is much easier to produce a nuclear explosion if the plutonium is “weapon-grade” (more than 93% Pu-239). [Definition]

High burn-up Pu can approach ~ 40% Pu-239, ~30% Pu-240, ~15% Pu-241, and ~15% Pu-242.

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

Producing a Nuclear Explosion Using Plutonium – 1

- Virtually any combination of plutonium isotopes — the different forms of an element, having different numbers of neutrons in their nuclei — can be used to make a nuclear weapon. Not all combinations, however, are equally convenient or efficient.
- The plutonium isotope 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.
- 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.

Producing a Nuclear Explosion Using Plutonium – 2

- 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, so in power reactors the fuel is left in the reactor much longer This produces “high burn-up” plutonium, which includes more of the heavier isotopes of plutonium. It is called "reactor grade" plutonium.

Producing a Nuclear Explosion 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.

Producing a Nuclear Explosion 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.

Producing a Nuclear Explosion 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 and CANDU)
  - –Fuel-grade: 80% to 93% Pu-239 (some other reactors)
  - –Weapons-grade: > 93% Pu-239

iClicker Question (Use Channel C-C)

India first tested a nuclear device in what year?

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

Blank

iClicker Answer

India first tested a nuclear device in what year?

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

---

iClicker Question (Use Channel C-C)

Pakistan first tested a nuclear device in what year?

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

Blank

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iClicker Answer

Pakistan first tested a nuclear device in what year?

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

iClicker Question (Use Channel C-C)

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

A = a marble

B = a softball

C = a basketball

D = a large beach ball

Blank

iClicker Answer

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

B = a softball

---

iClicker Question (Use Channel C-C)

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

A. A nuclear explosion can be created using any fissionable material

B. A nuclear explosion can be created using any fissile material

C. A nuclear explosion can be created using U(235)

D. A nuclear explosion can be created using Pu(239)

E. A nuclear explosion can be created using reactor fuel

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iClicker Answer

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

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

Physics of Nuclear Weapons

Implications for Nuclear Testing, Proliferation, and Terrorism

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Nuclear Weapon Design

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

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

Requirements for Making a Fission Bomb (Review)

1. Know the nuclear physics of fission
2. Have needed data on the physical and chemical properties of weapon materials
3. Build technical facilities to fabricate and test devices and components of the chosen design

All these requirements are now met in any significantly industrialized country

4. Obtain the needed nuclear-explosive material
5. Allocate the necessary resources

Capabilities of Crude Implosion Devices

The original, relatively crude implosion assembly used in the 1945 Trinity test was capable of —

- Producing a 20 kt yield from weapon-grade Plutonium with a probability of 88%
- Producing a 20 kt yield from HEU with near 100% probability
- Producing a multi-kiloton yield from any reactor-grade of Plutonium

The first implosion system had a diameter of less than five feet.

The design of this system was highly conservative. The size of a simple implosion weapon could be reduced substantially using the results of (non-nuclear) laboratory tests.

Implications for Proliferation – 1

- HEU enrichment and Pu production and separation facilities are large, industrial-scale enterprises using specialized technologies that are difficult (but not impossible) to hide.
- Efforts to acquire special materials (Be, D, T), and interest in high-quality explosives and detonators and high performance firing circuitry may provide additional clues that a country or organization is pursuing a program to develop nuclear weapons.
- Implosion studies are essential to develop a reliable fission bomb, but are difficult to detect unless a nuclear yield is achieved.
- A gun-type HEU weapon could be developed without testing.
- A crude implosion-type Pu weapon could also be developed without testing, but confidence in its performance would be low.

Implications for Proliferation – 2

- It is difficult to conduct nuclear tests at very low yields without substantial prior experience in nuclear testing.
- If a primary is tested, it will likely release at least a few kt.
- A program to develop secondaries for a thermonuclear weapon has a less dramatic signature than one to develop primaries.
- Without nuclear testing at the full yield of the *primary*, confidence in the performance of the *secondary* would be low to non-existent.
- The best way to stop nuclear weapon proliferation is by preventing states from developing a fission device (primary).
- The best way to prevent states from developing a fission device is to prevent them from acquiring NEM and weapon designs.

Some Problems Terrorists Would Face

Some problems that terrorist organizations wishing to construct a nuclear explosive would confront —

- Assembling a team of technical personnel
- Substantial financial costs
- Radiation and chemical hazards
- Possibility of detection
- Acquisition of nuclear-explosive material

Supplementary and Review Slides

Unification of Forces

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

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Key Forces Inside the Nucleus

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

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

Review of Important Definitions

Fissionable but non-fissile material —

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

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

Fertile material —

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

Examples: U-238 and Th-232

Nuclear Physics Terminology

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

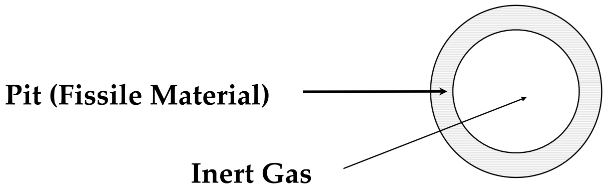
Importance of Delayed Neutrons for Controlling Nuclear Reactors

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

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

Hollow “Pit” Implosion Design – Step 1

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

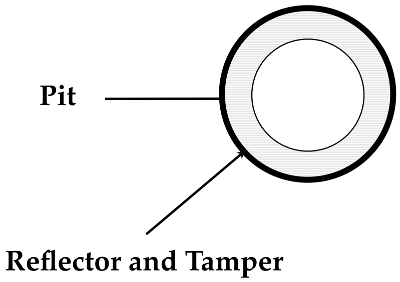


Advantage:

- Can implode an initially hollow spherical shell to a higher density than an initially solid sphere
- Explain using an analogy

Hollow “Pit” Implosion Design – Step 2

Add a reflector and tamper —



Advantages:

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

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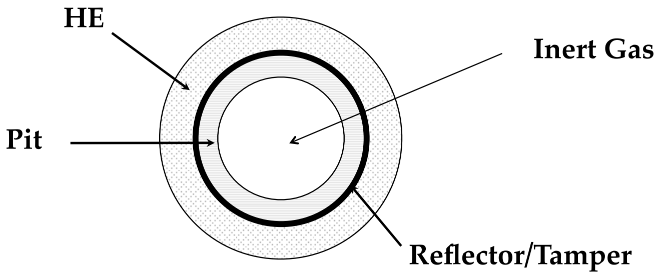
Hollow “Pit” Implosion Design – Step 3

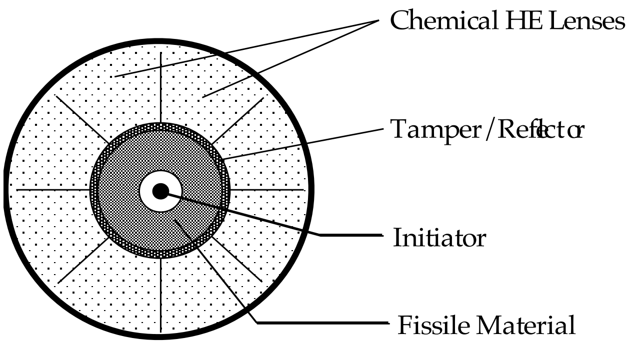
Add the HE lenses, initiator, and fusing and firings circuits (latter two parts not shown) —



Advantages:

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

Fission Weapons – Implosion Type



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

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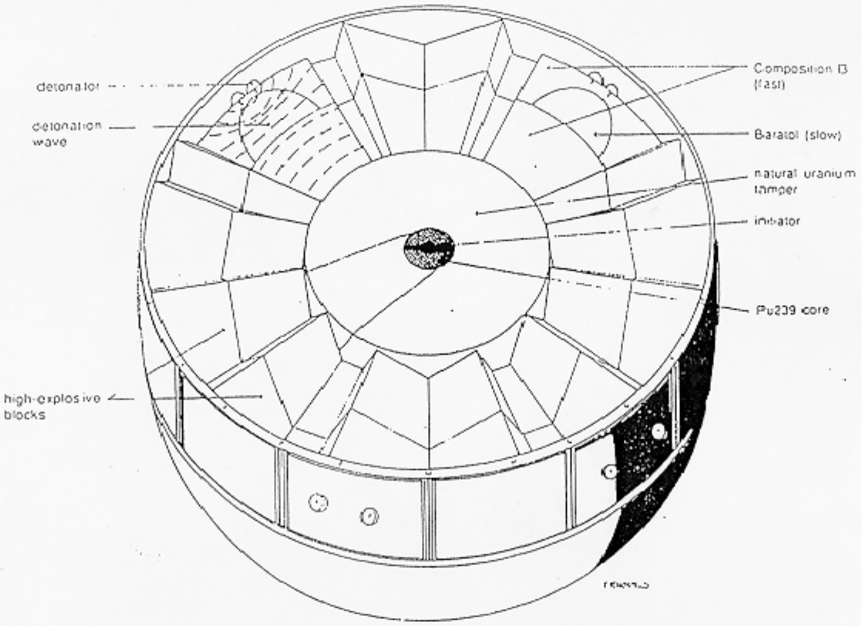
Fission Weapons – Implosion Type

View of the interior of an implosion weapon



Initiators – 1

Example of a simple initiator —

- Mixture of Polonium (Po) and Lithium (Li)
  - Polonium has several radioactive isotopes
    Po-218 → Pb-214 + α
    Po-216 → Pb-212 + α
    Po-210 → Pb-206 + α
  - High probability nuclear reaction
    α + Li-7 → B-10 + n
- Essential to keep Po and Li separate until desired time of initiation

Aluminum foil is perfect

Pure Li-7 is not required

Be-9 can be used instead of Li-7

Initiators – 2

Example of a sophisticated initiator —

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

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

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

Boosted Fission Weapons – 1 (Details)

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

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

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

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

Boosted Fission Weapons – 2 (Details)

Advantages —

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

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

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

This also increases the safety of the weapon.

Fusion Nuclear Reactions (Details)

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

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

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

True Thermonuclear Weapons

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

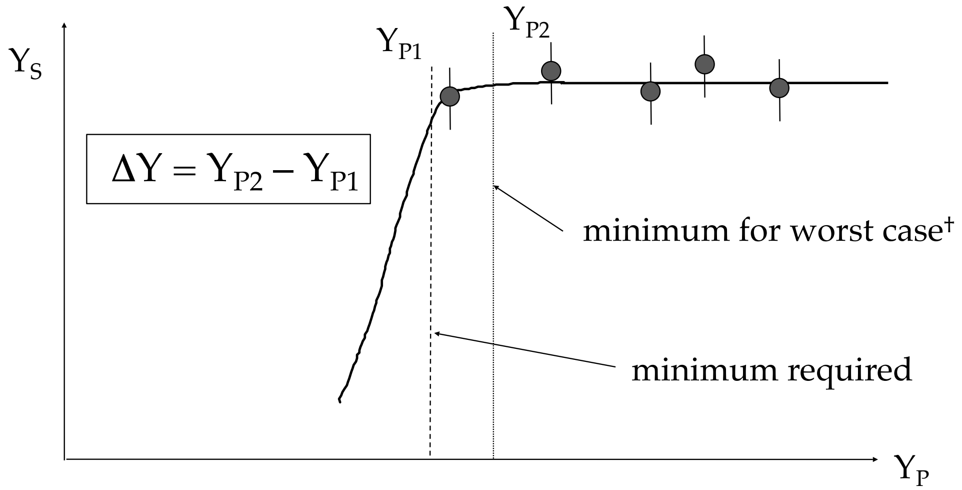
Review of Two-Stage Nuclear Weapons – 1

- 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

Review of Two-Stage Nuclear Weapons – 2

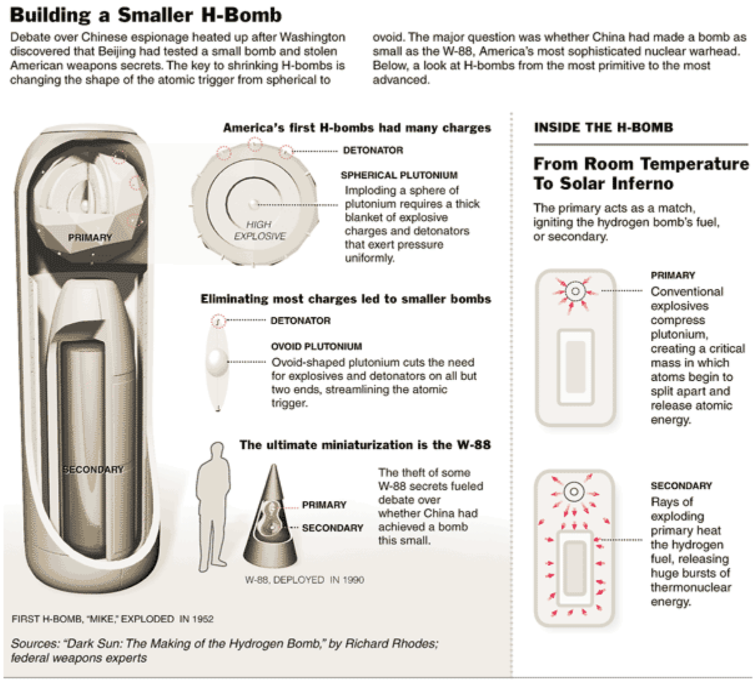
- The basic materials required for the 'secondary' (Li-6 and D) are widely available
- The geometry of the 'secondary' is not critical (a spherical shape is *not* required!)
- Compression and ignition of the 'secondary' is described by *radiation-hydrodynamics* —
  - Electromagnetic radiation moves at 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

Primary Margin ΔY



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

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



Building a Smaller H-Bomb

Debate over Chinese espionage heated up after Washington discovered that Beijing had tested a small bomb and stolen American weapons secrets. The key to shrinking H-bombs is changing the shape of the atomic trigger from spherical to ovoid. The major question was whether China had made a bomb as small as the W-88, America's most sophisticated nuclear warhead. Below, a look at H-bombs from the most primitive to the most advanced.

America's first H-bombs had many charges

SPHERICAL PLUTONIUM
Imploding a sphere of plutonium requires a thick blanket of explosive charges and detonators that exert pressure uniformly.

Eliminating most charges led to smaller bombs

OVOID PLUTONIUM
Ovoid-shaped plutonium cuts the need for explosives and detonators on all but two ends, streamlining the atomic trigger.

The ultimate miniaturization is the W-88

The theft of some W-88 secrets fueled debate over whether China had achieved a bomb this small.

W-88, DEPLOYED IN 1990

FIRST H-BOMB, "MIKE," EXPLODED IN 1952

Sources: "Dark Sun: The Making of the Hydrogen Bomb," by Richard Rhodes; federal weapons experts

INSIDE THE H-BOMB

From Room Temperature To Solar Inferno

The primary acts as a match, igniting the hydrogen bomb's fuel, or secondary.

PRIMARY
Conventional explosives compress plutonium, creating a critical mass in which atoms begin to split apart and release atomic energy.

SECONDARY
Rays of exploding primary heat the hydrogen fuel, releasing huge bursts of thermonuclear energy.

Review of Modern Thermonuclear Weapons – 2

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

Designing Nuclear Weapons To Use Reactor-Grade Plutonium

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

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

Designing Nuclear Weapons To Use Reactor-Grade Plutonium

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

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

Enhanced Radiation Weapons – 1

Purpose —

- To kill people without destroying or contaminating structures or areas

Design principles —

- Minimize the fission yield
- Maximize the fusion yield

Methodology —

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

These are technically challenging requirements

Enhanced Radiation Weapons – 2

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

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

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

End of Nuclear Weapons Module