

Physics 280: Session 4

Plan for This Session

Extra Credit Essay Opportunity A

“Nuclear Nonproliferation Verification and Compliance”

12:00 – 1:00 p.m. Thursday, February 4, in 151 Loomis

Student questions?

News and discussion

iClicker questions

Types of armed conflict

Module 2: Nuclear weapons

10p280 Course Intro, p. 1

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Session 4: News and Discussion

Global Strike Command Set to Take Control of Dual-Capable Bombers

Wednesday, Jan. 27, 2010

By Elaine M. Grossman
Global Security Newswire

WASHINGTON -- As part of an U.S. Air Force effort to overhaul management of its nuclear weapons, the service's new Global Strike Command is preparing to assume oversight next week for the nation's B-2 and B-52 dual-capable bombers (see **GSN**, Dec. 2, 2009).

New START Accord Might be Finished in Weeks, Russia Says

Wednesday, Jan. 27, 2010

Russia said today that negotiations on a replacement for the expired Strategic Arms Reduction Treaty could be finished in a matter of weeks, Reuters reported (see **GSN**, Jan. 25).

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Session 4: News and Discussion

Signs Point to North Korean Missile Tests

Tuesday, Jan. 26, 2010

North Korea could be preparing for another round of missile launches following its announcement of a no-sail zone in the waters along its western coast, Reuters reported today (see **GSN**, Oct. 29, 2009).

New HEU Storage Site OK'd to Open

Tuesday, Jan. 26, 2010

The U.S. National Nuclear Security Administration said yesterday it had given the final go-ahead to begin the transfer of highly enriched uranium to a new, high-security storage facility at the Y-12 National Security Complex in Oak Ridge, Tenn. (see **GSN**, Dec. 17, 2009).

Uranium Ore Seized in Brazil

Tuesday, Jan. 26, 2010

Brazilian authorities seized nearly 1,000 pounds of uranium-rich uraninite Friday in an isolated rain forest region, RIA Novosti reported (see **GSN**, Sept. 28, 2009).

Police tracked down the highly radioactive substance in the northern state of Amapa following a four-month probe (**RIA Novosti**, Jan. 23).

Physics 280: Session 4

iClicker Question

Which of the following *is allowed* by University rules?

- A. Helping another student write a paper
- B. Using a quotation from a source that is quoting another source
- C. Allowing another student to borrow your notes on an Extra Credit Essay event to help them write their Extra Credit Essay
- D. Writing papers for two different courses on the same topic
- E. None of the above is permissible

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Physics 280: Session 3

iClicker Question

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- E. None of the above is permissible**

Physics/Global Studies 280

Module 2: Nuclear Weapons

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Module 2: 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

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

Do not be overly concerned!

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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

Introduction

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Physics of Nuclear Weapons

Atoms and Nuclei

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Fundamental Forces of Nature – 1

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

1. Gravitational

- Weakest, attractive; only one sign of charge (= mass)
- First of the fundamental forces to be discovered
- Classical gravitational force decreases as $1/r^2$ (long-range)

2. Electromagnetic

- Classical electrical force decreases as $1/r^2$ (long-range), can be attractive or repulsive
- Classical magnetic force decreases as $1/r^3$ (bar magnet) or faster, because magnetic charges have not been detected (so far)
- Electromagnetism = first example of a unified theory (electricity + magnetism)
- First example of a relativistic theory (special relativity)
- Fundamental theory is Quantum Electrodynamics (QED), involves charged particles and photons

Fundamental Forces of Nature – 2

3. Weak nuclear force

- Responsible for beta (β^- and β^+) decay
- Extremely short range (much smaller than the diameter of proton or neutron)
- No classical approximation (because it vanishes at long distances); a quantum mechanical description is required

[electroweak force = unification of electromagnetic + weak]

4. Strong nuclear (“strong”) force

- Holds protons and neutrons together in the atomic nucleus, the positively charged central core of an atom which contains most of its mass
- The strongest known force
- Short-range (reaches approximately the diameter of a proton, vanishes at larger distances)
- No classical approximation, so a quantum mechanical description is required
- Fundamental theory is Quantum Chromodynamics (QCD), involves quarks and gluons

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 quarks and gluons (unimportant for nuclear weapon physics)
- All protons (and all neutrons, and all electrons) are *identical and indistinguishable*

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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 ($\sim 10^{-13}$ 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 —

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

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Atomic Nuclei

- A distinct atomic nucleus (“nuclide”) is specified by the number of protons (denoted Z – always an integer) and the number of neutrons (denoted N – always an integer) within it.
- 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 –

$${}^A_ZX_N = {}^A_ZX = {}^AX = X(A)$$

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

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 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*.

The process is described by the *half life* $\tau_{1/2}$ of the original nuclide, or equivalently the *average rate of decay* λ ($= 0.693/\tau_{1/2}$).

All radioactive decays are *probabilistic*.

Probability is intrinsic to *Quantum Mechanics*, which governs the Universe.

Four Types of Radioactive Decay (Basics)

1. Alpha decay

Parent $\rightarrow$ Daughter + alpha particle (^4He)

2. Beta decay

Parent $\rightarrow$ Daughter + electron (+ anti-neutrino)

Parent $\rightarrow$ Daughter + anti-electron (+ neutrino)

3. Gamma decay

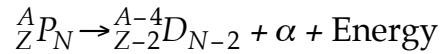
Parent $\rightarrow$ Daughter + gamma-ray

4. Spontaneous fission

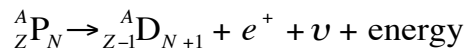
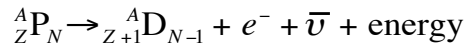
Parent $\rightarrow$ Fragment 1 + Fragment 2 + neutrons

Four Types of Radioactive Decay (Details)

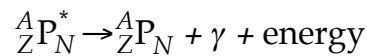
1. Alpha decay: α



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

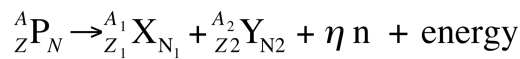


3. Gamma decay: γ



Four Types of Radioactive Decay (cont'd)

4. Spontaneous fission: fission products



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

$$Z = Z_1 + Z_2$$

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

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

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

Bombardment by n , γ , or β particles can make the target nuclide radioactive.

This process is called *activation* (e.g., *neutron activation*). It is *not* called induced radioactivity.

Physics 280: Session 5

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Student questions, news, and discussion

iClicker questions

Module 2: Nuclear weapons (cont'd)

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Session 5: News and Discussion



Missile Defense Test Flops as U.S. Unveils New Strategy

By [Nathan Hodge](#) February 1, 2010 | 5:43 pm | Categories: [Rogue States](#)

Over the weekend, the Missile Defense Agency released news of another [failed intercept](#) test. And no, the interceptor didn't [fail to lift off or fly off course](#). This time, it was the tracking radar that wasn't up to scratch.

According to an military [news release](#), a Sea-Based X-Band (SBX) radar in the middle of the Pacific Ocean was supposed track a target missile launched from Kwajalein Atoll, relaying the data to a ground-based interceptor launched from Vandenberg Air Force Base, Calif. While both the target missile and interceptor launched successfully, the interceptor failed to hit the target. According to the agency, the SBX “did not perform as expected.”

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Session 5: News and Discussion

It was supposed to be a test of a new concept: using the SBX as the primary engagement radar for the Ground-based Midcourse Defense system. But it was also supposed to be an advertisement for a missile defense system that was gradually working out the kinks.

President Barack Obama is pursuing a new vision of ballistic missile defense, one billed as a more prudent — and more realistic — alternative to the plans backed by his predecessor. But as the [newly released Pentagon review](#) acknowledges, building a capable, and affordable, missile shield won't happen overnight.

As part of the February 1st budget-'n-strategy extravaganza, the Pentagon released the [Ballistic Missile Defense Review](#). It's a blueprint for building missile defenses that are "cost-effective and proven," and that can stand up to realistic testing. The new mantra here is the "phased adaptive approach," which means gradually bulking up regional defenses against short- and medium-range missiles, instead of a more immediate focus on knocking down long-range missiles.

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Session 5: News and Discussion

The review is built around this assumption: "Rogue states" like Iran and North Korea don't yet pose a credible threat to U.S. territory. But the military needs to prepare for a possible surprise advance in the missile threat.

Obama took the first step in this direction when he [scrapped plans](#) to site ground-based interceptors in Europe. The new "phased plan" calls for fielding a more advanced sea-based missile interceptor (the [Standard Missile-3](#), pictured here) and stationing more sensors in Europe. The next stage would involve placing land-based SM-3s in southern Europe to expand coverage to more NATO allies; further down the road — 2018 and beyond — the plan calls for improved coverage against medium- and intermediate-range threats by stationing land-based SM-3s somewhere in northern Europe, as well as by fielding an upgraded interceptor, the SM-3 Block IIA.

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Physics 280: Session 5

iClicker Questions

When did the United States first test a nuclear weapon?

A. 1945 B. 1946 C. 1947 D. 1948 E. 1949

When did the Soviet Union first test a nuclear weapon?

B. 1945 B. 1946 C. 1947 D. 1948 E. 1949

When did President Truman start the U.S. H-bomb program?

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

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Physics 280: Session 5

iClicker Answers

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When did President Truman start the U.S. H-bomb program?

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

Physics 280: Session 3

iClicker Questions

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

Blank

Physics 280: Session 3

iClicker Answer

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Physics 280: Session 5

iClicker Question

How does the power of the (primitive) Hiroshima nuclear weapon compare with the power of a large conventional (high-explosive) weapon?

- A. About the same
- B. 10 times more
- C. 100 times more
- D. 1,000 times more
- E. 1,000,000 times more

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Physics 280: Session 5

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

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Physics of Nuclear Weapons

Nuclear Fission and Fusion

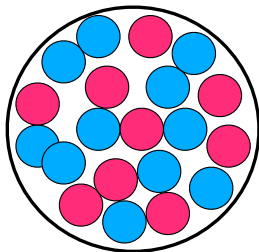
The Neutron

- 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.

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Key Forces Inside the 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 nuclear mass M and total binding energy B_T :

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

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

Nuclear Term

Electrical Term

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

Eventually repulsion exceeds attraction: $B_T < 0$.

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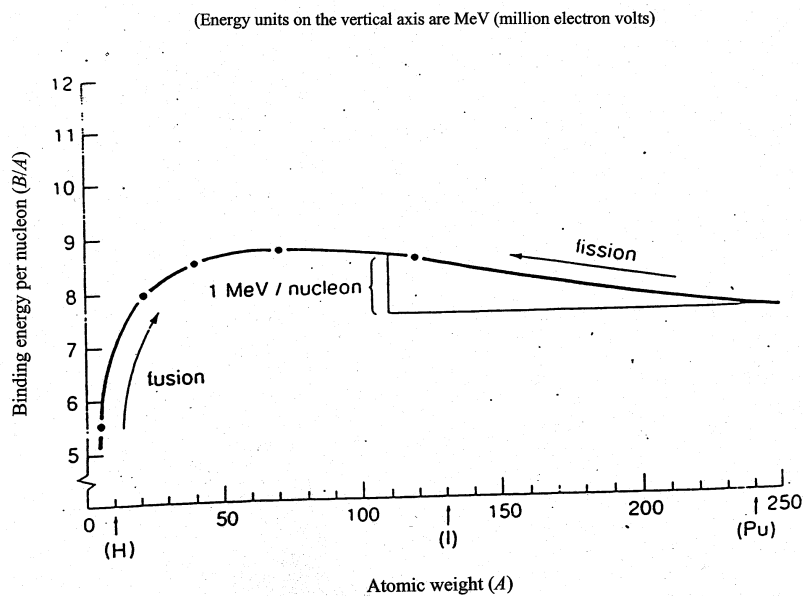
The Binding Energy Per Nucleon

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

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

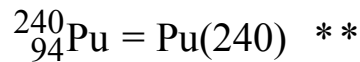
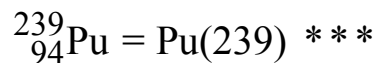
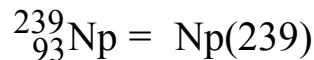
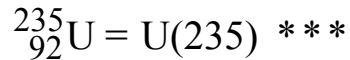
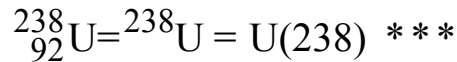
- The plot of B vs. A is called “the curve of the binding energy”

The Curve of Binding Energy



Nuclides Important for Fission Bombs

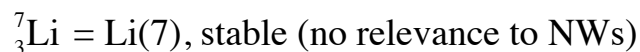
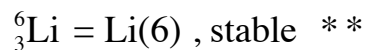
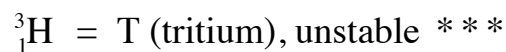
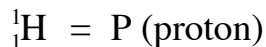
Heavy elements (high Z) —



*, **, *** denotes increasing importance

Nuclides Important for Fusion Bombs

Light elements (low Z) —



*, **, *** denotes increasing importance

The Two Types of Fission

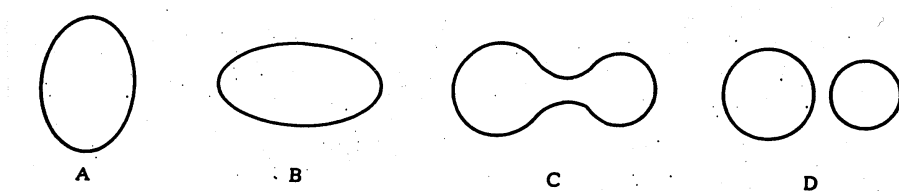
Spontaneous fission —

- 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

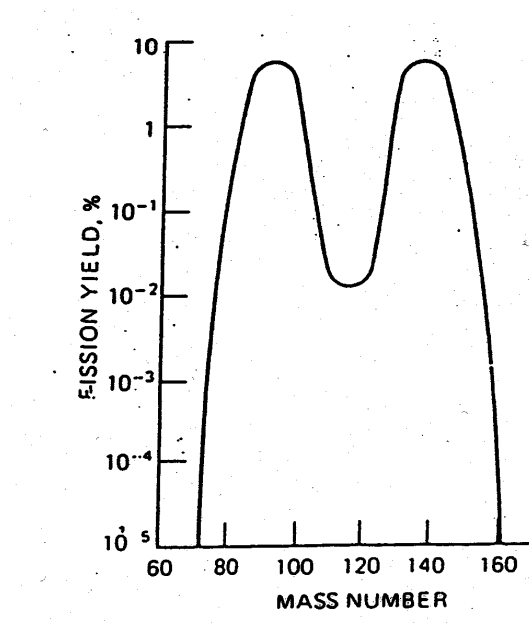
Induced fission —

- 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

Liquid Drop Model of Fission



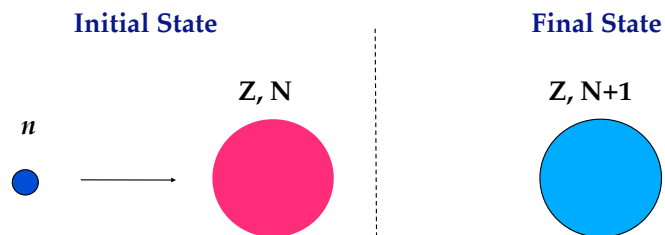
Distribution of Fission Fragment Masses



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Neutron Capture



The resulting nucleus may be stable or unstable.

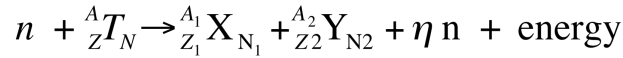
If unstable, we call this process *neutron activation*. It typically results in a β -decay.

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Induced Fission – 1

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



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

$$Z = Z_1 + Z_2,$$

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

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

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

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.

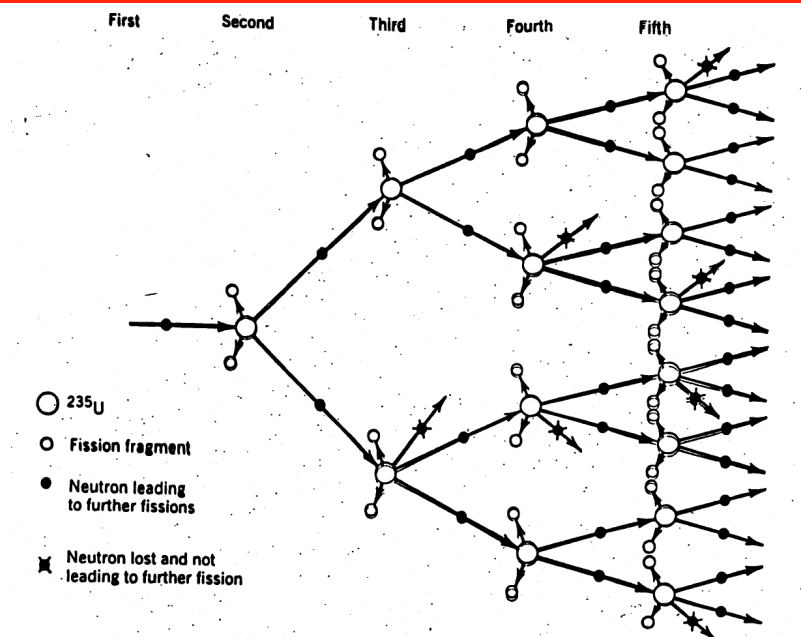
Lise Meitner, a Jewish scientist who had fled Germany to Copenhagen, was the first person to understand what was happening in the experiments.

Unfortunately, Niels Bohr was too excited to keep her insight secret, and *she was not included* in the Nobel Prize awarded for the discovery! A shameful omission.

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)

Explosive Chain Reaction



Physics of Nuclear Weapons

Nuclear Reactors and Nuclear Bombs

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Definition of the Critical Mass

The *critical mass* is the mass of

- a given nuclear material (composition, density, chemical form, etc.)
- in a given configuration (geometry, surroundings, etc.)

that is needed to create a *steady rate* of fissions.

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

Such a system is said to be *critical*.

The critical mass depends on —

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

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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.

Physics of Nuclear Reactors

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.

Fissile nuclides can sustain a chain reaction under these circumstances.

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

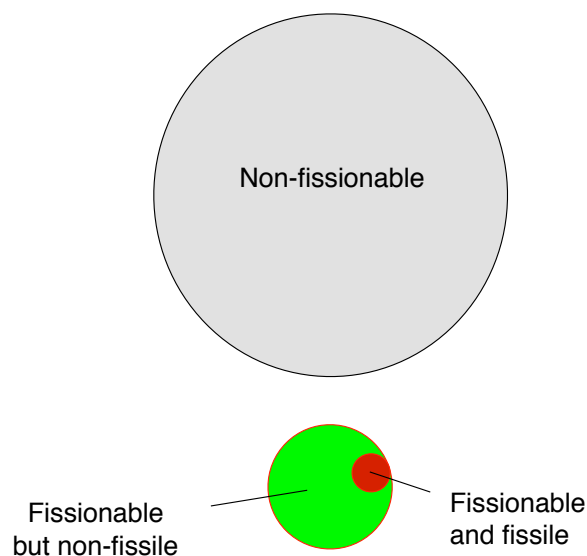
Fissionable but not fissile nuclides cannot be used in a nuclear reactor but some can be used in nuclear bombs.

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

All nuclides (fissionable and non-fissionable)

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

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



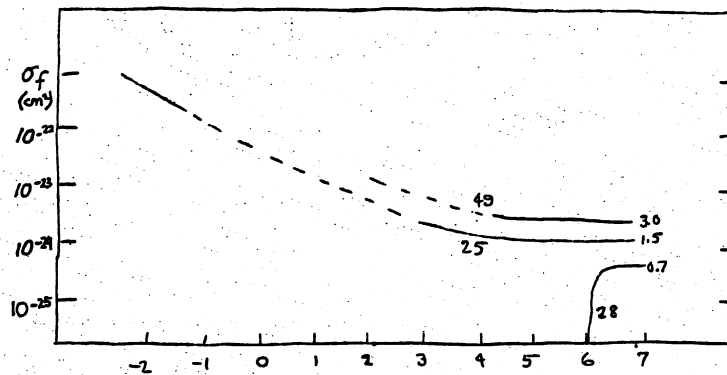
Neutron-Induced Fission Probability for Three Important Fissile and Non-fissile Nuclides

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

10p280 Nuclear Weapons, p. 59

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Physics of Nuclear Weapons – 1

Nuclear weapons require nuclides that can support an explosive (exponentially growing) chain reaction of fissions induced by “fast” neutrons, when they are present in 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

10p280 Nuclear Weapons, p. 60

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Physics of Nuclear Weapons – 2

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

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

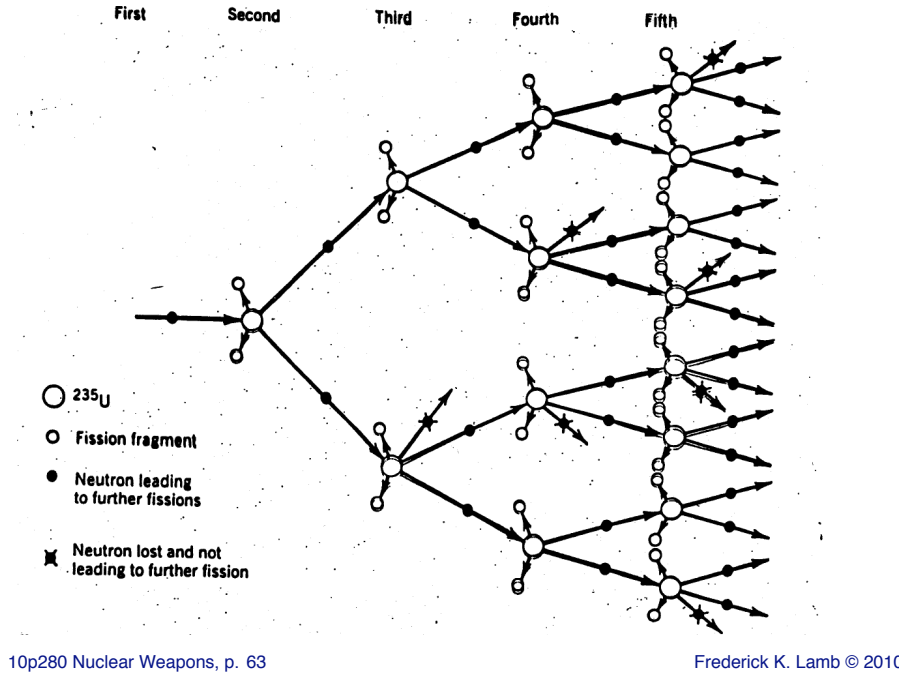
A nuclear explosion is achieved by the rapid assembly, in a suitable geometry, of NEM with sufficient nuclear reactivity to initiate and sustain a chain reaction driven by *fast* neutrons.

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



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

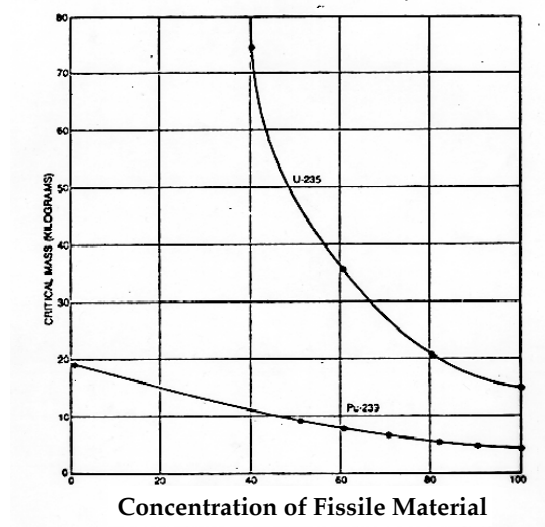
Properties of Nuclear Explosive Materials

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 no propensity to capture neutrons
- The lightest practical material is Beryllium, the lightest strong metal
- Heavy materials (e.g., U-238) sometimes used instead to reflect neutrons and “tamp” explosion

Mass Required for a Given Technology

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

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

10p280 Nuclear Weapons, p. 69

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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.

10p280 Nuclear Weapons, p. 70

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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

10p280 Nuclear Weapons, p. 71

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Physics 280: Session 6

Plan for This Session

Extra Credit Opportunity A Essays Due Feb 11

Student questions, news, and discussion

iClicker questions

Module 2: Nuclear weapons (cont'd)

Session 6: News and Discussion

On Heels of Failed Intercept Test, Missile Defense Leader Excoriates Contractors

Tuesday, Feb. 2, 2010

By Elaine M. Grossman
Global Security Newswire

WASHINGTON -- Just one day after the Missile Defense Agency failed to achieve an intercept in a major flight test of its Ground-based Midcourse Defense system, its executive director took broad aim at defense contractors for chronic quality-control lapses (see [GSN](#), Feb. 1).

In six of 16 GMD intercept flight tests since 1999, the missile has failed to hit its target. There have been eight such tests that ended with a successful intercept. In another two, target or missile-decoy failures made it impossible for the main test objectives to be met.

Prior to this weekend, the most recent intercept attempt occurred in December 2008. An intercept was achieved but decoys failed to deploy, according to officials.

Session 6: News and Discussion

The Pentagon is requesting \$8.4 billion for MDA programs for fiscal 2011, a \$525 million increase over 2010 appropriations. The funds include spending upticks for a wide variety of missile defense efforts, according to detail provided in an MDA budget request [overview](#).

The fiscal 2011 missile defense budget is part of an overall Defense Department request totaling \$708 billion, a 1.8 percent hike over the current year, after accounting for inflation.

For the Ground-Based Midcourse Defense effort, the Missile Defense Agency is requesting \$1.3 billion in the coming fiscal year.

Once complete, the GMD system would encompass 26 interceptors fielded at Fort Greely in Alaska and four missiles at Vandenberg. The agency is also expanding its missile fields in Alaska so that it could deploy up to eight additional interceptors there, if necessary, over the next decade, according to budget documents.

Faulty missile defense components have led to an enormous amount of "rework" that costs taxpayer money -- "the unfortunate aspect," said Altwegg, the agency's No. 3 official. The GMD program carries an estimated \$35.5 billion price tag, [according](#) to the Government Accountability Office.

Session 6: News and Discussion

A major congressionally mandated review of missile defense -- released yesterday along with the new budget figures -- suggests that increasingly realistic test scenarios are in the offing.

"Before new capabilities are deployed, they must undergo testing that enables assessment under realistic operational conditions," according to the Ballistic Missile Defense Review **report**.

North Korea Could Have Nuclear Missiles in 10 Years, U.S. Says

Tuesday, Feb. 2, 2010

North Korea could develop the capacity to attach nuclear warheads to ballistic missiles in the next 10 years, according to a U.S. Defense Department report released yesterday (see **GSN**, Feb. 1).

Session 6: News and Discussion

At a news conference yesterday in Washington, U.S. Defense Undersecretary Michele Flournoy said the United States was presently safeguarded from a ballistic missile strike from North Korea, the Yonhap News Agency reported.

Ballistic Missile Defense Review Report - February 2010

Defending the Homeland

The United States is currently protected against limited ICBM attacks. This is a result of investments made over the past decade in a system based on ground-based midcourse defense (GMD). Because of continuing improvements in the GMD system and the number of ground-based interceptors now deployed compared to potential North Korean and Iranian long-range ballistic missile capabilities, the United States possesses a capability to counter the projected threat from North Korea and Iran for the foreseeable future.

Physics 280: Session 6

iClicker Questions

When did the United States first test a nuclear weapon?

A. 1945 B. 1946 C. 1947 D. 1948 E. 1949

When did the Soviet Union first test a nuclear weapon?

B. 1945 B. 1946 C. 1947 D. 1948 E. 1949

When did President Truman start the U.S. H-bomb program?

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

Blank

Physics 280: Session 6

iClicker Answers

When did the United States first test a nuclear weapon?

A. **1945** B. 1946 C. 1947 D. 1948 E. 1949

When did the Soviet Union first test a nuclear weapon?

B. 1945 B. 1946 C. 1947 D. 1948 E. **1949**

When did President Truman start the U.S. H-bomb program?

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

Physics 280: Session 6

iClicker Question

1. 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

Blank

Physics 280: Session 6

iClicker Question

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**

Physics of Nuclear Weapons

Fission Weapons (“A-bombs”)

10p280 Nuclear Weapons, p. 83

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Review of Important Concepts

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

10p280 Nuclear Weapons, p. 84

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How to Make a Chemical Explosion – 1

Explosive —

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

Packaging —

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

Ignition —

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

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 fusion 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

10p280 Nuclear Weapons, p. 87

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Energy Released By a Single Fission (Details)



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

10p280 Nuclear Weapons, p. 88

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Energy Yields of Nuclear Weapons – 1

- The *yield* of a nuclear weapon is defined (roughly) as *the total energy it releases when it explodes*
- The energy release is quoted in units of the energy released by a ton of TNT
 - 1 kiloton (kt) = 1 thousand tons of TNT
 - 1 Megaton (Mt) = 1 million tons of TNT
- For this purpose the energy of 1 kt of TNT is defined as 10^{12} Calories = 4.2×10^{12} Joules

Energy Yields of Nuclear Weapons – 2

Fission weapons (“A-bombs”) —

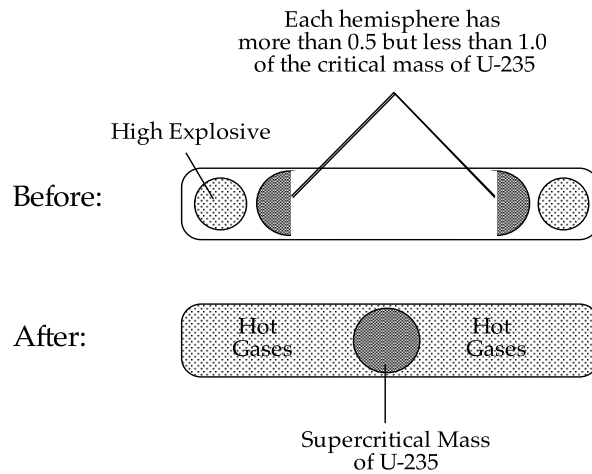
- Theoretical maximum yield-to-weight ratio:
8,000 tons = 8 kt TNT from 1 lb. of NEM
(~ 10,000,000 times as much per lb. as TNT)
- Difficult to make weapons larger than few 100 kt
(Yields of tested weapons: 1–500 kt)

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

Fission Weapons – Gun Type

Works Only With HEU
(relevant today only for terrorists or non-state groups)

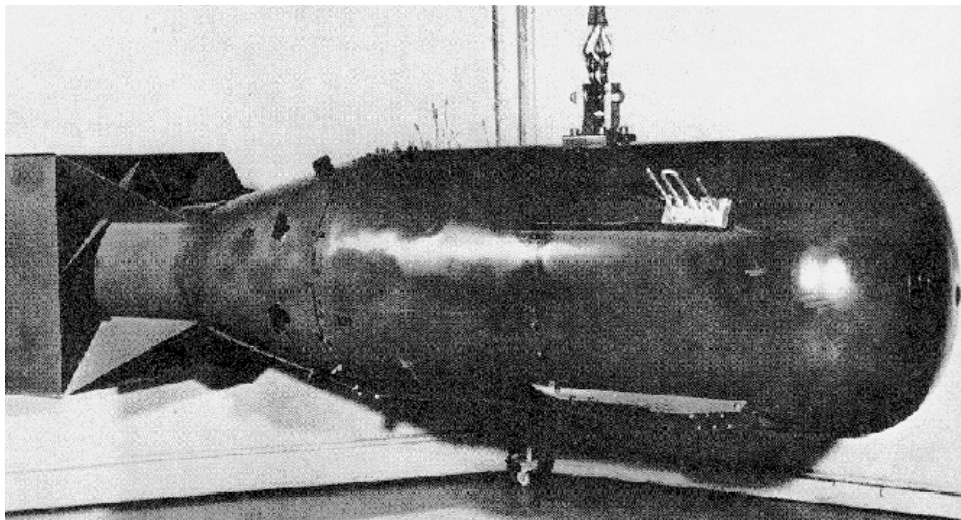


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Fission Weapons – Gun Type

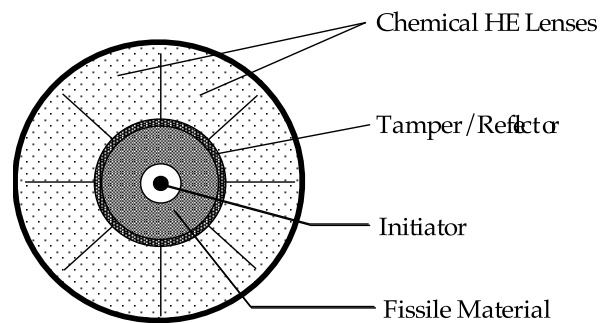
Little Boy



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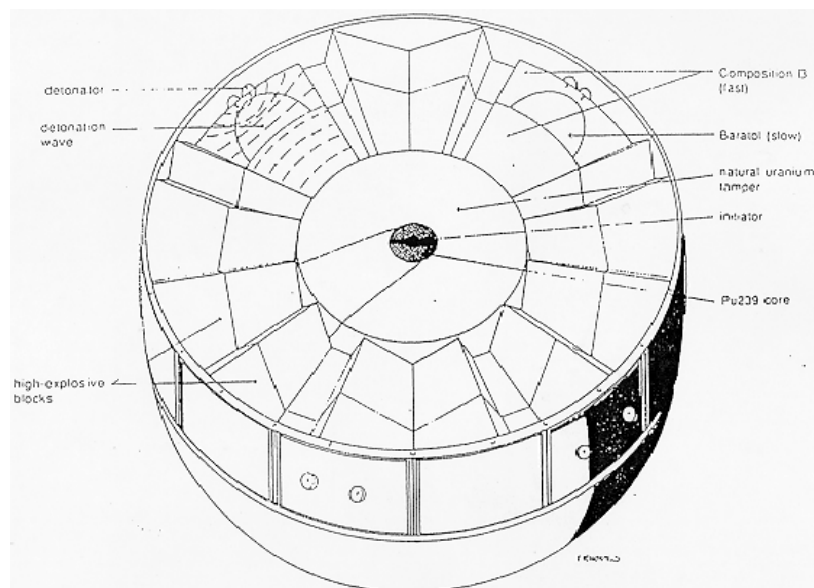
Fission Weapons – Implosion Type



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

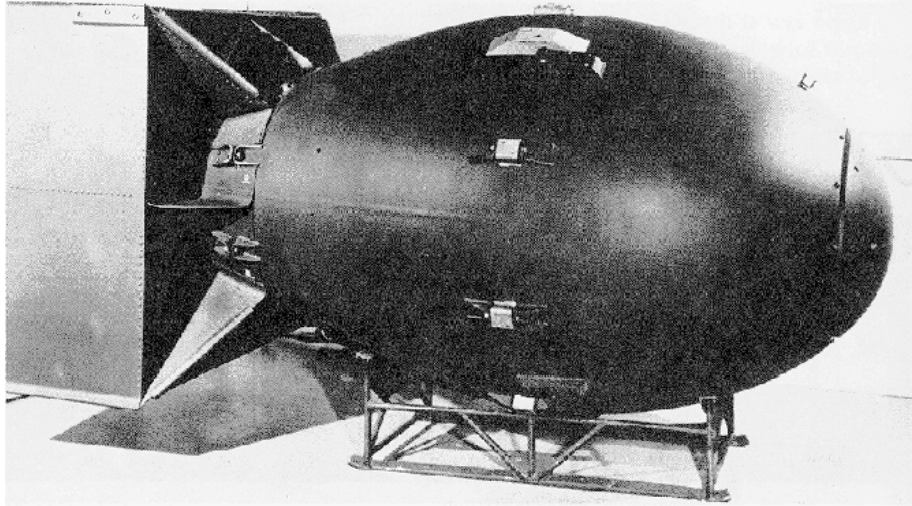
Fission Weapons – Implosion Type

View of the interior of an implosion weapon



Fission Weapons – Implosion Type

Fat Man



10p280 Nuclear Weapons, p. 95

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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*

10p280 Nuclear Weapons, p. 96

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Initiating a Fission Explosion – 2

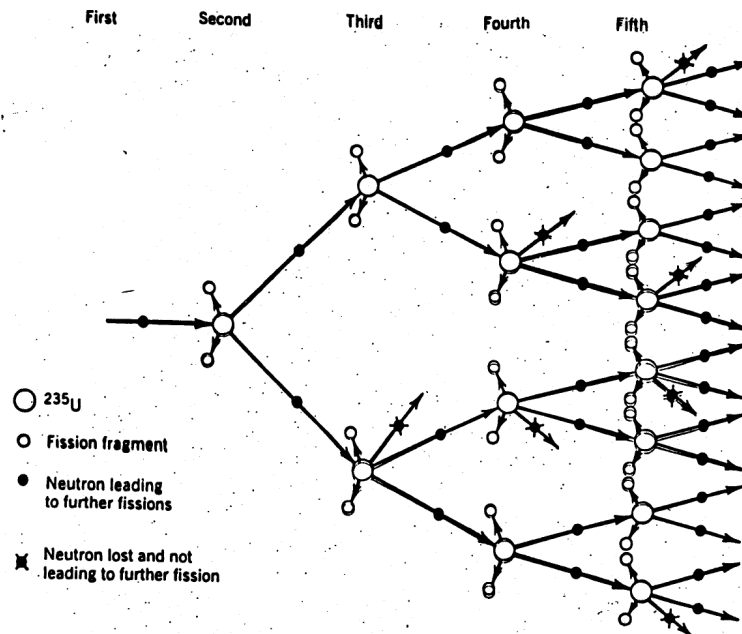
Timing is everything —

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

10p280 Nuclear Weapons, p. 97

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Explosive Chain Reaction



10p280 Nuclear Weapons, p. 98 [Mousetrap Demonstration] Frederick K. Lamb © 2010

Requirements for Making a Fission Bomb

1. Know the nuclear physics of fission
2. Have needed data on the physical and chemical properties of the necessary 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 financial resources and labor

Initiators – 1

Example of a simple initiator —

- Mixture of Polonium (Po) and Lithium (Li)
 - Polonium has several radioactive isotopes
 - Po-218 $\rightarrow$ Pb-214 + α
 - Po-216 $\rightarrow$ Pb-212 + α
 - Po-210 $\rightarrow$ Pb-206 + α
 - High probability nuclear reaction
 - $\alpha + \text{Li-7} \rightarrow \text{B-10} + \text{n}$
- 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)



- 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

10p280 Nuclear Weapons, p. 101

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Definitions of Fission and Nuclear Materials (Review)

- 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.

10p280 Nuclear Weapons, p. 102

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Physics of Nuclear Weapons

Thermonuclear Weapons (“H-Bombs”)

10p280 Nuclear Weapons, p. 103

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Fusion Nuclear Reactions (Basics)

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

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

Participants: deuteron (D), triton (T) neutron (n), and Li-6

10p280 Nuclear Weapons, p. 104

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Thermonuclear Weapon Designs

- Original configuration proposed by Edward Teller (the so-called “alarm clock” design) was later shown by theoretical analysis to be unworkable
- Andrei Sakharov proposed a workable thermonuclear design in the USSR, called the “layer-cake” (a “boosted fission” weapon, not a true thermonuclear weapon)
- Stanislaus Ulam came up with a new idea that was improved by Teller and is now called the “Ulam-Teller configuration”
- 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

Physics 280: Session 7

Plan for This Session

Extra Credit Opportunity A essays are due Thursday (Feb 11)

Student questions, news, and discussion

iClicker questions

Module 2: Nuclear weapons (cont'd)

Session 7: News and Discussion

The New York Times

February 10, 2010

Iran Is Said to Begin Nuclear Enrichment

By [ALAN COWELL](#) and [THOM SHANKER](#)

PARIS — Brushing aside international calls for stricter sanctions against it, [Iran](#) said Tuesday it had begun enriching uranium for use in a medical reactor to a higher level of purity, raising the stakes again in its dispute with the United States and other countries over its nuclear program.

The United States responded by saying it would seek [United Nations](#) backing for new sanctions within weeks.

10p280 Nuclear Weapons, p. 107

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Session 7: News and Discussion

Ali Akbar Salehi, the head of Iran's Atomic Energy Organization, said scientists at the Natanz nuclear facility south of Tehran began processing uranium to a purity level of 20 percent to provide fuel for a research reactor producing medical isotopes, the state-run [Press TV broadcaster](#) said.

Iranian state media, quoted by The Associated Press, said enrichment began on Tuesday after Iranian scientists injected 25 kilograms of 3.5 percent enriched uranium gas into a cascade of centrifuges in a laboratory at Natanz in the presence of inspectors from the [International Atomic Energy Agency](#), the nuclear oversight body of the United Nations.

10p280 Nuclear Weapons, p. 108

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Session 7: News and Discussion

But Mr. Salehi was also quoted as saying the enrichment did not preclude further negotiations with world powers on a proposal to swap Iran's uranium for imported fuel rods. Iran says it needs 120 kilograms of 20 percent enriched uranium to replace dwindling stocks at the Tehran reactor.

The level of purity Iran says it is seeking is significantly lower than the 90-percent levels needed for weapons. The Western concern is that enrichment to 20 percent would enable Iran to produce weapons-grade uranium in a comparatively short time, nuclear experts say. But it remains far from clear that Iran has the capacity to enrich fuel to that level.

10p280 Nuclear Weapons, p. 109

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iClicker Question

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

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

iClicker Answer

Which one of the following statements is true?

- A. A non-fissionable nuclide can sometimes be fissioned
- B. A fissile nuclide cannot be fissioned
- C. A fissile nuclide can be fissioned, but only by a neutron with sufficient kinetic energy
- D. **A fissile nuclide can be fissioned by a neutron of any energy**
- E. None of the above statements are true

iClicker Question

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

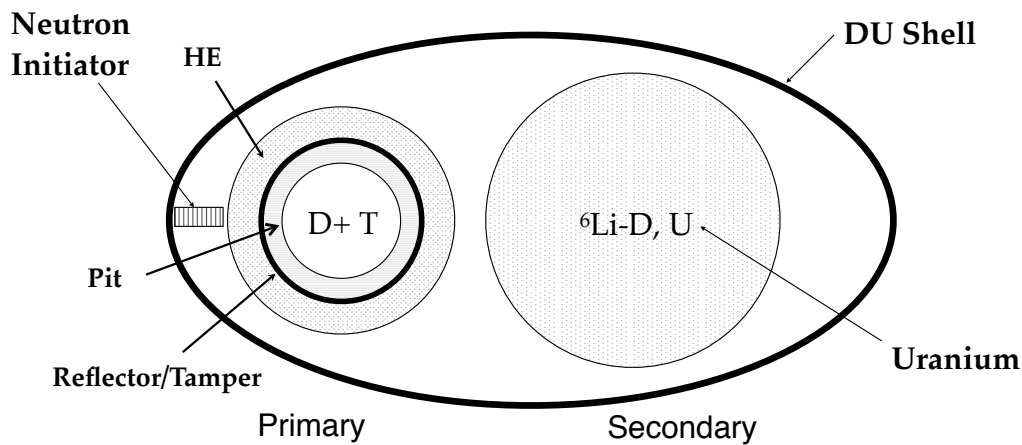
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iClicker Answer

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

Modern Nuclear Weapon (“P280 Design”)



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

Modern Thermonuclear Weapons – 1

- In a true thermonuclear explosion, the fusion packet (the ‘secondary’) is ignited by a fission bomb (the ‘primary’)
- The Mike device, the first U.S. fusion (thermonuclear) device, used liquefied D and T in the secondary
- The secondaries of deliverable bombs use ${}^6\text{Li-D}$ instead
- Burning grows quickly, but not exponentially (geometrically): fusion does not proceed by a chain reaction
- The largest thermonuclear weapons have three stages:
 - *fission* (the primary ‘burn’)
 - *fusion* (the secondary ‘burn’)
 - further *fissions* produced by neutrons from the fusion reactions

Modern Thermonuclear Weapons – 2

- Heating of the 'secondary' is initially done by X-rays from the 'primary'
 - Radiation pressure is not important
 - Ablation (blow off) of surface material is the dominant heating and compressive effect
- There is 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 (Sakharov rebelled)
 - The U.S. concluded that this particular design was capable of releasing 100 Mt

Modern Thermonuclear Weapons – 3

- Making a 50 Mt device makes no sense except (maybe) as propaganda, 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 (you will learn why later)
- All the nation-states that developed fission bombs developed true thermonuclear bombs soon afterward

Modern Thermonuclear Weapons – 4

Some of the neutrons produced by fusion in the secondary escape —

- The energy of these neutrons is well above the threshold for causing induced fission in U-238
- Vast quantities of depleted uranium (DU) are available from the U enrichment process

Enclose the entire weapon in a DU shell —

- The escaping neutrons will induce U-238 fissions in the shell (but no chain reactions)
- The result is considerable increase the net yield
- But the bomb becomes much “dirtier” (it will produce a much larger amount of radioactive debris)

Modern Thermonuclear Weapons – 5

Place HEU, DU, or natural U (or Pu) in the secondary —

- During the thermonuclear burn, vast numbers of energetic neutrons are present in the secondary
- These neutrons will fission the HEU, DU, or natural U (or Pu) placed in the secondary
- This will release additional energy, increasing the yield
- It will also make the bomb much “dirtier”

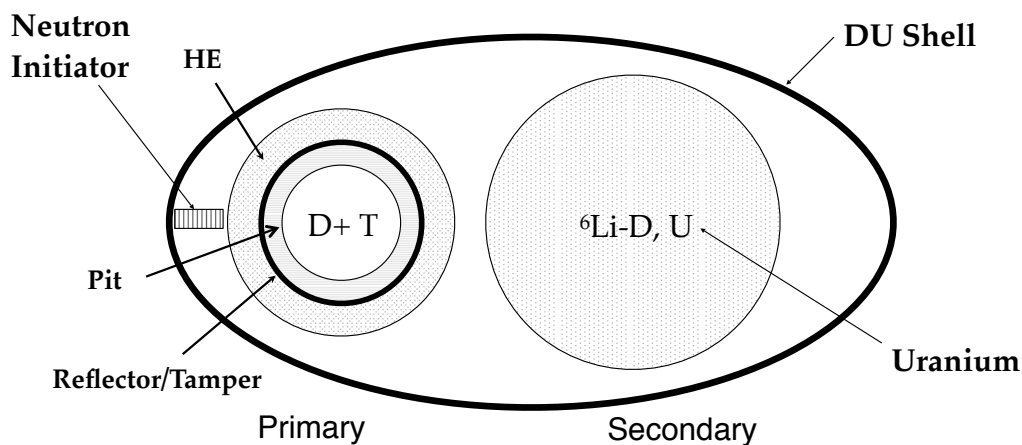
Modern Thermonuclear Weapons – 6

- 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

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Modern Nuclear Weapon (“P280 Design”)



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

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Components of a Modern 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”

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“Weaponizing” a Nuclear Device

Technologies needed to make a nuclear *weapon* —

- Technology to produce nuclear-explosive material (NEM)

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

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

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B-61 Bomb



10p280 Delivery Methods, p. 129

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

Physics and Engineering Requirements

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

- Small enough to fit inside the missile's diameter
- Light enough for the missile to be able to deliver it
- Able to survive the intense vibrations at lift-off
- Able to survive through maximum dynamic stress
- Able to survive accelerations and vibration during staging
- Able to survive 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 Mass Destruction

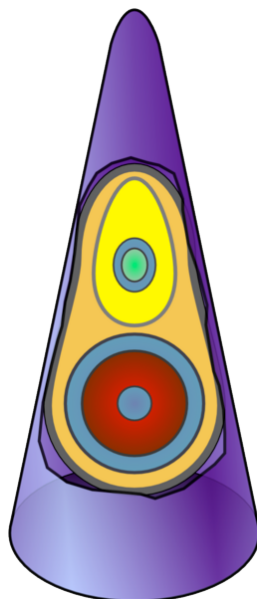
Initially, nuclear devices grew in size along with their destructive power. As technology advanced, designers focused on trimming the warhead's dimensions, allowing multiple warheads to be carried by a single missile.



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Making a Nuclear Warhead That Can Be Delivered By a Missile – 3



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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

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Nuclear Weapon Secrets

Nuclear weapon information is “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 280: Session 8

Plan for This Session

Student questions, news, and discussion

iClicker questions

Module 2: Nuclear weapons (finish)

Module 3: Effects of nuclear Explosions

Session 8: News and Discussion



Al-Qaeda Seen as Weakened But Still Dangerous

Tuesday, Feb. 9, 2010

The Christmas Day bombing attempt on a U.S. airliner illustrates that drone strikes and other stepped-up antiterrorism measures have not eliminated al-Qaeda's ability and intent to wage new attacks on the United States, the *Washington Post* reported yesterday (see **GSN**, Feb. 3).

Officials have said that U.S. assaults on al-Qaeda training sites, leaders and sources of funding have greatly impaired the terrorist group's ability to mount complicated, large-scale acts of terrorism. However, experts believe that the organization has altered its operations to instead emphasize less-sophisticated assaults that are more difficult to expose and to stop.

Session 8: News and Discussion

India Fires Ballistic Missile

Tuesday, Feb. 9, 2010

India on Sunday conducted its fourth test-launch of the nuclear-capable Agni 3 ballistic missile, paving the way for the weapon's entry into military service, Agence France-Presse reported (see [GSN](#), Dec. 14, 2009).

The solid-fuel missile is considered capable of delivering a 1.5-metric-ton warhead as far as 2,000 miles (Pratap Mohanty, Agence France-Presse/[Google News](#), Feb. 7). The weapon's initial test-firing in 2006 was unsuccessful, but all later exercises were completed as expected.

The Sunday launch is not expected to dramatically affect India's relations with its nuclear-armed rival Pakistan, according to the Associated Press. The neighboring states, which have fought in multiple wars, typically inform each other of planned missile tests (Muneeza Naqvi, Associated Press/[Yahoo!News](#), Feb. 7).

Session 8: News and Discussion

North Korean Leader Reaffirms Nuclear Promise

Tuesday, Feb. 9, 2010

North Korean leader Kim Jong Il is believed to have repeated to a visiting Chinese official yesterday an earlier pledge to rid the Korean Peninsula of nuclear weapons, Agence France-Presse reported (see [GSN](#), Feb. 5).

The Xinhua News Agency reported that Kim told Chinese Communist Party official Wang Jiarui of Pyongyang's "persistent stance to realize the denuclearization of the Korean Peninsula."

Wang traveled to Pyongyang as part of Chinese efforts to draw the aspiring nuclear power back to six-nation negotiations intended to persuade the North to follow through on its pledges of denuclearization. The talks involve China, Japan, the two Koreas, Russia and the United States and were last held in Beijing in December 2008.

iClicker Question

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

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

10p280 Nuclear Weapons, p. 143

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iClicker Answer

The symbol “U(238)” is sufficient to specify

- A. The chemical element to which this nucleus corresponds
- B. The number of neutrons in this nucleus
- C. The number of protons in this nucleus
- D. The number of neutrons and protons in its nucleus
- E. **All of the above**

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iClicker Question

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

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

Blank

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

Production of Nuclear-Explosive Material

Isotope Requirements for Uranium Nuclear Weapons

- 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.

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Enriching Uranium – Overview

There are 4 main
uranium enrichment processes

All depend in one way or another on the U-238/U-235
mass difference

- Gaseous diffusion
- Electromagnetic isotope separation
- Gas centrifuge (currently preferred)
- Molecular laser isotope separation
(not perfected on an industrial scale)

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Enriching Uranium – Details 1

- Gaseous diffusion
 - Developed in WW II Manhattan Project at Oak Ridge National Laboratory, TN
 - Uranium Hexafluoride (UF_6) gas diffusion through semi-permeable membranes under high pressures
 - thousands of stages required: typical stage enrichment factor ~ 1.004
- Electromagnetic isotope separation
 - calutrons (California cyclotrons)
 - Manhattan Project vintage
 - basically a high throughput mass spectrometer that sorts atoms by charge to mass ratios (q/m); 2-3 stages adequate

Enriching Uranium – Details 2

- Gas centrifuge
 - massive version of centrifuges used in medicine and biological research
 - feed stock is Uranium Hexafluoride (UF_6) gas
 - compact, easy to hide, and energy efficient; 40-90 stages
 - requires high strength materials (Al, Fe)
- Molecular laser isotope separation
 - High-tech, 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 killed the market for this technology before it ever took hold

Making Plutonium

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

- $\text{U}(238) + n \rightarrow \text{Pu}(239)$ (two step process)
- $\text{Th}(232) + n \rightarrow \text{U}(233)$ (two step process) ???
(non-fissile) (fissile)

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

- $\text{Pu-239} \rightarrow \text{Pu-240} \rightarrow \text{Pu-241} \rightarrow \text{Pu-242}$, etc.
- Pu-240 undergoes spontaneous fission
- Heavier Pu isotopes are highly radioactive

Making Plutonium for Nuclear Weapons – 1

Making a nuclear explosive 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 create 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.

Making Plutonium for Nuclear Weapons – 2

- 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 most common isotope, Pu-239, is produced when the most common isotope of uranium, U-238, absorbs a neutron and then quickly decays to plutonium. It is this plutonium isotope that is most useful in making nuclear weapons, and 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, higher 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.

Making Plutonium for Nuclear Weapons – 3

- Because of the preference for relatively pure Pu-239 for weapons purposes, when a reactor is used specifically for creating weapons plutonium, the fuel rods are removed and the plutonium is separated from them after relatively brief irradiation (at “low burn-up”). The resulting “weapons-grade” plutonium is typically about 93 percent Pu-239.
- Such brief irradiation is quite inefficient for power production, so in power reactors the fuel is left in the reactor much longer, resulting in a mix that includes more of the higher isotopes of plutonium (“reactor grade” plutonium).

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

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Designing Nuclear Weapons To Use 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 be of the order of one or a few 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. With a more sophisticated design, weapons could be built with reactor-grade plutonium that would be assured of having higher yields.

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Designing Nuclear Weapons To Use 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, and more using an advanced design.

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

Categories of Nuclear 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

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 was to be learned from testing
- Purposes of testing —
 - Proof of design (“proof testing”)
 - System optimization
 - Weapon effects tests

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

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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

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 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 experimental evidence will be forthcoming
 - For nuclear weapons purposes Electroweak and String Theory can be ignored

Key Forces Inside the Nucleus

The pattern (Z , N) for stable 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")

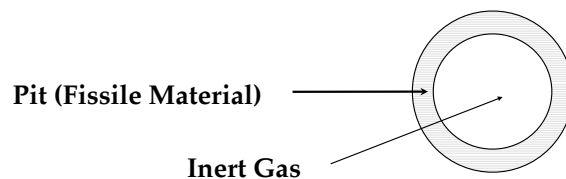
Importance of Delayed Neutrons for

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

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

Hollow “Pit” Implosion Design – Step 1

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

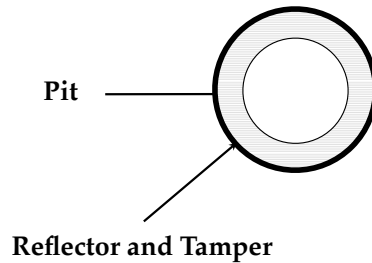


Advantage:

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

Hollow “Pit” Implosion Design – Step 2

Add a reflector and tamper —

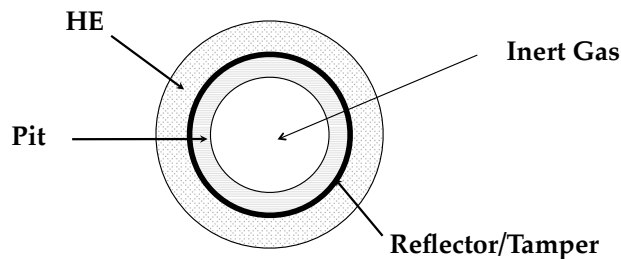


Advantages:

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

Hollow “Pit” Implosion Design – Step 3

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



Advantages:

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

True Thermonuclear Weapons

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

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Review of Modern Thermonuclear Weapons – 1

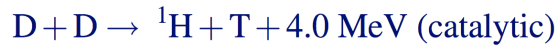
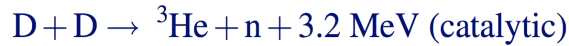
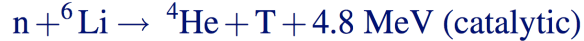
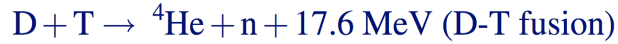
- There is fission and a small amount of fusion in a (boosted) primary
- There is lots of fusion and fission in the secondary (which is understood to include the DU shell)
- The yield Y_p of the primary may be 10 kiloton (kt)
- The yield Y_s of the secondary can range from a few 100 kt to a few Mt
- Overall, approximately
 - 50% of the energy released comes from fission
 - 50% of the energy released comes from fusion

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Fusion Nuclear Reactions (Details)

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

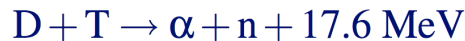


- At standard temperatures and pressures (STP), D and T are gasses whereas Li-D is a solid (it's a salt)
- To make the fusion reactions go, need extremely high temperatures, densities, and pressures
- D-T fusion has lowest energy threshold
- Once D-T fusion (burning) has started, D-D fusion also contributes,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

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)



- 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 —

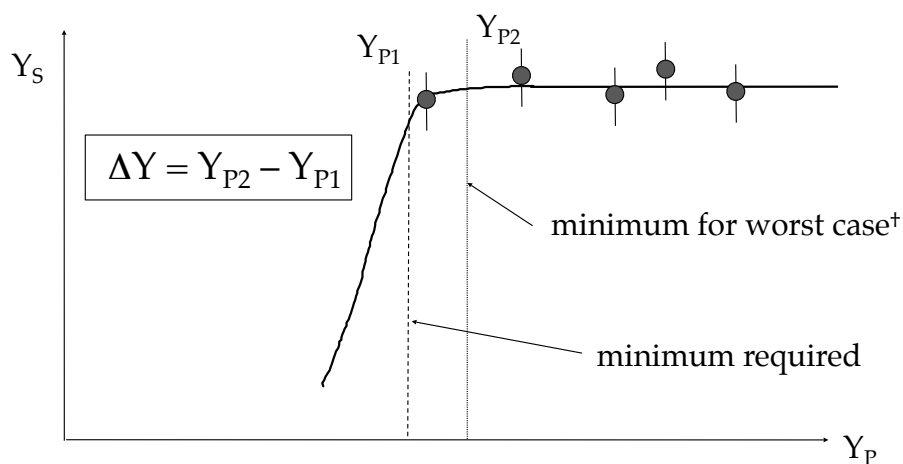
- Increases the maximum possible fission yield
- Less hard-to-produce Pu or HEU is required for a given yield — the “efficiency” is higher
- Warheads of a given yield can be smaller and lighter

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.

Primary Margin ΔY



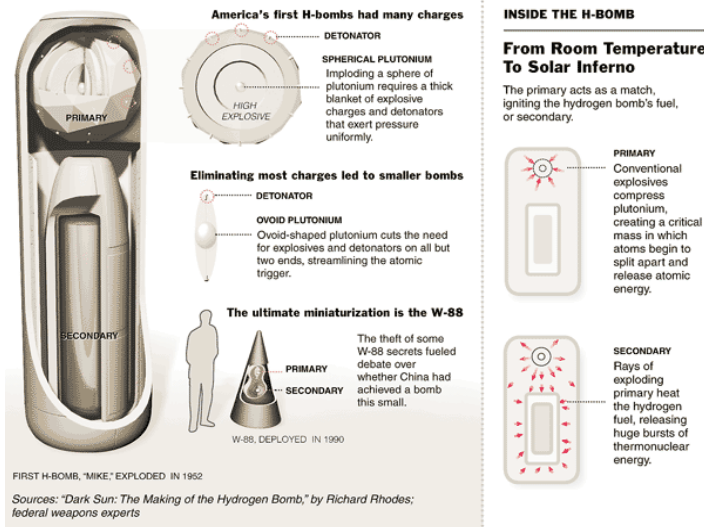
[†]Worst case: T supply at end of life, over-initiated, cold HE

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.



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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*

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Designing Nuclear Weapons To Use

2. 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

3. 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 ${}^6\text{LiD}$ 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

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End

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