

# Physics/Global Studies 280: Session 4

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## Plan for This Session

Turn in paper copy of RE1

Announcements

Questions

News

**Module 2: Nuclear Weapons**

# Physics/Global Studies 280: Session 4

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## Announcements

- (1) Please report possible problems with electronic submission!
- (2) Reading assignment for today (could be subject to a pop quiz in Monday's writing lab!).
  - The Last Train from Hiroshima
  - <https://courses.physics.illinois.edu/phys280/sp2020/reading.html>
- (3) Please read the essay prompts prior to the writing labs. Make sure to ask your TA in case you have questions concerning a prompt. Next prompt RE2v1!

# *Russia Shows Off New Cruise Missile and Says It Abides by Landmark Treaty*

## *Russia Shows Off New Cruise Missile and Says It Abides by Landmark Treaty*

By Neil MacFarquhar

Jan. 23, 2019

**The New York Times**



MOSCOW — Senior Russian officials on Wednesday put their new cruise missile on display for a foreign audience for the first time, in an attempt to rebut American accusations that the weapon violates a key nuclear arms accord.

Using the slightly odd backdrop of a military theme park outside Moscow, military officers and Russia's senior arms control diplomat insisted that the land-based cruise missile, the Novator 9M729, conforms to the limited range allowed under the 1987 Intermediate-Range Nuclear Forces Treaty, or I.N.F.

The display for foreign military attachés and the press was meant to underscore Russia's "increased transparency and our adherence to the I.N.F. treaty," said Lt. Gen. Mikhail Matveyevskiy, the chief of missiles and artillery for the Russian armed forces.

The United States, under both President Barack Obama and President Trump, has said that the Russian weapon violates the ban on producing, testing or deploying any land-based cruise or ballistic missile with a range of 500 to 5,500 kilometers, or 310 to more than 3,400 miles.

The Trump administration has announced its intention to leave the treaty, giving Russia a Feb. 2 deadline to come into compliance with the pact before the United States starts suspending its own compliance.

The two sides met in Geneva last week to address their differences, with Russia offering the Americans a chance to inspect the missile, which is called the SSC-8 by NATO.

## News:

### Deployment of new US nuclear warhead on submarine a dangerous step, critics say

First submarine to go on patrol armed with the W76-2 warhead makes a nuclear launch more likely, arms control advocates warn.

*Washington*

Wed 29 Jan 2020 12.53 EST

The US has deployed its first low-yield Trident nuclear warhead on a submarine that is currently patrolling the Atlantic Ocean, it has been reported, in what arms control advocates warn is a dangerous step towards making a nuclear launch more likely. According to the Federation of American Scientists, the USS Tennessee – which left port in Georgia at the end of last year – is the first submarine to go on patrol armed with the W76-2 warhead, commissioned by Donald Trump two years ago. It has an explosive yield of five kilotons, a third of the power of the “Little Boy” bomb dropped on Hiroshima and considerably lower than the 90- and 455-kiloton warheads on other US submarine-launched ballistic missiles. The Trump administration’s nuclear posture review (NPR) in February 2018, portrays this warhead as a counter to a perceived Russian threat to use its own “tactical” nuclear weapons to win a quick victory on the battlefield. Advocates of W76-2 argued that the US had no effective deterrent against Russian tactical weapons because Moscow assumed Washington would not risk using the overwhelming power of its intercontinental ballistic missiles in response, for fear of escalating from a regional conflict to a civilian-destroying war. Critics of the warhead say it accelerates a drift towards thinking of nuclear weapons as a means to fight and win wars, rather than as purely a deterrent of last resort. And the fielding of a tactical nuclear weapon, they warn, gives US political and military leaders a dangerous new option in confronting adversaries other than Russia.

### Deployment of new US nuclear warhead on submarine a dangerous step, critics say

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First submarine to go on patrol armed with the W76-2 warhead makes a nuclear launch more likely, arms control advocates warn.

Trump's NPR says the US could use nuclear weapons in response to "significant nonnuclear strategic attacks", including but not limited to "attacks on US, allied or partner civilian population or infrastructure". The US Navy and Strategic Command did not immediately respond to a request for comment. Hans Kristensen, the director of the nuclear information project at FAS, said the report on the arming of the USS Tennessee is based on briefings from officials. "We have had conversations with people inside, and they've been pretty clear that this has happened," Kristensen said. "They see a need to talk about it to some extent, because if people don't know it's out there, then how can it deter?" "This is a very rapid mind quick turnaround for a nuclear weapon, and that's obviously because it was a fairly simple adjustment of an existing warhead," he added. "They have argued that this is to deter Russia, but it also has clear implications or potential use against other adversaries, not least North Korea and Iran." Kristensen said: "Certainly the low-yield collateral effect that would come from this weapon would be very beneficial to a military officer who was going to advise to the president whether we should cross the nuclear threshold."

# Physics/Global Studies 280

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## Module 2: Nuclear Weapons

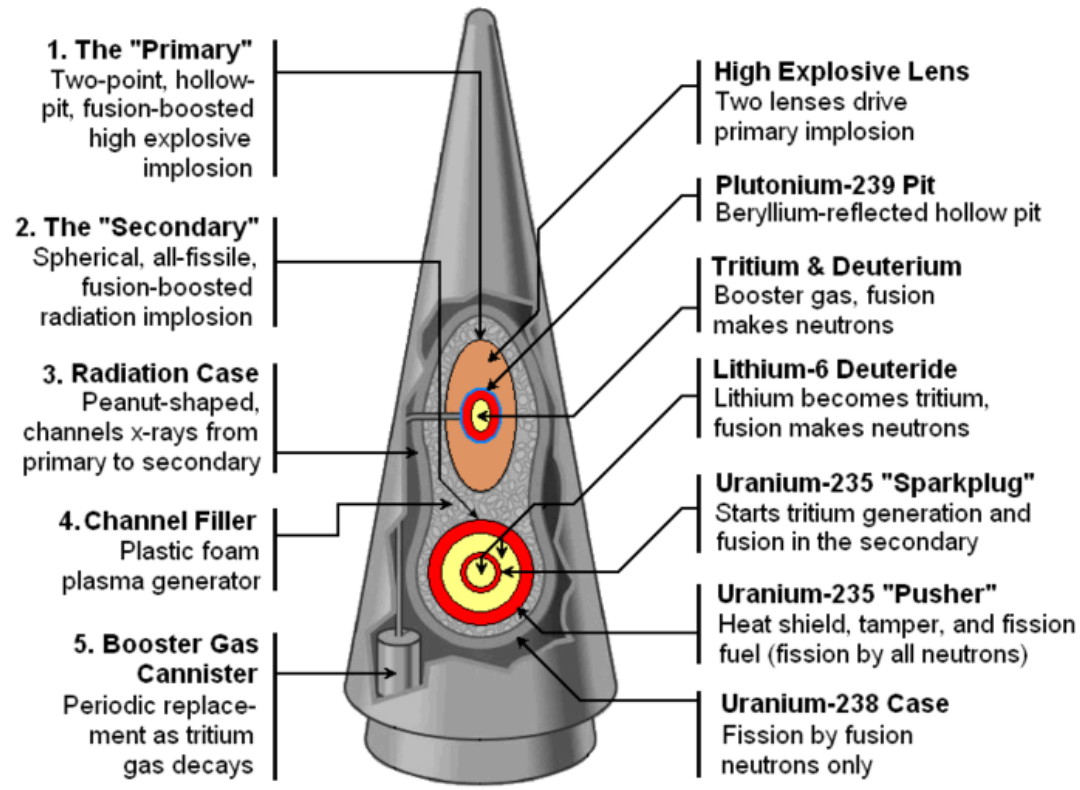


# Physics of Nuclear Weapons

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



## *W88 Warhead for Trident D-5 Ballistic Missile*



# Physics of Nuclear Weapons

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A basic understanding of the nuclear physics and design of nuclear weapons is helpful in developing informed opinions about —

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



# Physics of Nuclear Weapons

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Topics covered in this module —

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

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

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

# Physics of Nuclear Weapons

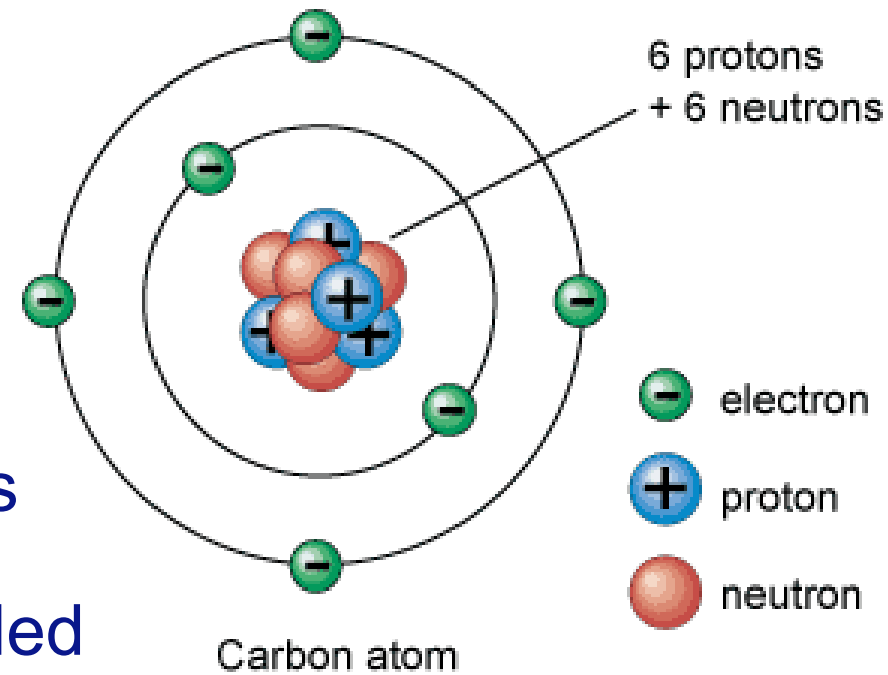
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## Atoms and Nuclei

# Atomic Nature of Matter

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



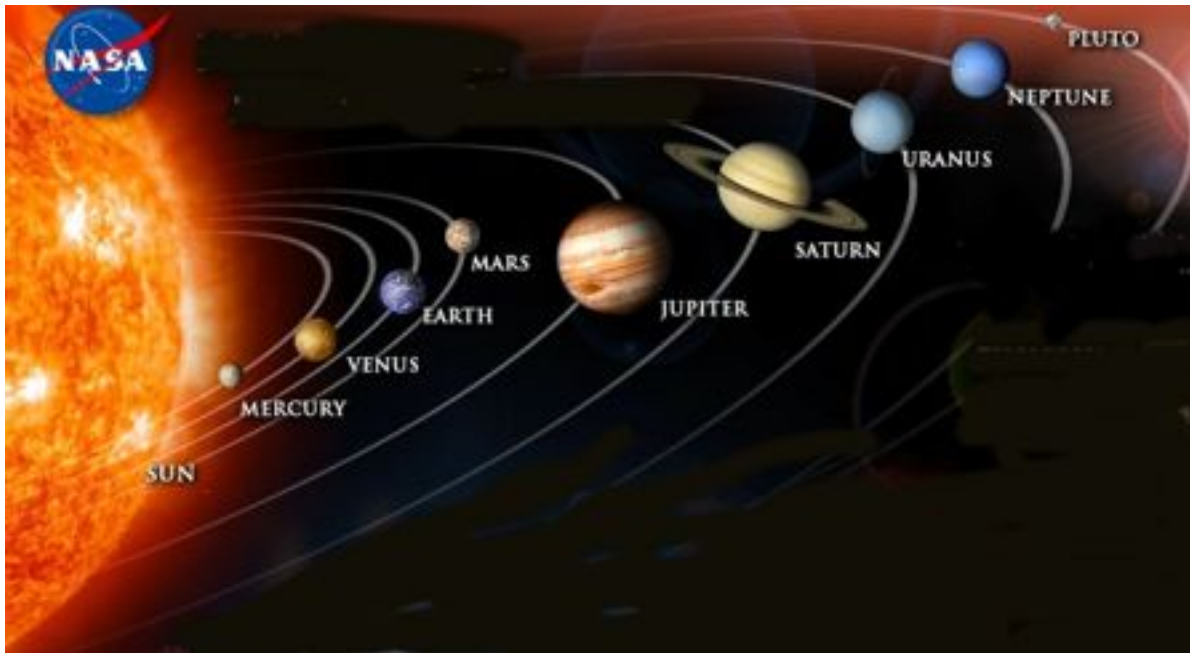
# Fundamental Forces of Nature – 1

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

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

- Always attractive, weakest but first to be discovered
- Strength decreases as  $1/r^2$  (“long-range”,  $r \rightarrow$  distance between objects)



Gravity:  
Relative Strength

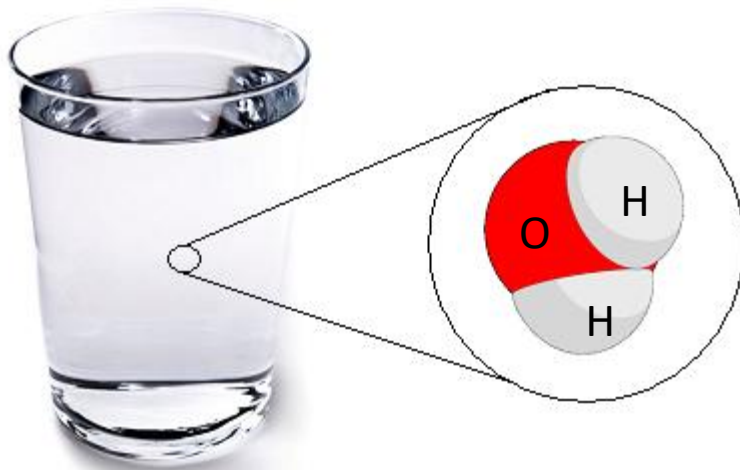
$10^{-41}$

# Fundamental Forces of Nature – 2

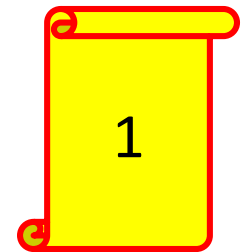
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## 2. Electromagnetic force (structure of atoms and molecules)

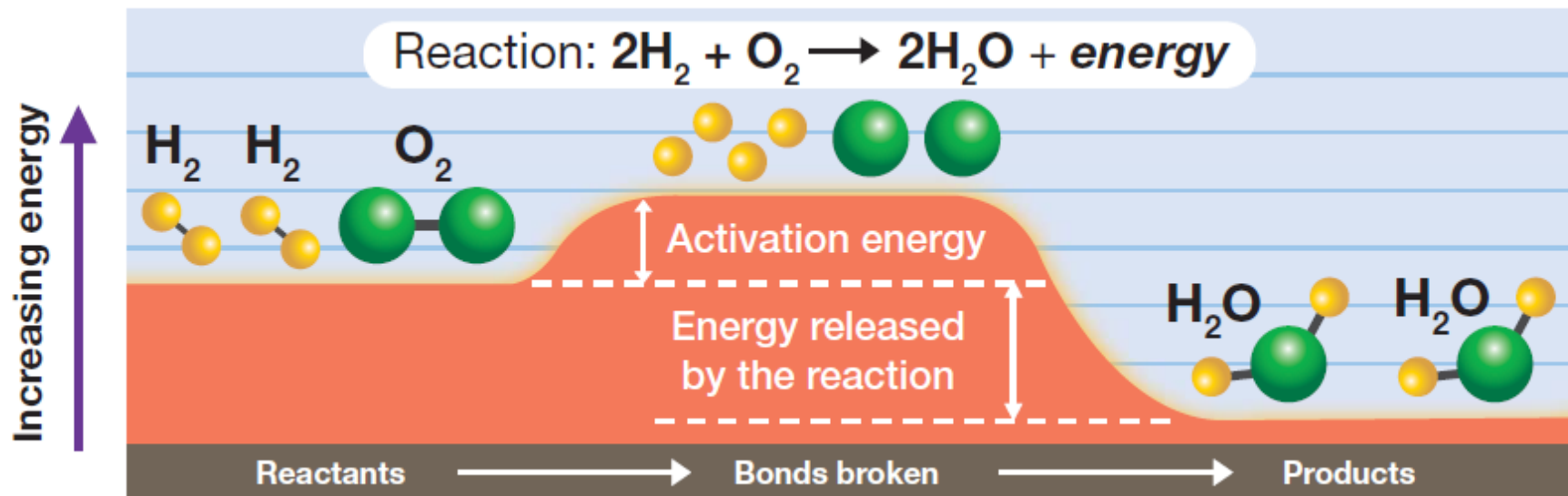
- Can be attractive or repulsive
- Classical electrical force decreases as  $1/r^2$  (“long-range”)
- Described by the theory of electromagnetism, developed in the late 19th Century
- The quantum theory of electromagnetism is called Quantum Electrodynamics



Electromagnetic Force  
Relative Strength



# Energy Released by Electromagnetic Reactions between Atoms and Molecules



We use electromagnetic energy from chemical bounds frequently:

wood fire

car engine

coal electrical power plant

explosives

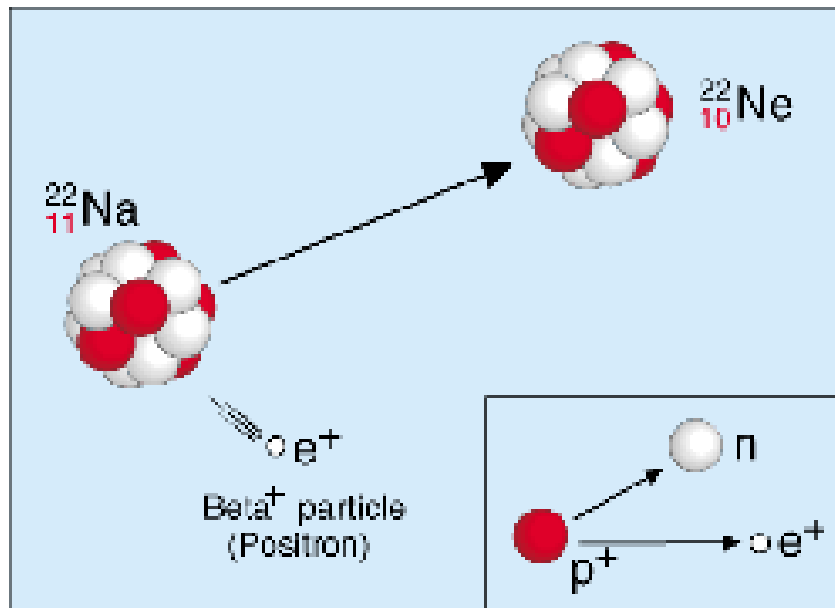


# Fundamental Forces of Nature – 3

## 3. Weak nuclear force (radioactivity)

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

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



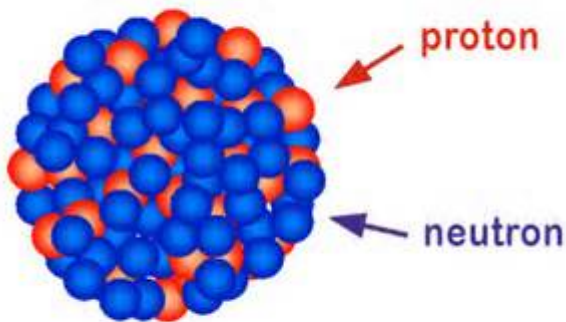
Weak Nuclear Force:  
Relative Strength

$10^{-7}$

# Fundamental Forces of Nature – 4

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

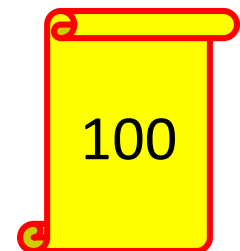
- The strongest known force, it holds protons and neutrons together in the atomic nucleus
- Short-range (reaches approximately the diameter of a proton, vanishes at larger distance)
- Has no classical approximation, a quantum description is required
- The quantum theory of the strong force is called Quantum Chromodynamics
- Nuclear binding energies are about 1,000,000 times larger compared to atomic binding energies



Uranium Nucleus

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

Strong Nuclear Force  
Relative Strength



# Annual US Electricity Consumption:

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

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

→ energy taken from electromagnetic force fields in chemical bounds

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

→ energy taken from nuclear force fields inside nuclei

“Nuclear fire” burns ~ 1 million times hotter than “chemical fire”

# Fundamental Forces of Nature – Summary

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Luke, the Force is Strong with you ...



... yeah, all four!

...

Gravitation keeps me on the ground

...

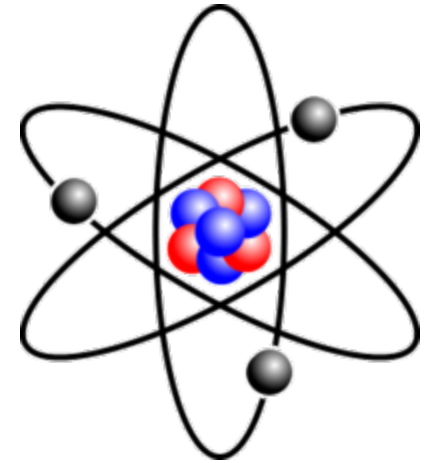
Electromagnetism holds my  
Molecules and atoms together.

...

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

# Atoms and Nuclei

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## Sizes of atoms and nuclei

- The size of an *atom* is defined by the extent of its electron cloud :  $\sim 10^{-10}$  m
- The size of a *nucleus* is defined by the size of a nucleon  $\sim 10^{-15}$  m and the number of nucleons it contains.

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

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

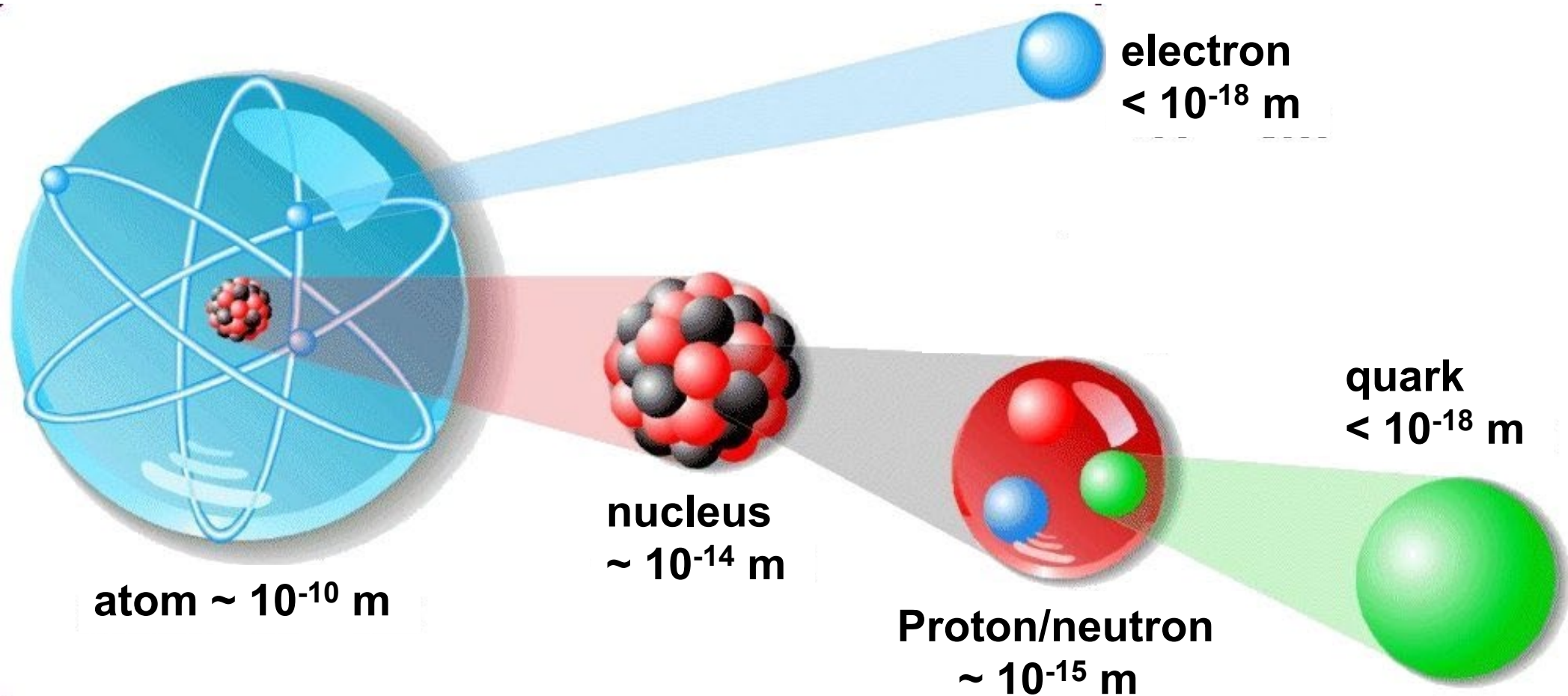
1.0 nm = 1 billionth of a meter

## Masses of Protons and Neutrons compared to Electrons

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



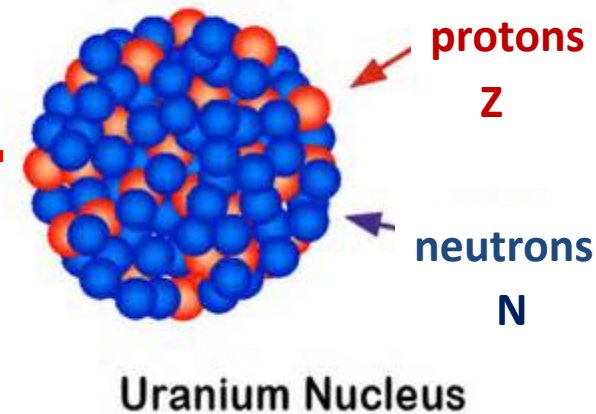
# Atomic Structure and Length Scales





# Atomic Nuclei

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

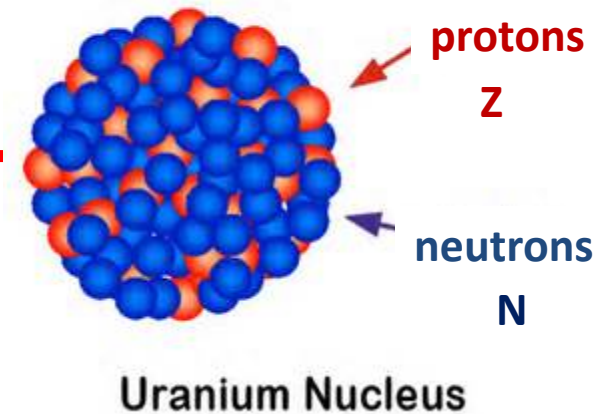
# Chemical Properties of Atoms

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- The **chemical properties of an atom** (i.e., to what other atoms it can bind to form molecules and compounds, with what strengths, and in what geometries) **are determined by the number of electrons** in its electron cloud.
- The electron cloud of a ***neutral atom*** has  **$Z$  electrons**: the positive charge of the  $Z$  protons in its nucleus is *exactly* offset by the negative charge of  $Z$  electrons in its electron cloud.
- The **mass of an atom is determined by the total number  $A = N + Z$  of the nucleons in its nucleus**, because the mass of a proton is almost equal to the mass of a neutron and both are about 2,000 times more than the mass of an electron. Recall  $A$  is called the “atomic weight” of the atom.

# Atoms with Different Nuclei: Isotopes and Isotones

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Several notations are in common use for nuclides –

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

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

**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

# Facts About Naturally Occurring Chemical Elements

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

# Physics/Global Studies 280: Session 5

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## Plan for This Session

Announcements

Questions

Module 2: Nuclear weapons cont'd

# Physics/Global Studies 280: Session 5

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## Announcements

RE2v1 will be due tomorrow, Wednesday, 2-5

- o electronic submission (**10pm**)

- o prompt is posted on course web-page

  - <https://courses.physics.illinois.edu/phys280/sp2020/re2.html>

- o follow all instructions stated in the prompt

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



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**Reuters**

Feb. 3, 2020

WASHINGTON/PARIS — The Trump administration on Thursday said it will allow Russian, Chinese and European companies to continue their work at Iranian nuclear sites, arguing that their presence makes it harder for Tehran to develop nuclear weapons.

But the United States also imposed sanctions on Iran's Atomic Energy Organization (AEOI) and its chief, a move the Iranian entity's spokesman described as a sign of Washington's "despair."

The Trump administration, which in 2018 pulled out of the 2015 Iran nuclear deal and reimposed sanctions on Iran, will let the work go forward by issuing waivers to sanctions that bar non-U.S. firms from dealing with the AEOI. The waivers' renewal for 60 days will allow nonproliferation work to continue at the Arak heavy-water research reactor, the Bushehr nuclear power plant, the Tehran Research Reactor and other nuclear cooperation initiatives. Tehran has rejected Western assertions that it has sought to develop nuclear weapons, and on Thursday AEOI spokesman Behrouz Kamalvandi reaffirmed that Iran's civilian nuclear program will continue "full force."

"Imposing sanctions ... is a political game played by Washington. These sanctions have no value and are childish measures," Kamalvandi told Iran's Fars news agency. **Leading Republican senators and other Iran hawks had lobbied intensively to stop the latest waivers as U.S. President Donald Trump seeks to exert more pressure on Iran after the two longtime foes came toward the brink of war earlier this month.**

# News *U.S. Renews Waivers on Iran Nuclear Work, but Sanctions Top Iran Nuclear Official*

The New York Times

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"We will closely monitor all developments in Iran's nuclear program and Secretary (Mike) Pompeo can end these projects as developments warrant," Brian Hook, U.S. special representative for Iran, told a news briefing. Republican Senator Marco Rubio expressed discontent with the waiver renewal.

"While I am glad to see new sanctions imposed against Iran's Atomic Energy Organization and its chief, the administration should terminate the controversial sanctions waivers on Iran's civil nuclear program and exert maximum pressure on the regime in Tehran," Rubio said in a statement. The waivers are a rare breather in a hardened U.S. policy toward Iran. The latest development follows weeks of extreme tension after Washington killed top Iranian general Qassem Soleimani and Iran retaliated with a missile strike on bases in Iraq housing U.S. troops.

Under the 2015 deal between Iran and six world powers - Britain, China, France, Germany, Russia and the United States - Tehran agreed to limit its nuclear program in return for the lifting of economic sanctions that had crippled its economy. Trump unilaterally abandoned the deal in May 2018, and reimposed U.S. sanctions in a "maximum pressure" campaign designed to force Iran to return to the negotiating table. Washington in November terminated the sanctions waiver related to Iran's Fordow nuclear plant after Tehran resumed uranium enrichment at the underground site. "There was a difference of opinion between the U.S. Treasury and State Department. The Treasury won," a Western diplomat said. "There is an appetite for more sanctions, so this was a surprise; but others argue that these waivers are vital to ensure nonproliferation."

**MORE SANCTIONS**

The United States on Thursday placed Ali Akbar Salehi, head of the AEOI, and the organization itself under U.S. sanctions, Hook said. The decision to sanction Salehi and the AEOI would have an impact on Iran's civilian nuclear program because it has operational control over the program, including purchasing parts for nuclear facilities. Last week three Republican senators known to be close to Trump - Tom Cotton of Arkansas, Ted Cruz of Texas and Lindsey Graham of South Carolina - had called for the remaining civil nuclear waivers to be rescinded. "Enough is enough," the senators and Republican U.S. congresswoman Liz Cheney said in a joint statement. The diplomat said the United States had likely opted to extend the Bushehr waiver because the Russian company targeted also provides nuclear fuel to U.S. facilities, causing a potential sanctions headache for the administration.

Feb. 4, 2020, 6:46 AM CST

By Associated Press

TEHRAN, Iran — Iran said Tuesday that its top court confirmed a death sentence for an Iranian man convicted of spying for the CIA, with state media alleging that he had shared details of the Islamic Republic's nuclear program with the American spy agency.

Judiciary spokesman Gholamhossein Esmaili identified the purported spy as Amir Rahimpour and said he would be executed soon. Esmaili did not elaborate on what Rahimpour was accused of doing, nor on his age or background. Officials also offered no evidence linking him to the CIA.

State media did not immediately name Rahimpour's lawyer. [A report by the state-run IRNA news agency alleged that Rahimpour received money from the CIA to share details of Iran's nuclear program.](#)

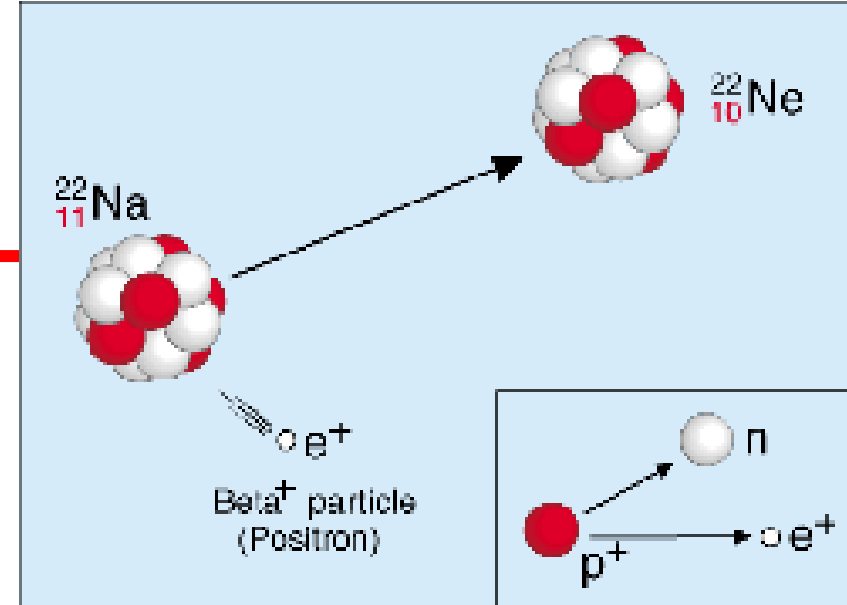
[“While being in touch with the spy agency, he earned a lot of money as wages as he tried to deliver some information from Iran's nuclear program to the American agency,” the IRNA report said. Rahimpour “had been identified and prosecuted and sentenced to death and recently, the country's National Supreme Court confirmed the sentence and, God willing, he will be punished soon.”](#)

The CIA had no comment on the news.

[Esmaili said two other alleged spies for the CIA each received 15-year prison sentences — 10 years for spying and five years for acting against national security charges.](#)

# Radioactivity

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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

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## 1. *Alpha decay*

Parent  $\longrightarrow$  Daughter + alpha particle ( ${}^4\text{He}$ )

## 2. *Beta decay*

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

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

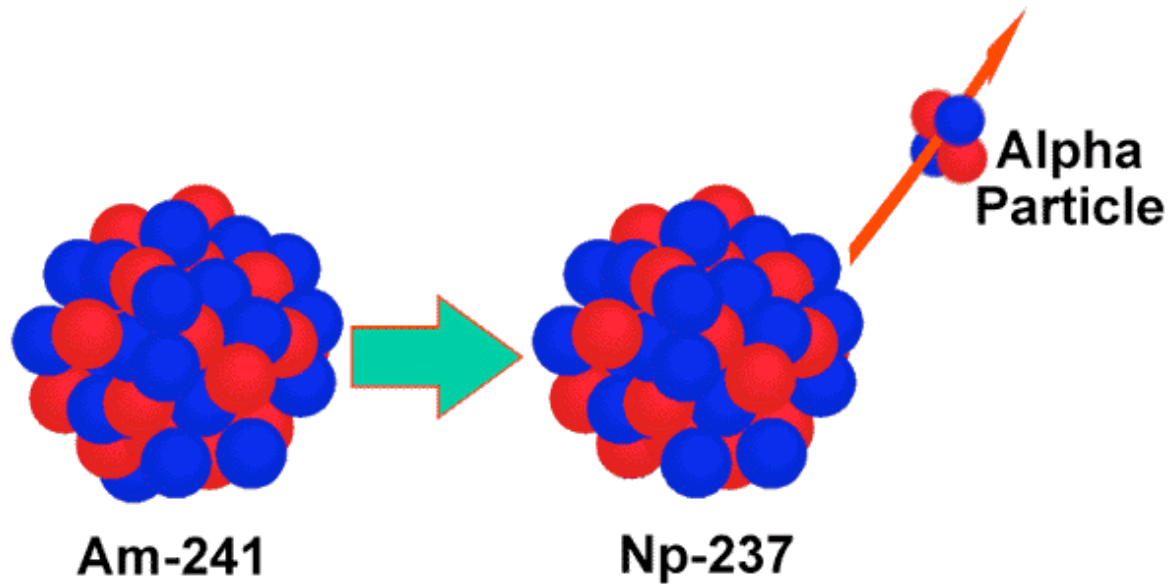
## 3. *Gamma decay*

Parent  $\longrightarrow$  Daughter + gamma-ray

## 4. *Spontaneous fission*

# Illustration of Alpha Decay

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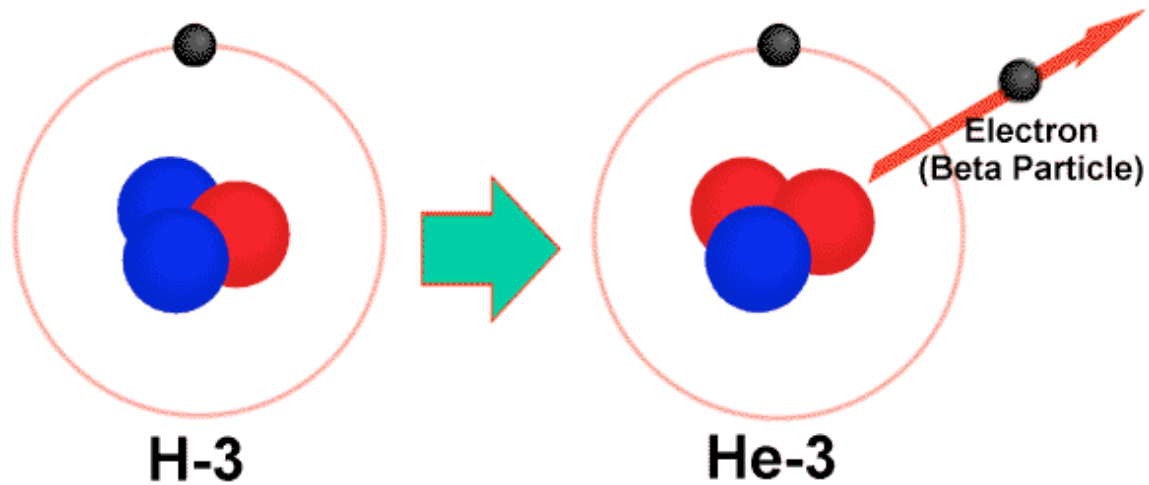


Americium as 95 protons and 136 neutrons

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

# Illustration of Negative Beta Decay (Electron Emission)

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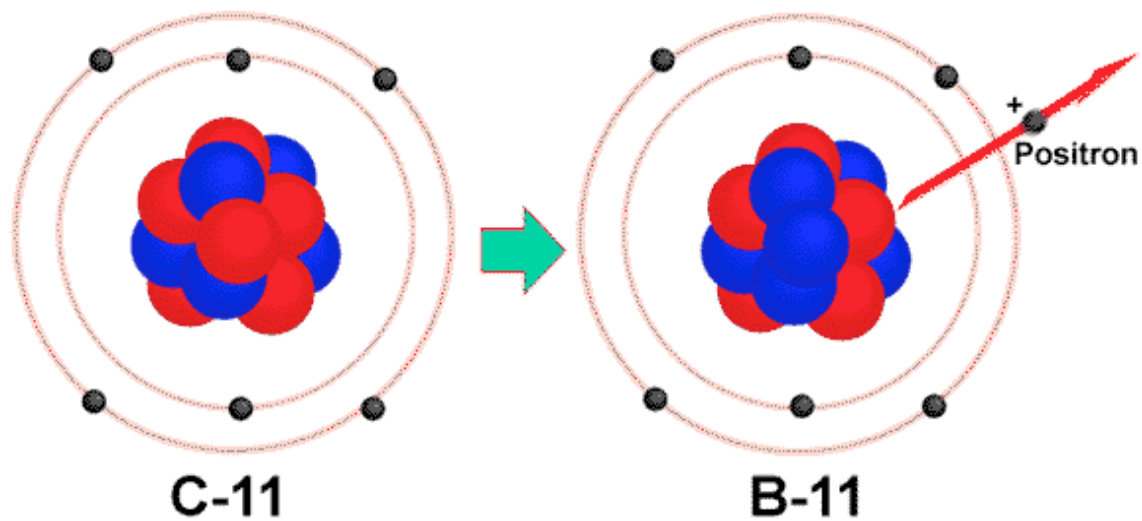


Tritium is a hydrogen isotope and decays into He-3, a helium isotope  
Negative Beta Decay increases  $Z$  !



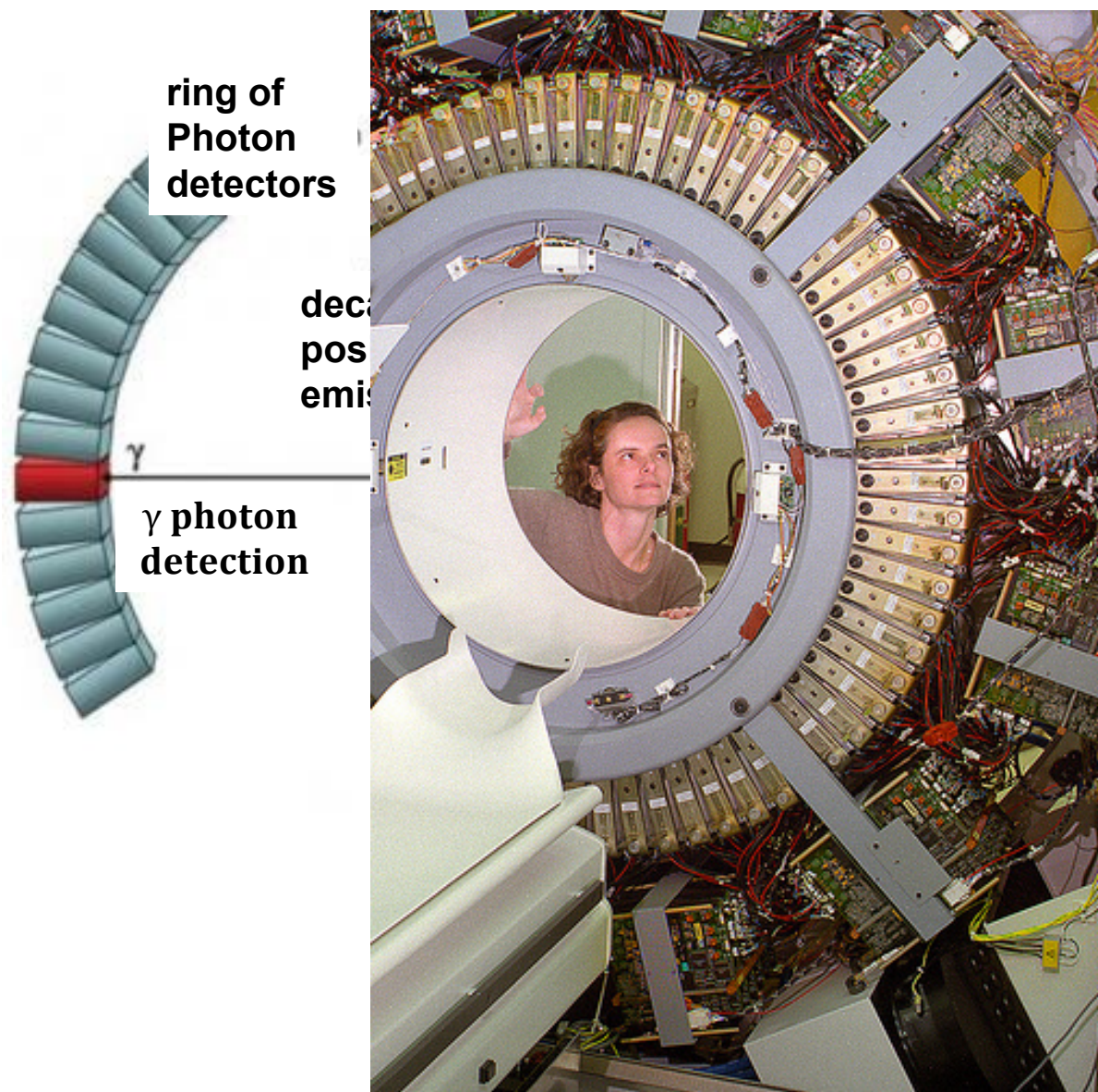
# Illustration of Positive Beta Decay (Positron Emission)

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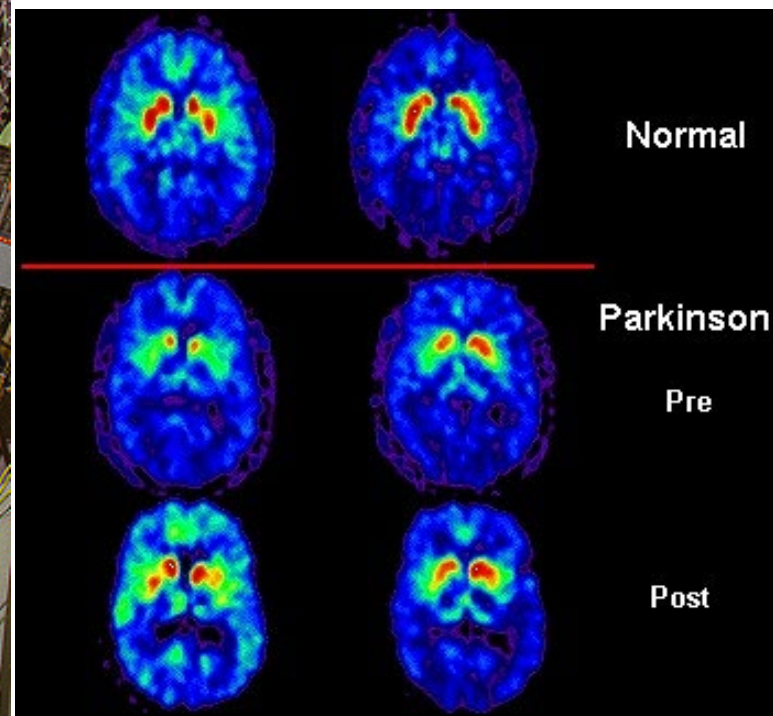


The positron from a positive beta decay is the anti-particle to the electron!  
Positive Beta Decay decreases  $Z$  !

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

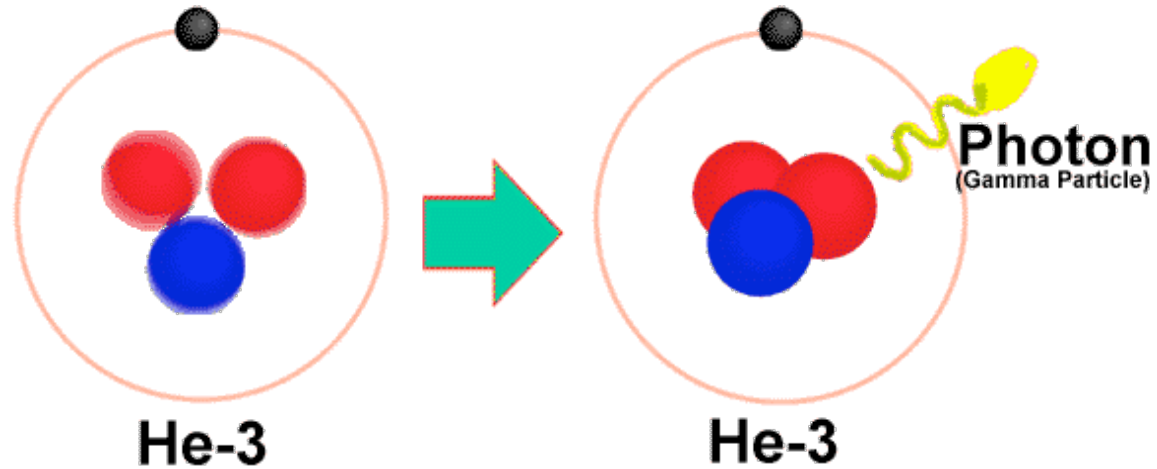


Positron emitting radioactive isotopes and gamma rays from Electron-positron annihilation are used for medical imaging



# Illustration of Gamma-Ray Emission

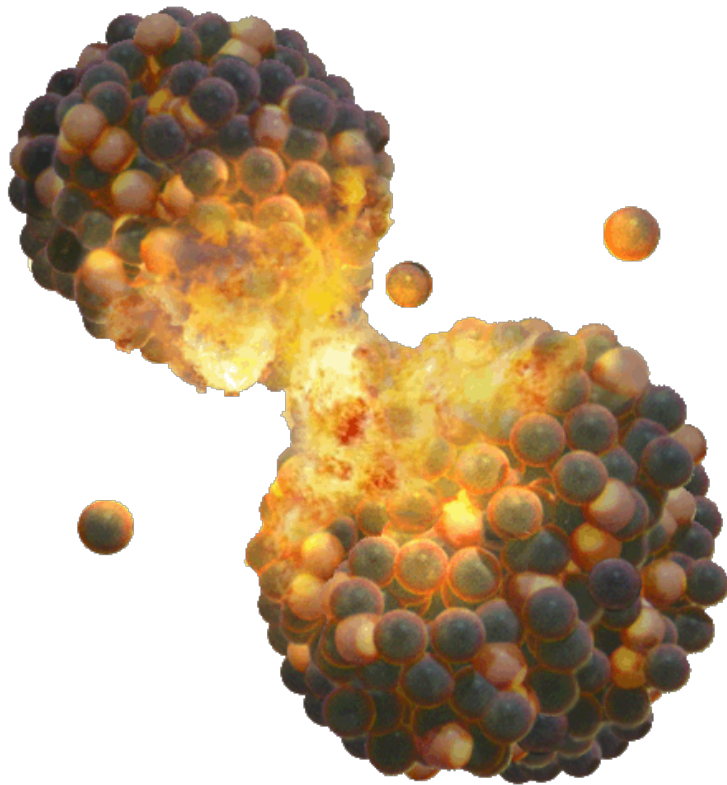
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If a nucleus is in a higher energy (excited) state it returns to a lower energy state by emitting a photon.

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

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

# Physics of Nuclear Weapons

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## Fission and Fusion

# The Two Types of Fission

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## 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 ( $\beta$ - and  $\gamma$ -radiation)
- Energy is released in the form of kinetic energy of the products and as excitation energy of the (radioactive) fission fragments

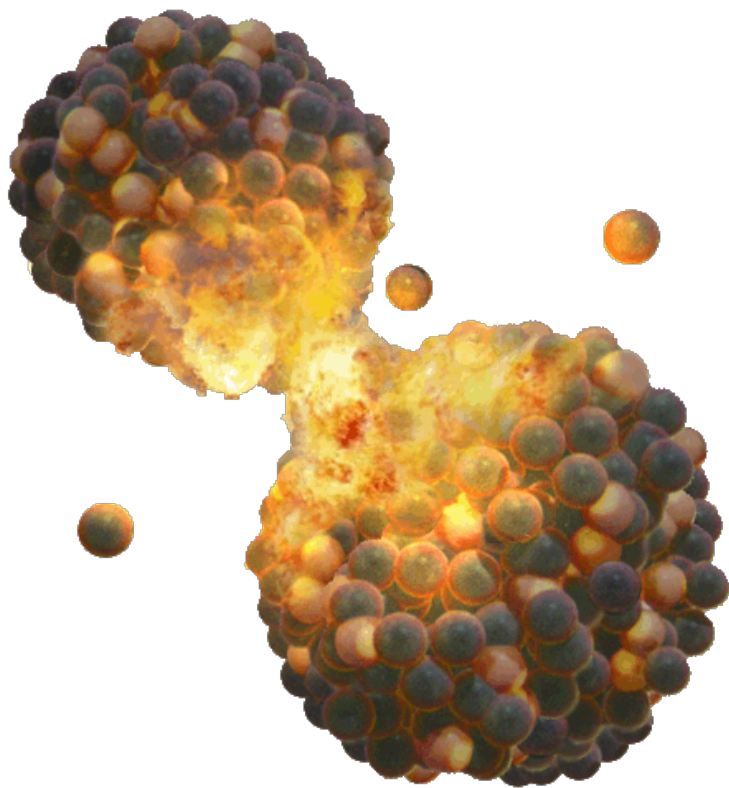
## Induced fission —

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



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

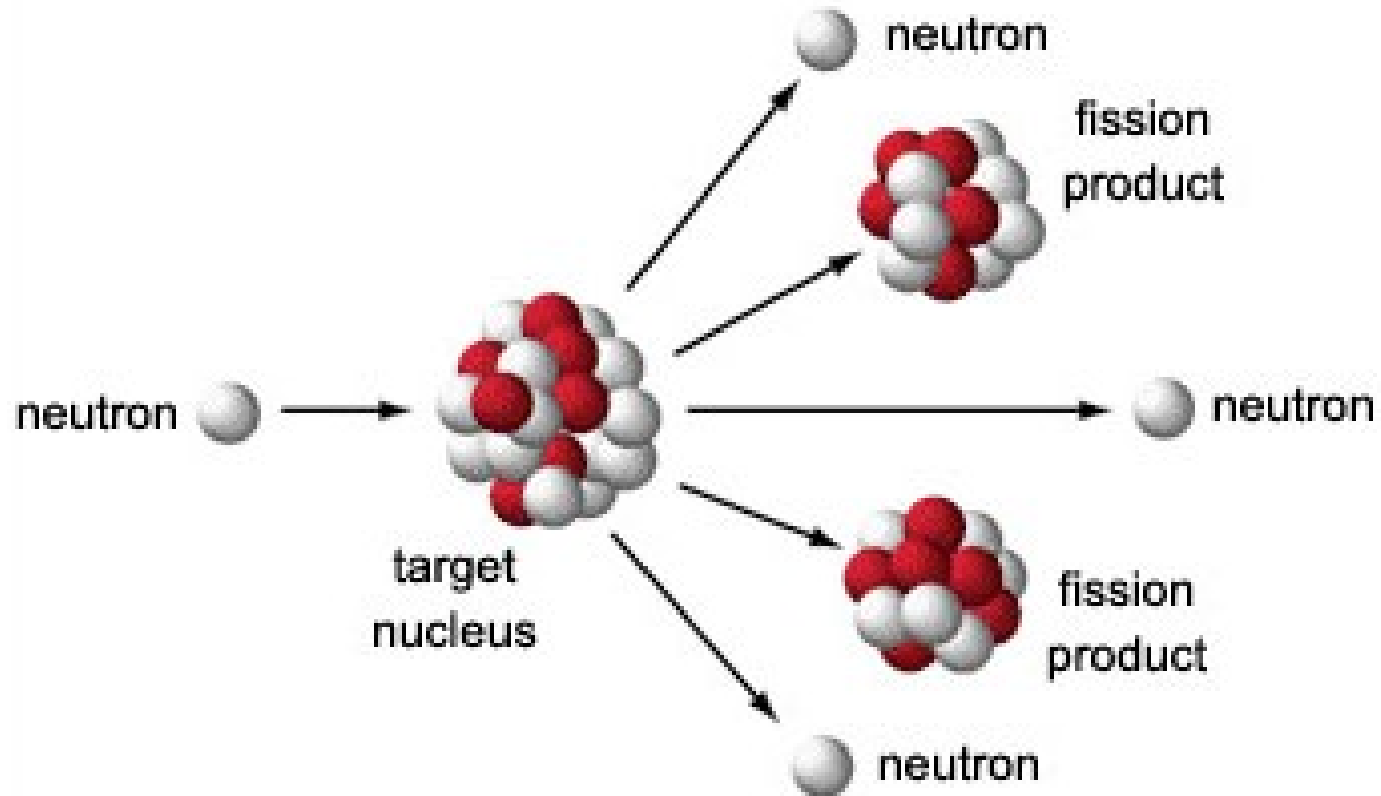
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Fission: a large nucleus splits into two daughter nuclei. In the process a small number of neutrons are emitted.

# Induced Fission

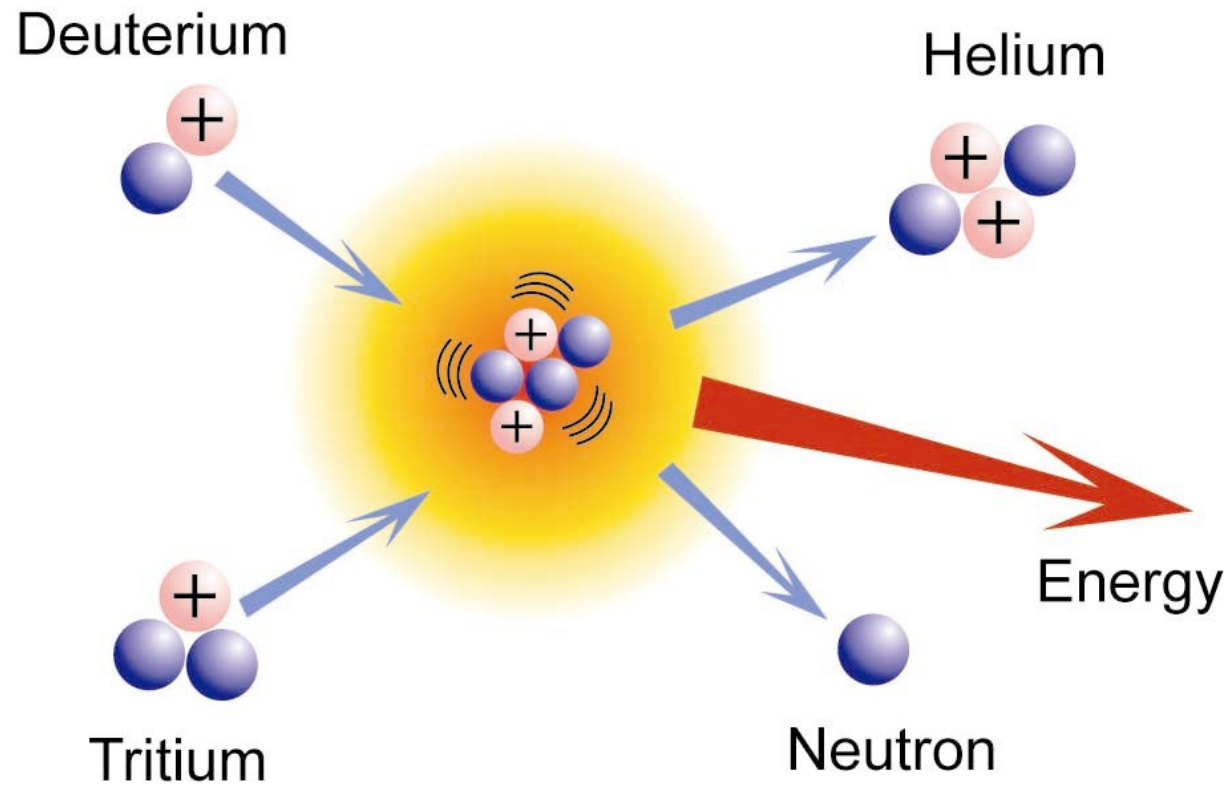
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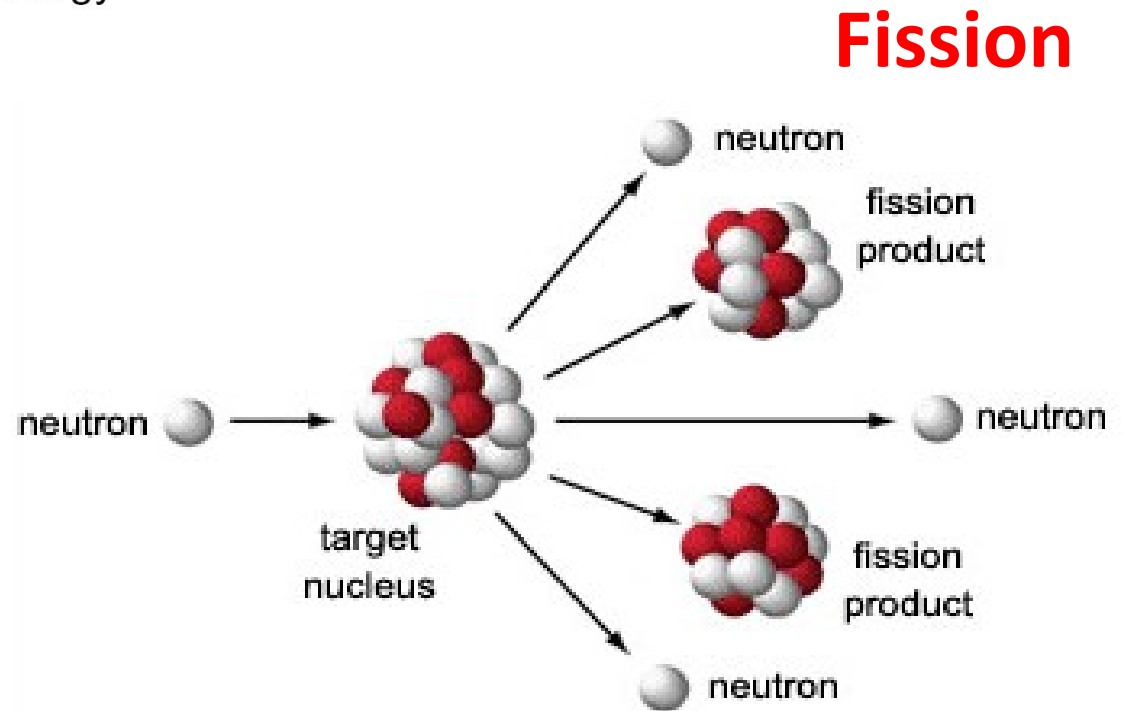
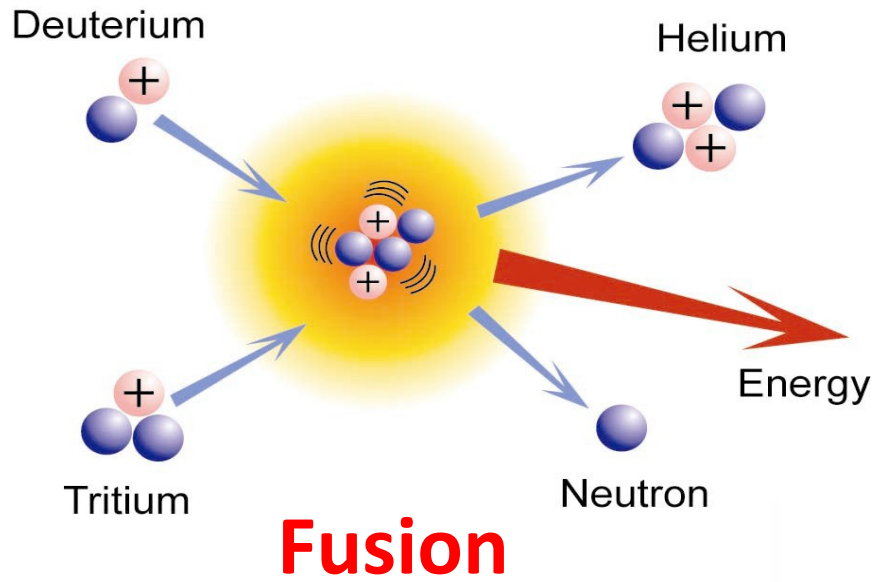


# Fusion

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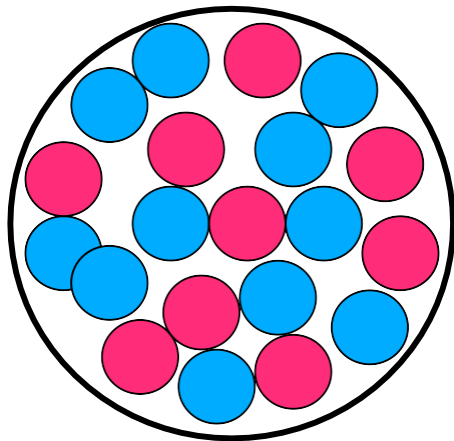


# Why can both, Fission and Fusion Reactions Yield Energy ?



# Binding Energy of Nucleons in a Nucleus

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Nucleus:  $N, Z$

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

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

Competition between (1) and (2) determine **total binding energy of a nucleus  $B_T$** :

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

**Nuclear Force**                      **Electrical Force**

**Nuclear Binding Energy is the source of nuclear energy utilized in nuclear reactors and released in nuclear bomb explosions !**

# The Binding Energy Per Nucleon

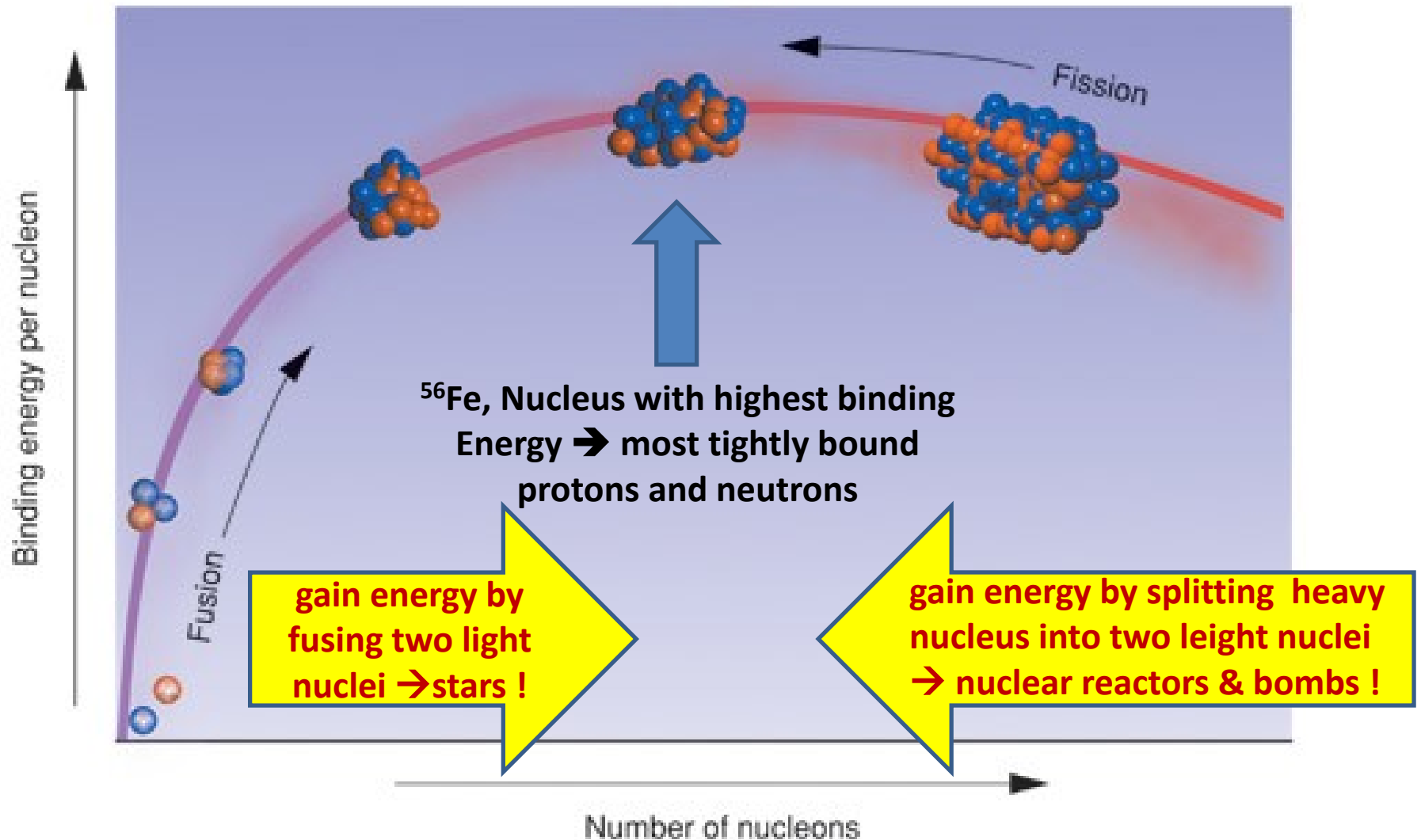
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- The easiest way to understand how fission and fusion liberate energy is by considering the *average binding energy*  $B$  of the nucleons in a nucleus —

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

- A graph of  $B$  (*binding energy*) vs.  $A$  (*atomic weight*) is called “the curve of the binding energy”
- A nuclear reaction that increases the binding energy of nucleons in the nucleus is “exothermic” and releases energy.

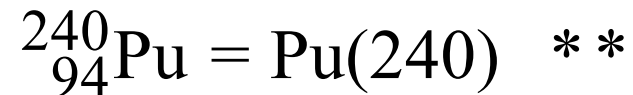
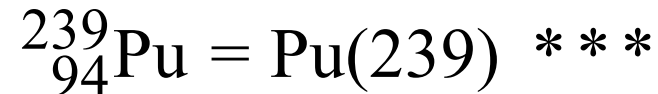
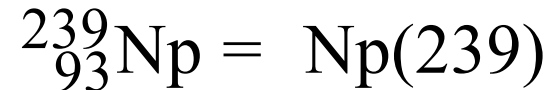
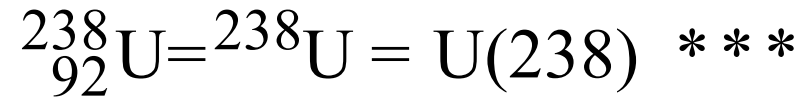
# The Curve of Binding Energy (Important)



# Nuclides Important for Fission Bombs

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Heavy elements (high Z) —



\*, \*\*, \*\*\* denotes increasing importance

# Nuclides Important for Fusion Bombs

---

Light elements (low Z) —

${}^1_1\text{H}$  = P (proton)

${}^2_1\text{H}$  = D (deuteron), stable \*\*\*

${}^3_1\text{H}$  = T (triton), unstable \*\*\*

${}^4_2\text{He}$  = He(4) =  $\alpha$  (alpha particle), very stable

${}^3_2\text{He}$  = He(3), stable (indirectly relevant to NWs) \*

${}^6_3\text{Li}$  = Li(6), stable \*\*

${}^7_3\text{Li}$  = Li(7), stable (no relevance to NWs)

${}^9_4\text{Be}$  = Be(9) stable (lightest metal) \*

\*, \*\*, \*\*\* denotes increasing importance

# The Neutron –

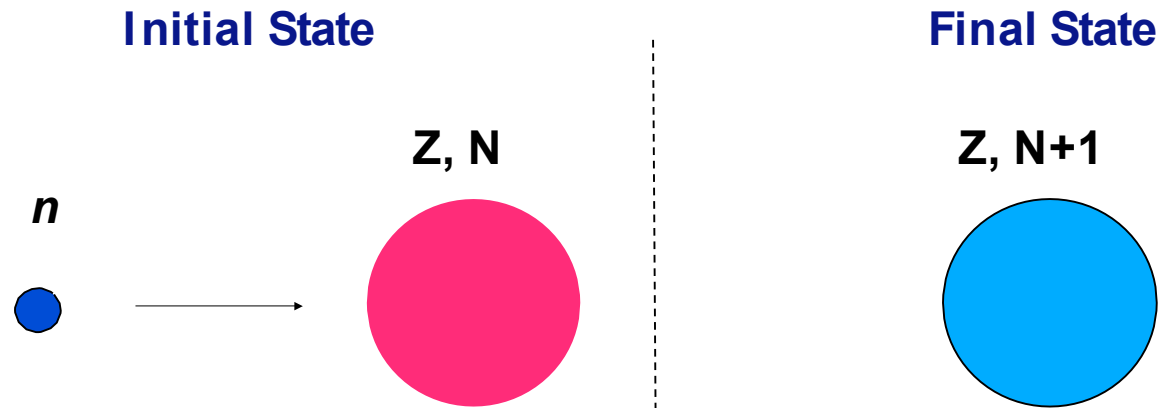
## Similar to Proton but without Electric Charge

---

- The discovery of the neutron in 1932 was the single most important discovery in nuclear physics after the discovery of the nucleus itself.
- Until the neutron was discovered, physicists could not understand nuclei, in particular how  $A$  could be greater than  $Z$ .
- The discovery of the neutron made it possible to understand for the first time that  $A = Z + N$  and could therefore be greater than  $Z$ .
- Neutrons are not repelled by the positive charge of a nucleus and therefore can approach and penetrate a nucleus without having to overcome an electrical energy barrier.
- The nuclear force between neutrons and protons, and between neutrons and nuclei, is generally attractive. Hence if a neutron gets close enough, it will be attracted by and become bound to a nucleus.
- Neutron bombardment of nuclei quickly became a tool for probing the structure of nuclei and the properties of the nuclear force.

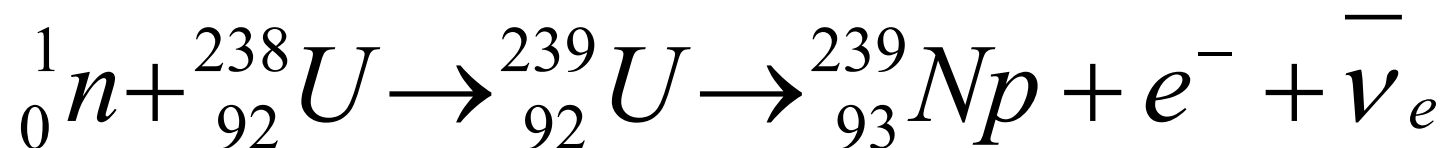


# Neutron Capture



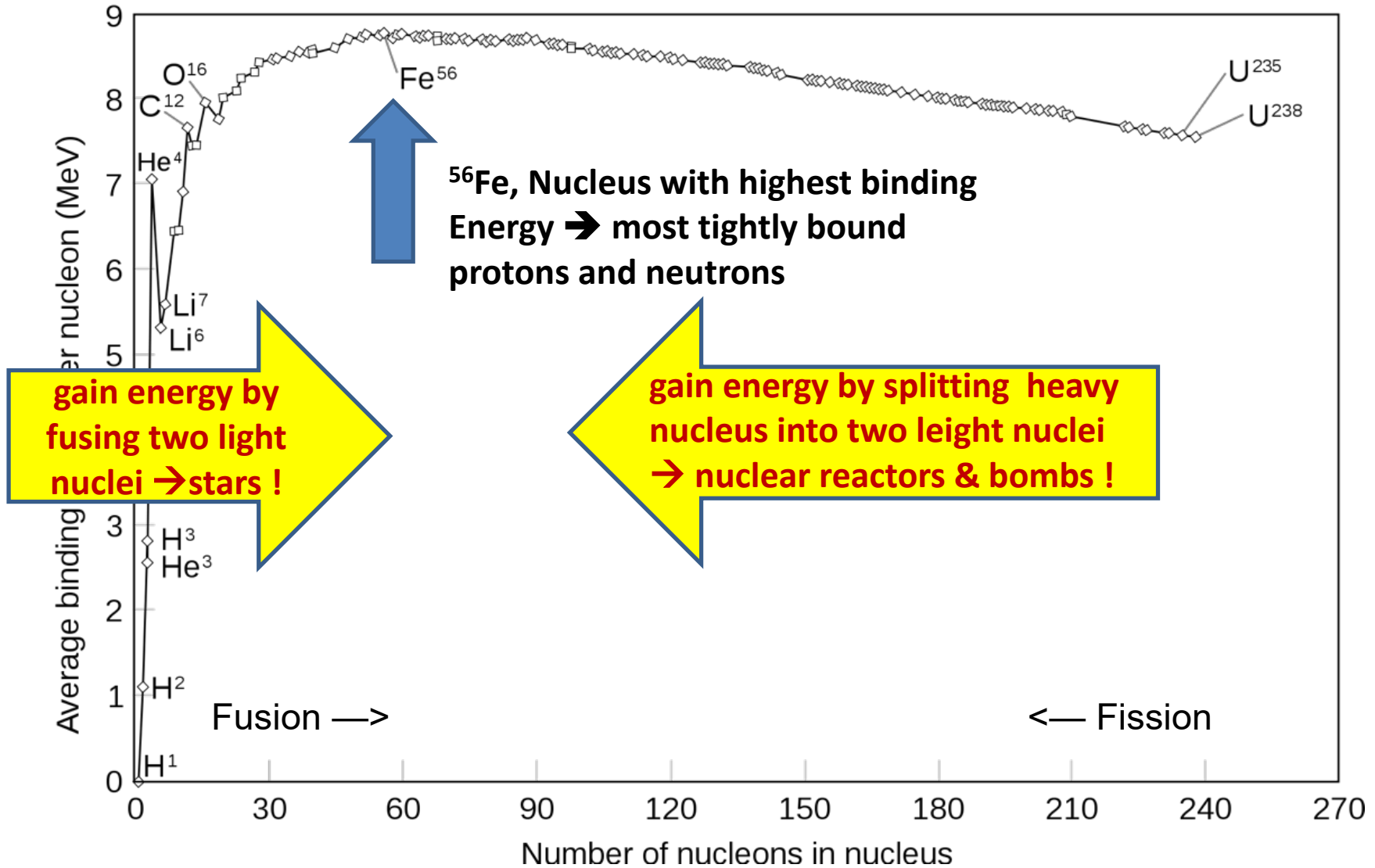
The resulting nucleus may be stable or unstable.

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



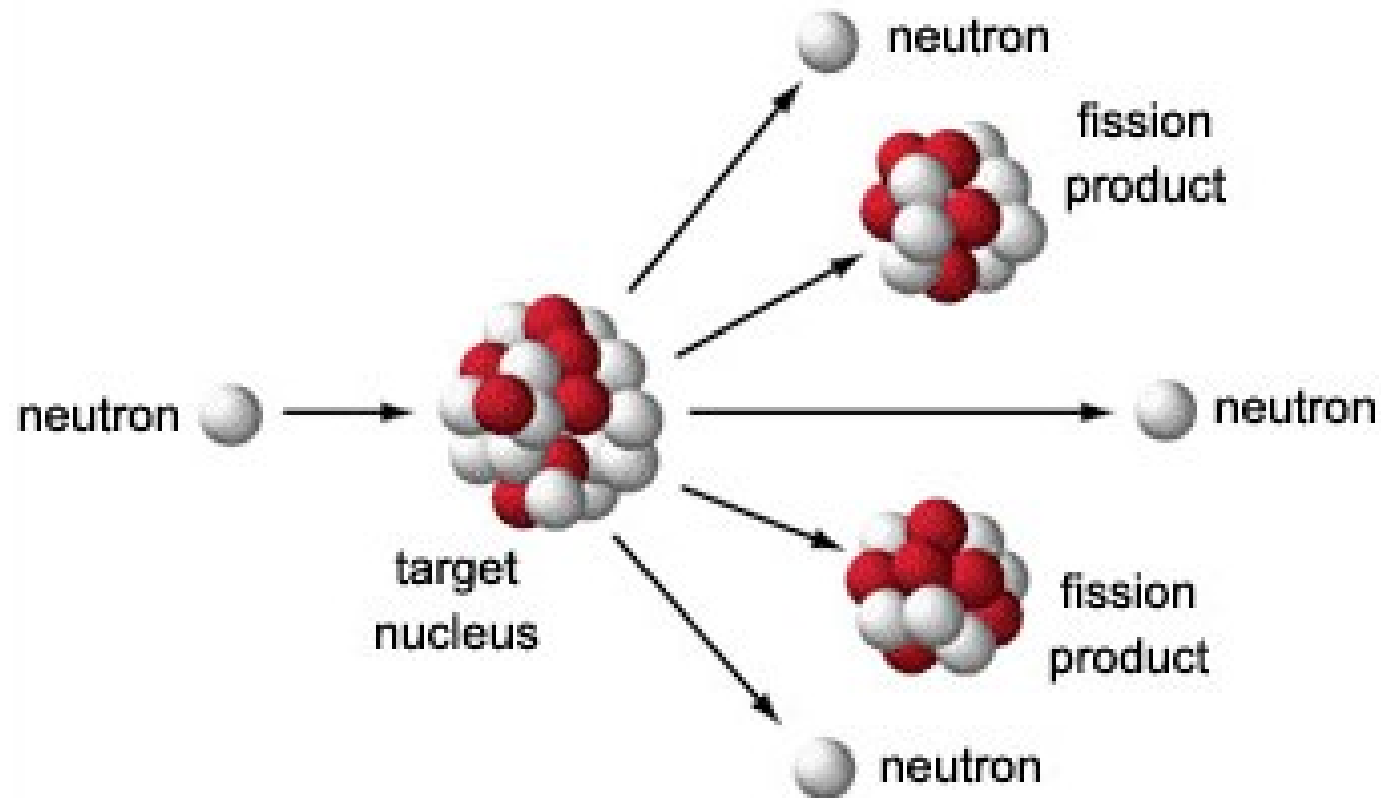
# Average Nucleon Binding Energy → Amount of Energy Released if 1 Neutron is Captured in Nucleus

Average Binding Energy [MeV]



# Induced Fission – 1

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# Induced Fission – 2

---

The discovery of induced fission was a great surprise!

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

Lise Meitner, a brilliant Jewish scientist who had fled from Germany to the Netherlands in 1938, was the first person to understand what was happening in the experiments.

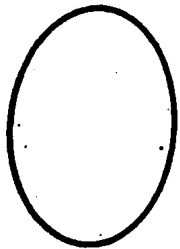
Unfortunately, *she was not included* in the Nobel Prize awarded for the discovery!

Element 109, Meitnerium, is named in her honor.

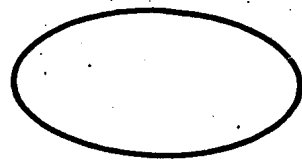
# Lise Meitner's Concept of Fission



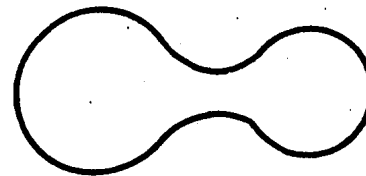
parent nucleus



A

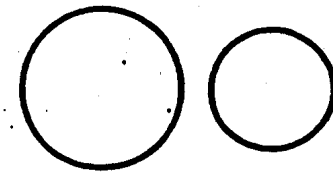


B



C

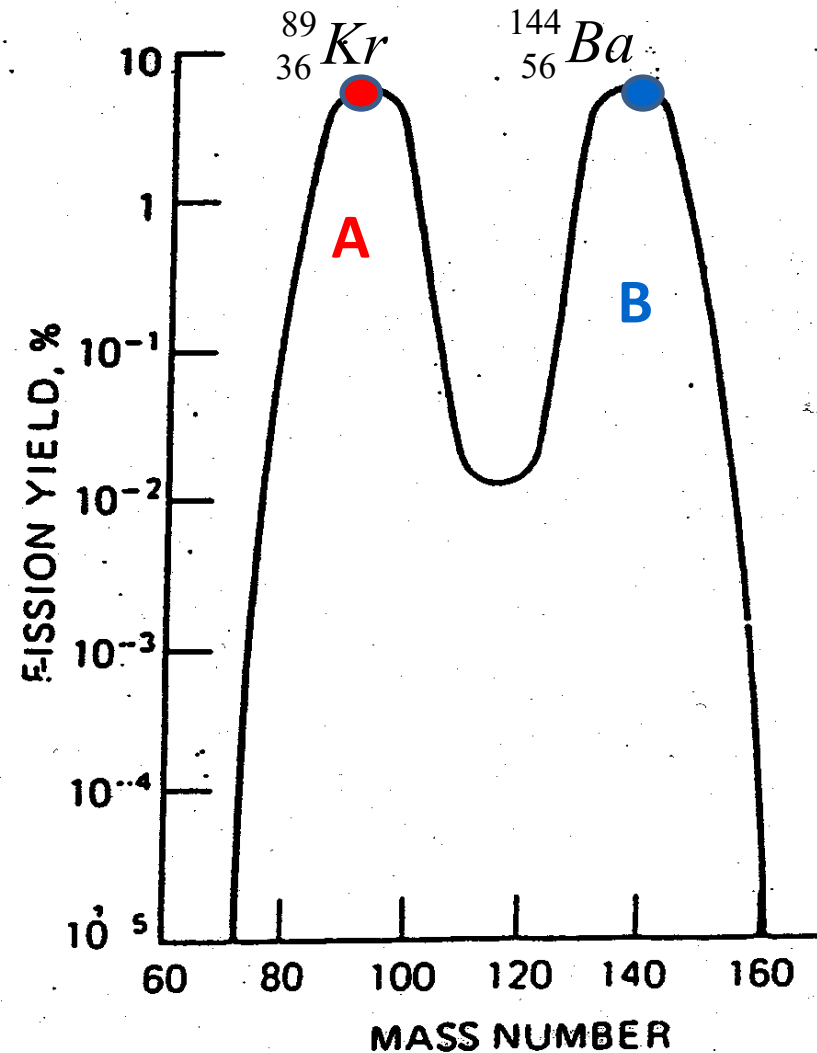
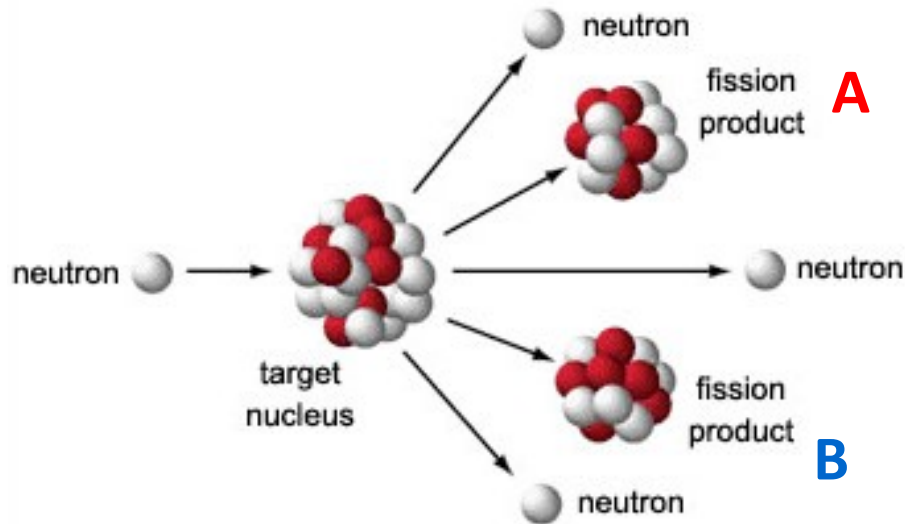
daughter nuclei



D

deformation of  
parent nucleus

# Distribution of Fission Fragment Masses

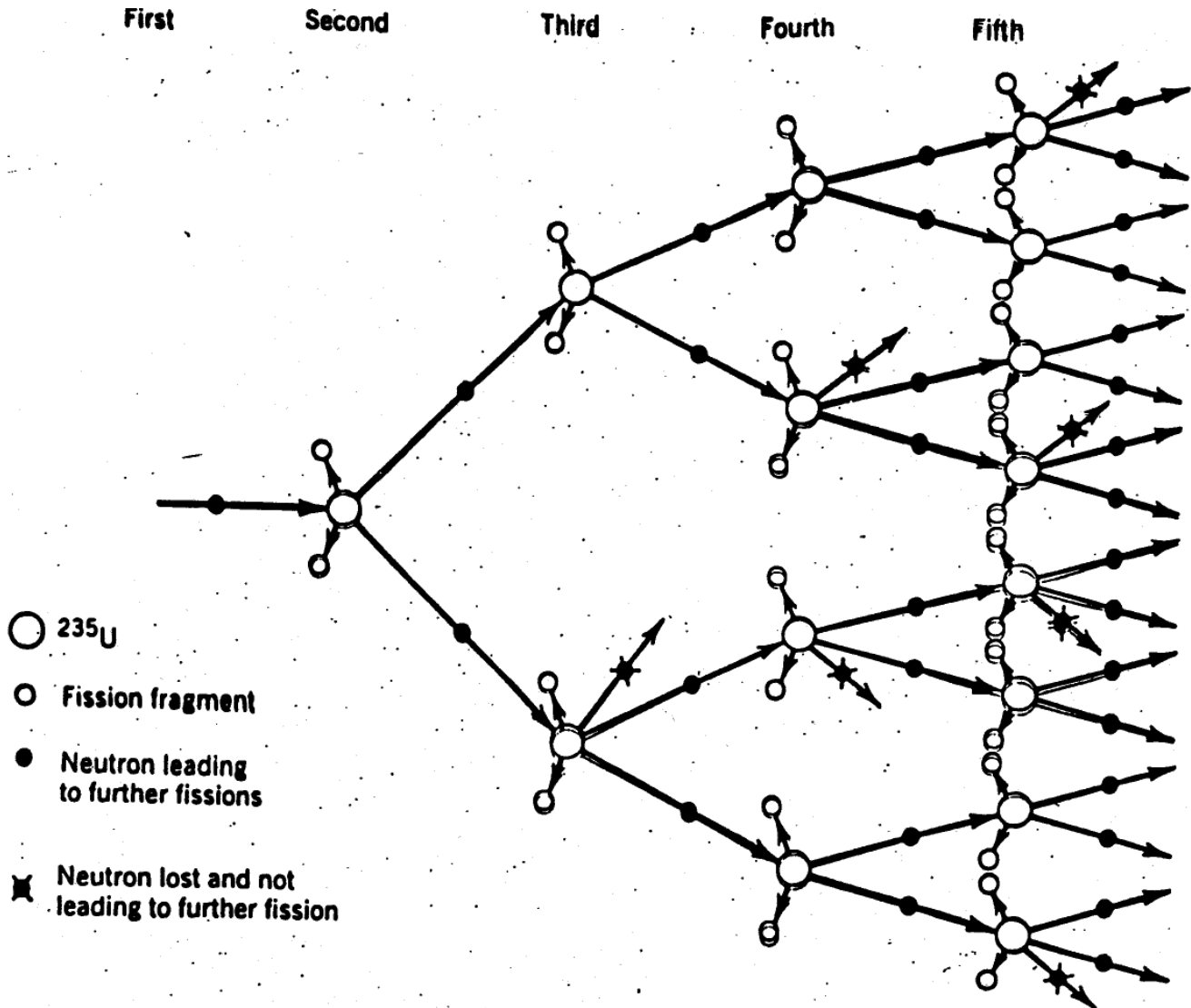


# Induced Fission – 3

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- 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

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## Nuclear Reactors and Nuclear Bombs

# What Is a Critical Configuration?

---

***A critical configuration is an assembly of fissionable nuclear material in an arrangement for which the rate of fissions in the assembly is steady.***

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

The quantity of a given nuclear material needed to produce a steady rate of fissions depends on —

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

These depend on the composition, density, chemical form, etc., of the nuclear material and its arrangement (geometry, surroundings, etc.).

# What is the “Neutron Multiplication Factor” $R$ ?

---

The number of neutrons released by each fission that cause a subsequent fission in a configuration of nuclear material depends on what fraction —

- Escape from the system
- Are captured but do not cause a fission
- Are captured and cause a fission

**The ratio  $R$  of the number of neutrons present in fission generation  $n + 1$  to the number present in fission generation  $n$  is called the *neutron multiplication factor* of that nuclear material configuration.**

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

If  $R = 1$ , the configuration is *critical* and the rate of fissions in it will remain the same as time goes on. Such configurations are used in nuclear reactors.

If  $R > 1$ , the configuration is *supercritical* and the rate of fissions in it will grow exponentially (usually quickly) with time. Such configurations are used in nuclear bombs.

# Nuclides Useful in Nuclear Reactors Versus Useful in Fission Bombs

---

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

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

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

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

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

# Physics/Global Studies 280: Session 6

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## Plan for This Session

### Announcements:

Peer Review: you will receive assignments to peer review another student's essay. This will count for 10% of your v2 grade. Peer Reviews are due Sunday at 10 pm through the assignment upload server.

Locations of essays to be reviewed:

<https://courses.physics.illinois.edu/phys280/secure/assignments/RE2v1/OnTime/>

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

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

## Module 2: Nuclear weapons cont'd

News:

Breaking Defense

# First 2020 Minuteman III Test Launches As New START Countdown Begins

No political message was intended by the launch. Testing "is not used as a 'signaling mechanism' politically," Col. Omar Colbert, Air Force Global Strike Command's 576th Flight Test Squadron commander, stressed on Monday.

By THERESA HITCHENS on February 05, 2020 at 3:20 PM



**News:****Breaking Defense**

# **First 2020 Minuteman III Test Launches As New START Countdown Begins**

Despite the cold, the VIP launch area was crowded. Soldiers, sailors, airmen, contractors and even some family members – with an atmosphere that one media colleague astutely compared to a high school football game, complete with metal bleachers and hot chocolate. We were told that more folks were packed into the Ronald Reagan Missile Defense Site farther away. Since there are only four or five opportunities a year to see the fruits of your labor, it's not surprising the turnout was so big.

The test itself, dubbed FTU-2, went off relatively cleanly at 12:33 am, with a short 15-minute delay caused by an unexplained anomaly. The missile splashed down some 30 minutes later 4,200 miles away near Kwajalein Atoll in the Marshall islands.

Today's launch coincides with the one-year countdown to the expiration of the 2010 New START treaty. That was not planned, however, since ICBM test launches are slated years in advance.



News:

Breaking Defense

# First 2020 Minuteman III Test Launches As New START Countdown Begins

But no message was intended. Testing “is not used as a ‘signaling mechanism’ politically,” Col. Omar Colbert, Air Force Global Strike Command’s 576th Flight Test Squadron commander, stressed on Monday.

New START is the only current bilateral treaty that caps US and Russian nuclear weapons. It limits Russia and the US each to no more than 1,550 deployed strategic warheads and 700 deployed strategic delivery vehicles — that is, ICBMs, submarines and bombers). As *Breaking D* readers know, the Trump Administration has been waffling on whether or not to give the treaty five more years of life.



*1st Lt. Claire Waldo, 12th Missile Squadron missile combat crew commander, conducts a dry-run for a test launch in the Launch Control Center Feb. 3, 2020, at Vandenberg AFB.*

As I reported yesterday, the “developmental test” was aimed at perfecting a new chemically explosive fuze to set off the Minuteman’s W-87 nuclear warhead. The fuze program, budgeted at just over \$2 billion, is expected to reach operational capability in 2024, when replacement of the current fuze in all 400 ICBMs will start. The

Minuteman’s replacement, the Ground-Based Strategic Deterrent (GBSD) will be designed with an interface to back-fit the new fuze.



## The American Conservative

**T**he Chinese government has restated (<https://www.scmp.com/news/china/military/article/3047220/china-says-it-has-no-intention-joining-arms-talks-us-and-russia>) its refusal to participate in any arms control talks with the U.S. and Russia:

But Chinese foreign ministry spokesman Geng Shuang accused the US of using China's involvement as "a pretext to shirk and shift its own nuclear disarmament responsibilities".

"China has no intention to participate in the so-called China-US-Russia trilateral arms control negotiations," Geng said at a regular press briefing in Beijing.

China has never wanted to be part of a trilateral arms control treaty, and that isn't about to change. The Trump administration has refused to extend New START, and it has used this idea of including China in a larger treaty as a smokescreen to justify killing the existing treaty. The administration's feigned interest in a much more ambitious arms control treaty is a transparent attempt at distracting from their desire to let the last remaining major arms control agreement wither and die. Some current and former administration officials imagine that by delaying the extension of the treaty it somehow gives the U.S. additional leverage with Russia, but each day that the treaty's expiration draws closer the less seriously Moscow will take U.S. demands.

## The American Conservative

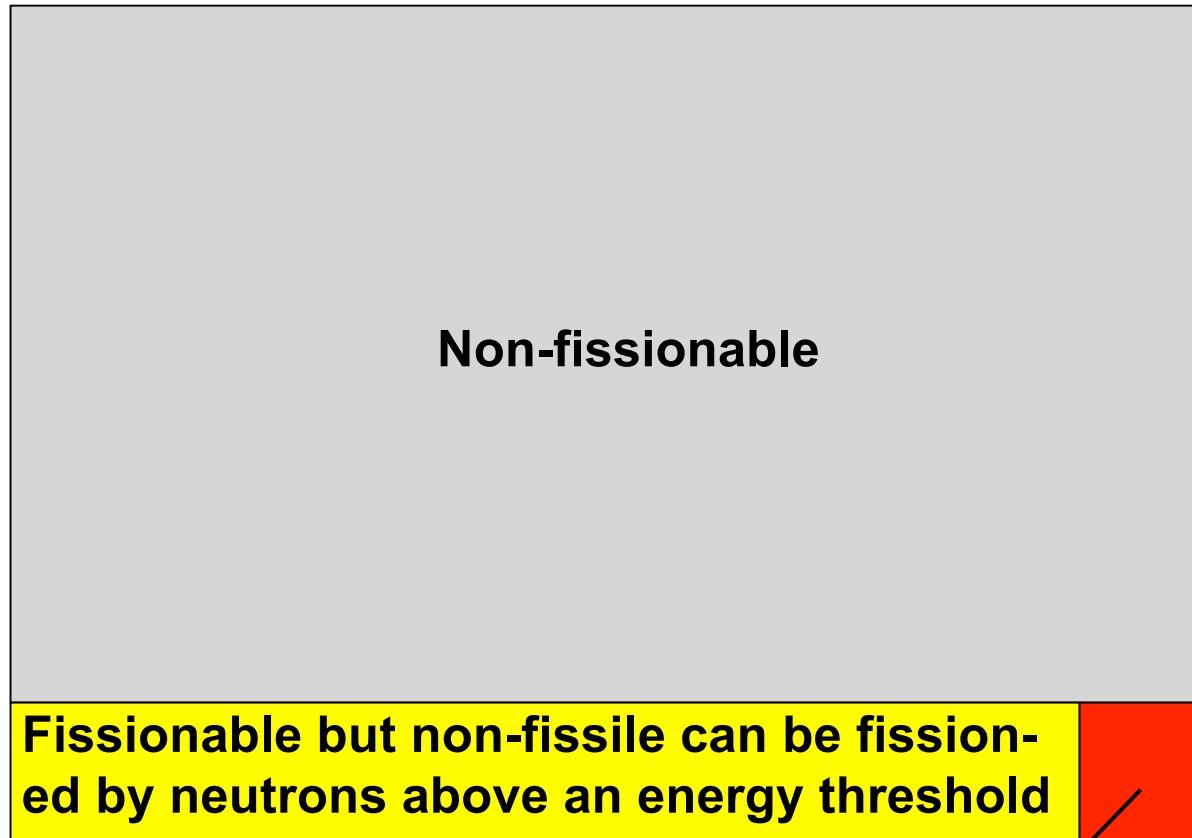
New START has just one year left without an extension. Even if China were willing to talk, there is not remotely enough time to put together a new treaty and ratify it before the current treaty expires. Under the circumstances, the Trump administration's stalling on the extension is obvious proof of their bad faith. Hard-liners in and around the administration are ideologically opposed to arms control agreements, and they have been eager to get rid of all of them.

Letting the treaty die would be one of the more irresponsible things that Trump has done as president. At best, this will have a destabilizing effect on U.S.-Russian relations and it will significantly reduce what our military knows about Russia's nuclear forces. At worst, this will open the door to a new costly and ruinous arms race that puts the world in greater peril.

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

---

**All nuclei**



**Fissionable and fissile  
can be fissioned by neutrons  
of any energy**

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

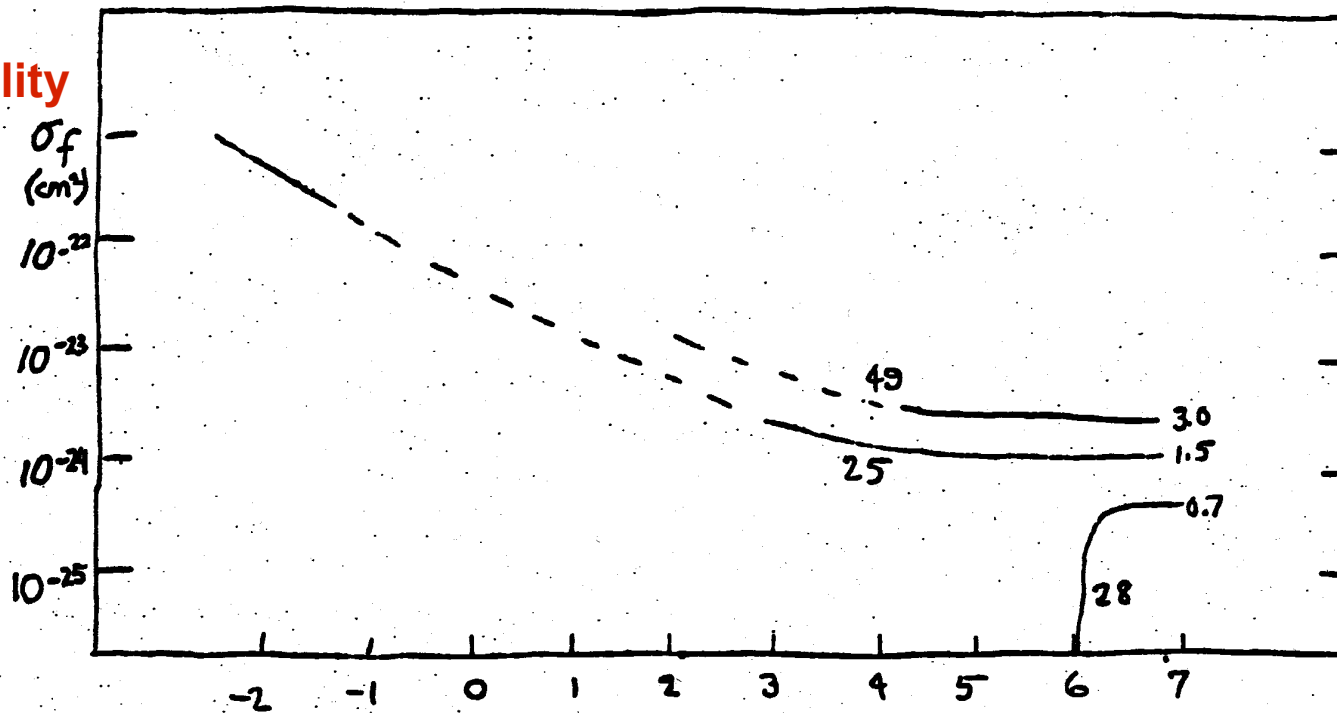
From: Los Alamos Primer, Robert Serber (Manhattan Project, ~1943)

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

FISSION CROSS-SECTIONS

15

Fission  
Probability



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

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

---

**Nuclear-explosive *nuclide*** —in a configuration with suitable quantity, purity, and geometry—can support an explosive (exponentially growing) fast-neutron fission chain reaction.

“Fast” neutrons are fission-produced neutrons that have not been slowed by interacting with their environment.

**Nuclear-explosive *material (NEM)*** is a mixture of various nuclear-explosive nuclides and other nuclides that—in a configuration with suitable quantity, purity, and geometry—can support a fast-neutron fission chain reaction.

Nuclear-explosive material can be used to create a nuclear bomb.

# Some Nuclear-Explosive Nuclides Are Not Fissile

---

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

However, the underlying physics is such that —

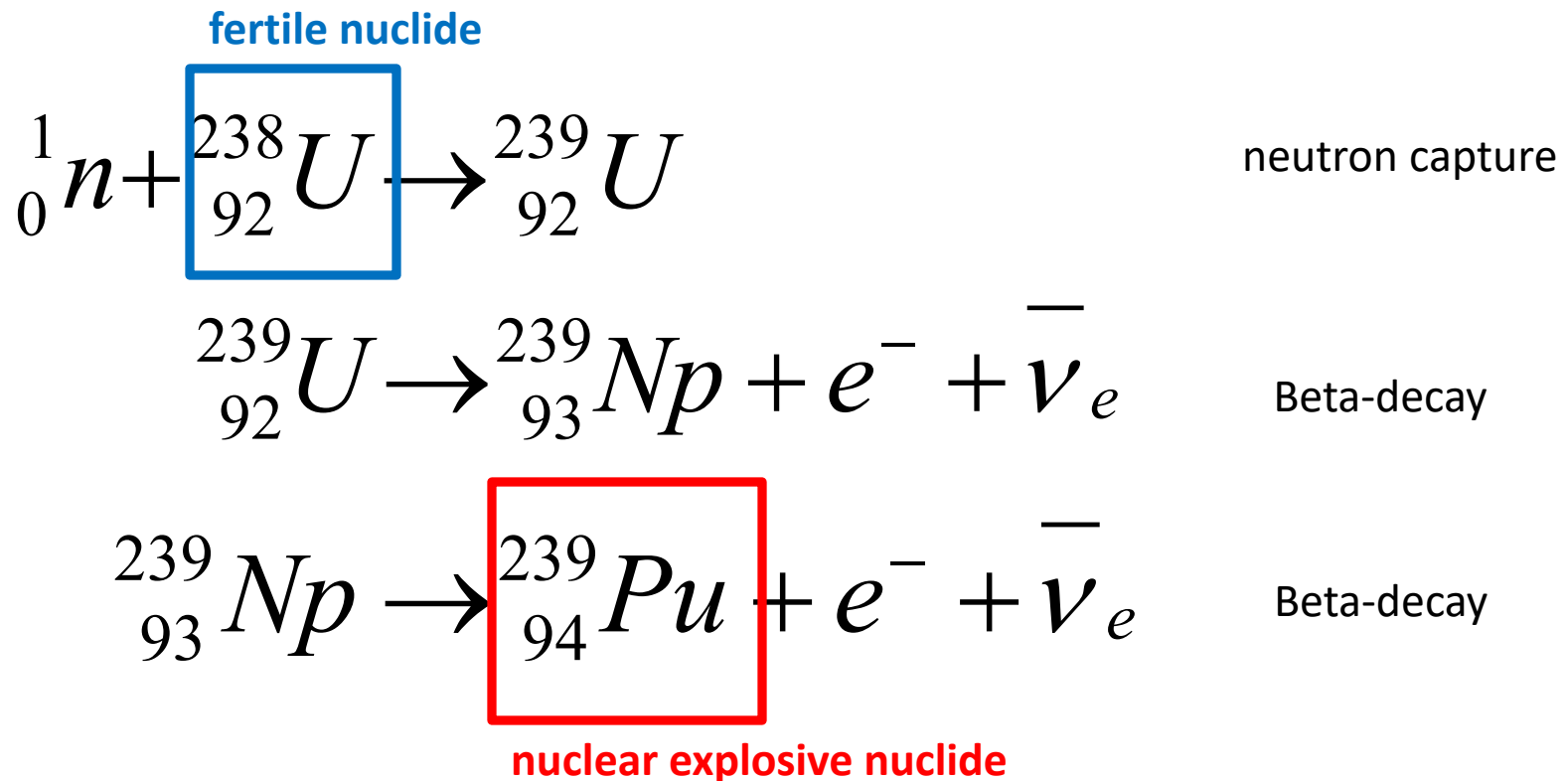
- All fissile nuclides are nuclear-explosive
- Some nuclides that are not fissile are nuclear-explosive

Fissionable but non-fissile nuclides cannot be used in a nuclear reactor, but some can be used to create nuclear-explosive material.

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

# Fertile Nuclides → Breed Nuclear Explosive Nuclides

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



# Definitions of Fission and Nuclear Materials Summary – Important !

---

- **Nuclear fission** is the breakup of a heavy nucleus, such as uranium, into two medium-weight nuclei. Fission is usually accompanied by emission of a few neutrons and  $\gamma$ -rays.
- A **fissionable nuclide** is one that can be fissioned by bombardment with neutrons.
- A **fissionable but non-fissile nuclide** is one that can be fissioned only by neutrons with energies above a certain threshold energy.
- A **fissile nuclide** is one that can be fissioned by neutrons of any energy; in fact, the lower the neutron's energy, the greater the probability that it will cause the nuclide to fission.
- **Nuclear-explosive material** is a mixture of nuclides that can support an explosive fast-neutron chain reaction.
- **Fertile material** is a mixture of nuclides that are transformed into fissile nuclides by capturing a neutron.



# Examples of Fissile, Fissionable but Non-fissile, and Fertile Nuclides (Important)

---

U-235 and Pu-239 are *fissile*

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

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

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

# How to Produce a Nuclear Explosion

---

***A nuclear explosion can be produced by the rapid assembly of NEM into a configuration that will sustain a fast-neutron chain reaction.***

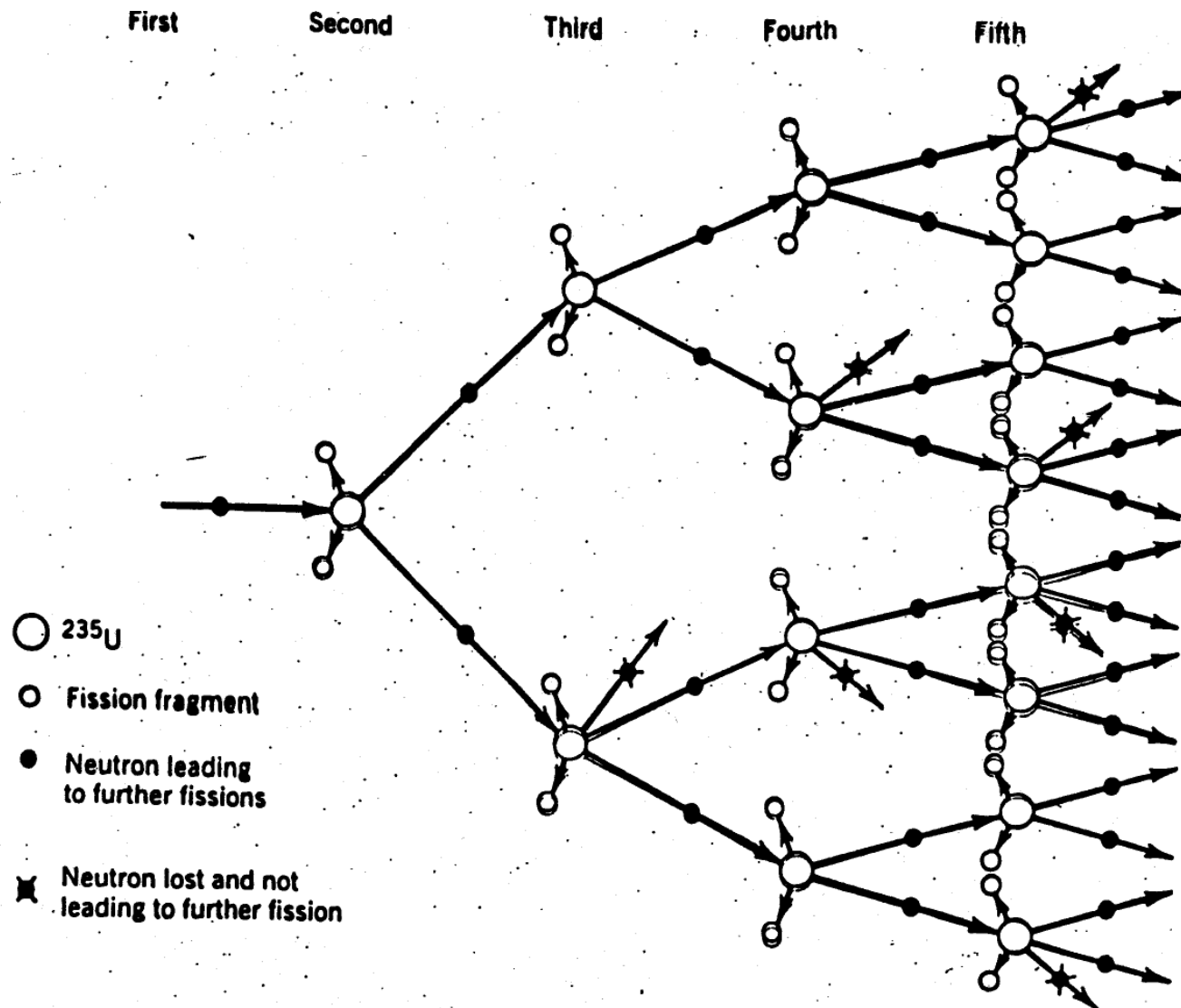
To sustain a fast-neutron chain reaction, on average at least one of the several energetic neutrons released per fission must be “productively” captured, i.e., it must produce another fission following its capture.

To be productive, the neutron must cause a fission before it is unproductively captured or escapes from the configuration.

To produce a nuclear explosion, the fast neutrons from each “generation” of fissions must produce *more* fast neutrons in the next “generation”.

Such a configuration is “prompt supercritical” and will explode.

# Explosive Chain Reaction: Generations



# Number of Fissions When a Nuclear Weapon is Exploded

---

Generation	Fissions in the generation	Energy released
1	$2^0 = 1$	
2	$2^1 = 2$	
3	$2^2 = 2 \times 2 = 4$	
4	$2^3 = 2 \times 2 \times 2 = 8$	
5	$2^4 = 2 \times 2 \times 2 \times 2 = 16$	
10	$2^9 = 512$	
30	$2^{29} = 5.3 \times 10^8$	
70	$2^{69} = 5.9 \times 10^{20}$	0.025% of Yield
79	$2^{78} = 3.0 \times 10^{23}$	12% of Yield
80	$2^{79} = 6.0 \times 10^{23}$	25% of Yield
81	$2^{80} = 1.2 \times 10^{24}$	50% of Yield
82	$2^{81} = 2.4 \times 10^{24}$	100% of Yield

---

Each generation lasts about 1 “shake” =  $10^{-8}$  sec = 1/100,000,000 sec.

All 82 generations last  $82 \times 10^{-8}$  sec =  $0.8 \times 10^{-6}$  sec  $\approx$  1 microsecond.

# Number of Fissions When a Nuclear Weapon is Exploded

Generation	Fissions in the generation	Energy released
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81	$2^{80} = 1.2 \times 10^{24}$	50% of Yield
82	$2^{81} = 2.4 \times 10^{24}$	100% of Yield

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

Each generation lasts about 1 “shake” =  $10^{-8}$  sec = 1/100,000,000 sec.  
 All 82 generations last  $82 \times 10^{-8}$  sec =  $0.8 \times 10^{-6}$  sec  $\approx$  1 microsecond.

# Properties of Nuclear Explosive Nuclides

## Reactivity, Critical Mass, and Explosive Yield

**TABLE A-1** Properties of Nuclear-Explosive Nuclides

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

Properties are important for usage of NEN in nucl. weapons:

- heat from rad. Decay  
→ requires cooling
- radiation from rad. Decay  
→ must control damage to personal and materials
- neutrons from spontaneous fission → early trigger of chain reaction

# Properties of Nuclear Explosive Materials

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

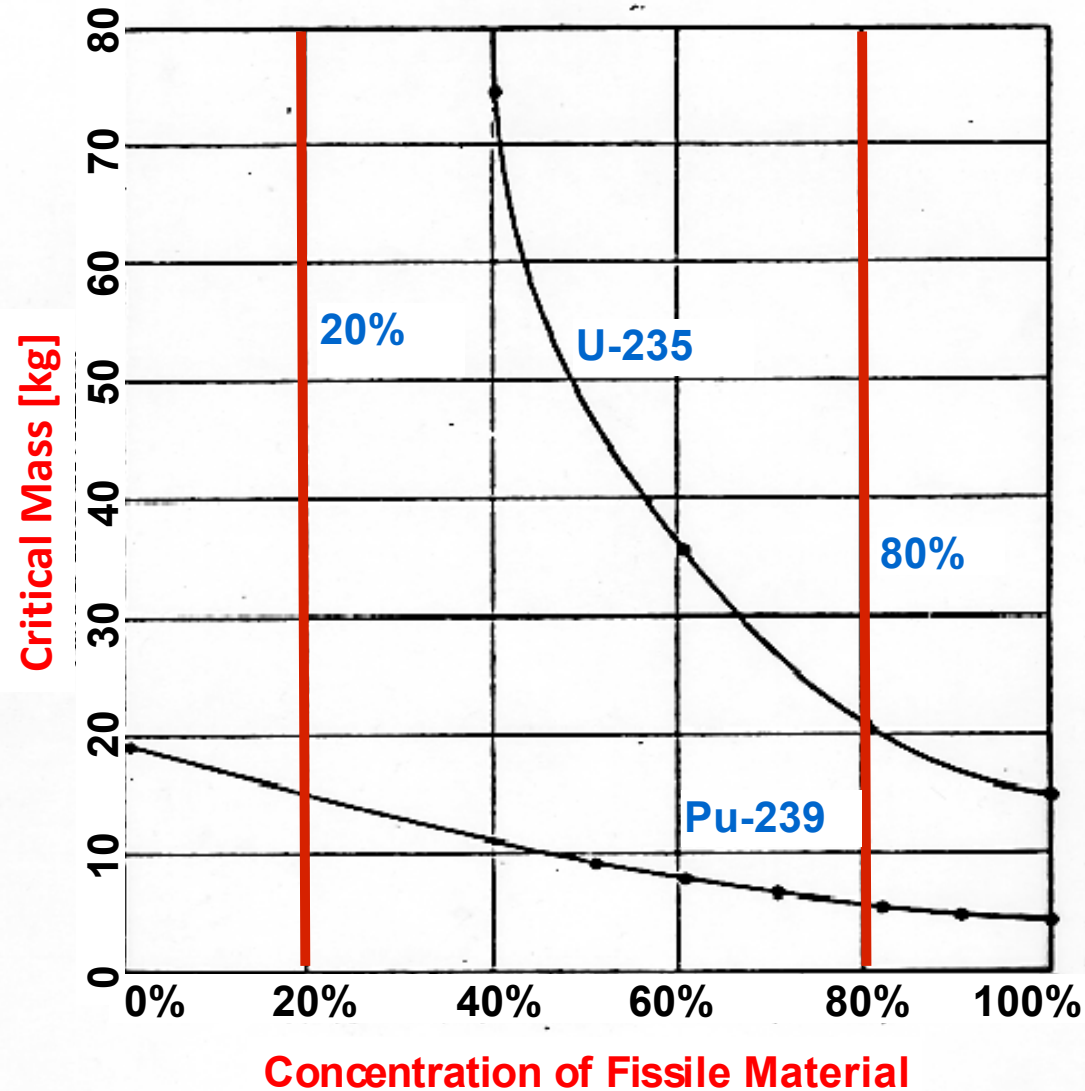
Material	Radioactivity (Ci/g)	Neutron Generation (n/g-sec)	Heat Release (W/kg)	Gamma Dose (rem/hr)
Natural U	0.0000007	0.013	0.000019	0.000012
LEU	0.0000019	0.012	0.000054	0.000057
Weapon-grade HEU	0.0000095	0.0014	0.00026	0.0015
Weapon-Grade Pu	0.22	52	2.5	0.94
Reactor-Grade Pu	6.2	340	14	15

Properties are important for usage of nuclear explosive materials in nuclear weapons:

- heat from rad. Decay → requires cooling
- radiation from rad. Decay → must control damage to personal and materials
- neutrons from spontaneous fission → early trigger of chain reaction

# Reducing the Fast-Neutron Critical Mass – 1

## Critical Mass versus the Concentration of the Fissile Material





# Reducing the Fast-Neutron Critical Mass – 2


---

## Dependence on the Density $\rho$ 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  $\rho_0$  is normal density and  $\rho$  is actual density

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

# Reducing the Fast-Neutron Critical Mass – 3

---

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

# Mass Required for a Given Technology

---

kg of Weapon-Grade Pu for

kg of Highly Enriched U for

Technical Capability

Technical Capability

Low	Medium	High	Yield (kt)	Low	Medium	High
3	1.5	1.0	1	8	4	2.5
4	2.5	1.5	5	11	6	3.5
5	3.0	2.0	10	13	7	4.0
6	3.5	3.0	20	16	9	5.0

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

# Physics of Nuclear Weapons

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## Fission Weapons (“A-bombs”)

# Important Concepts

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

# First Let's Discuss Chemical Bombs

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Simulated road side bomb attack with chemical explosive

# How to Make a Chemical Explosion – 1

---

## Explosive —

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

## Packaging —

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

## Ignition —

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

# How to Make a Chemical Explosion – 2

---

## Stages —

- Explosive is ignited
- Fuel and oxidizer burn (chemically), releasing ~ 5 eV per molecule
- Hot burned gases have high pressure, break bomb case and expand

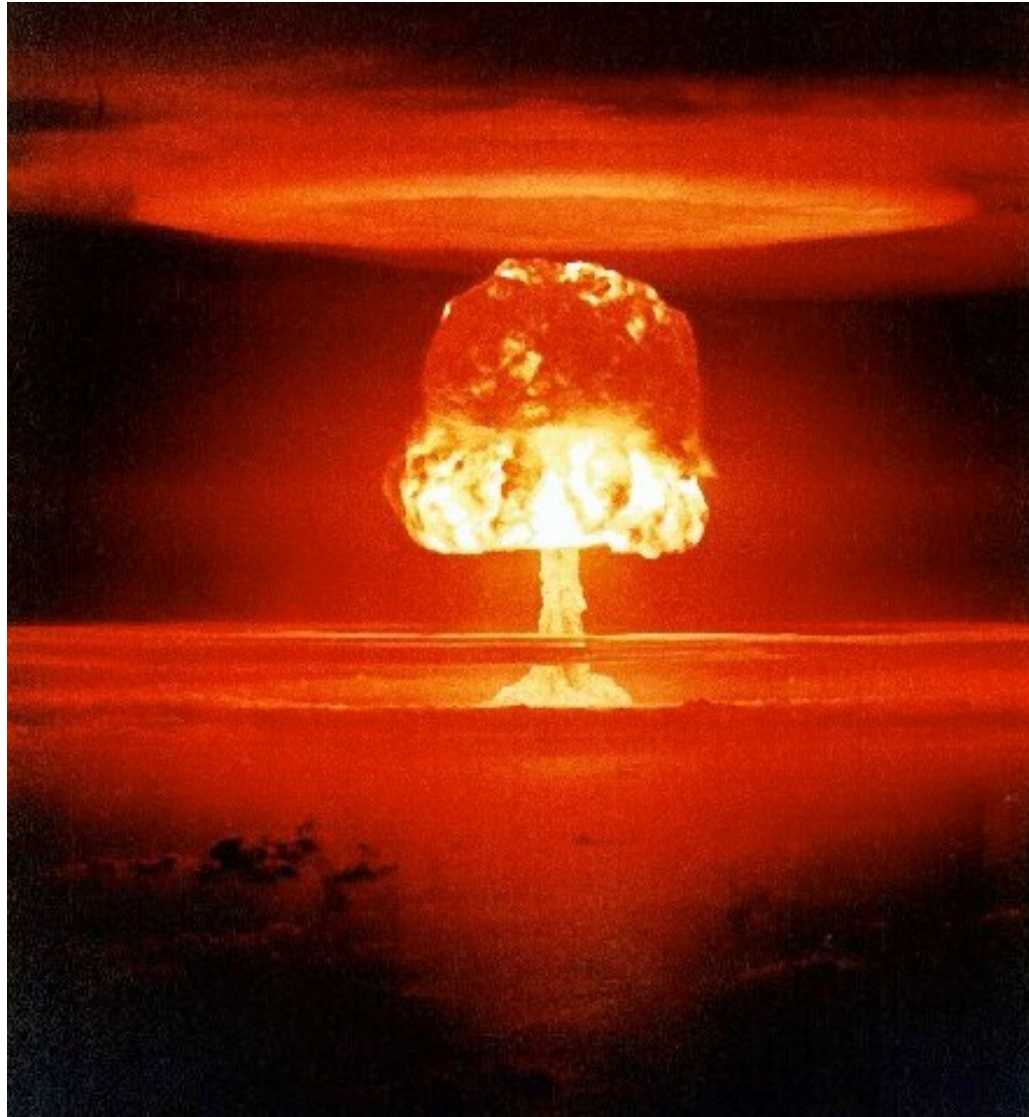
## Energy released goes into —

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



# Now Let's Discuss Nuclear Bombs

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

# How to Make a Nuclear Explosion

---

Key steps required to create a fission explosion —

- Collect at least a critical mass of NEM (*be sure to keep the material in pieces, each with a subcritical mass!* )
- Quickly assemble the pieces into a single supercritical mass
- Initiate a fast-neutron chain reaction in the assembled mass
- Hold the assembly together until enough of it has fissioned

Additional steps required to create a thermonuclear (two-stage) explosion —

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

# Energy Released By a Single Fission (Details)

---



## Energy Distribution (MeV)

Kinetic energy (KE) of fission fragments	~ 165*
Energy of prompt gamma-rays	7*
KE of prompt neutrons	5
KE of beta-rays from fragments	7
E of gamma-rays from fragments	6
E of neutrinos from fragments	10
Total	~ 200

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

# Energy Yields of Nuclear Weapons – 1

---

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

# Energy Yields of Nuclear Weapons – 2

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## Fission weapons (“A-bombs”) —

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

## Thermonuclear weapons (“H-bombs”) —

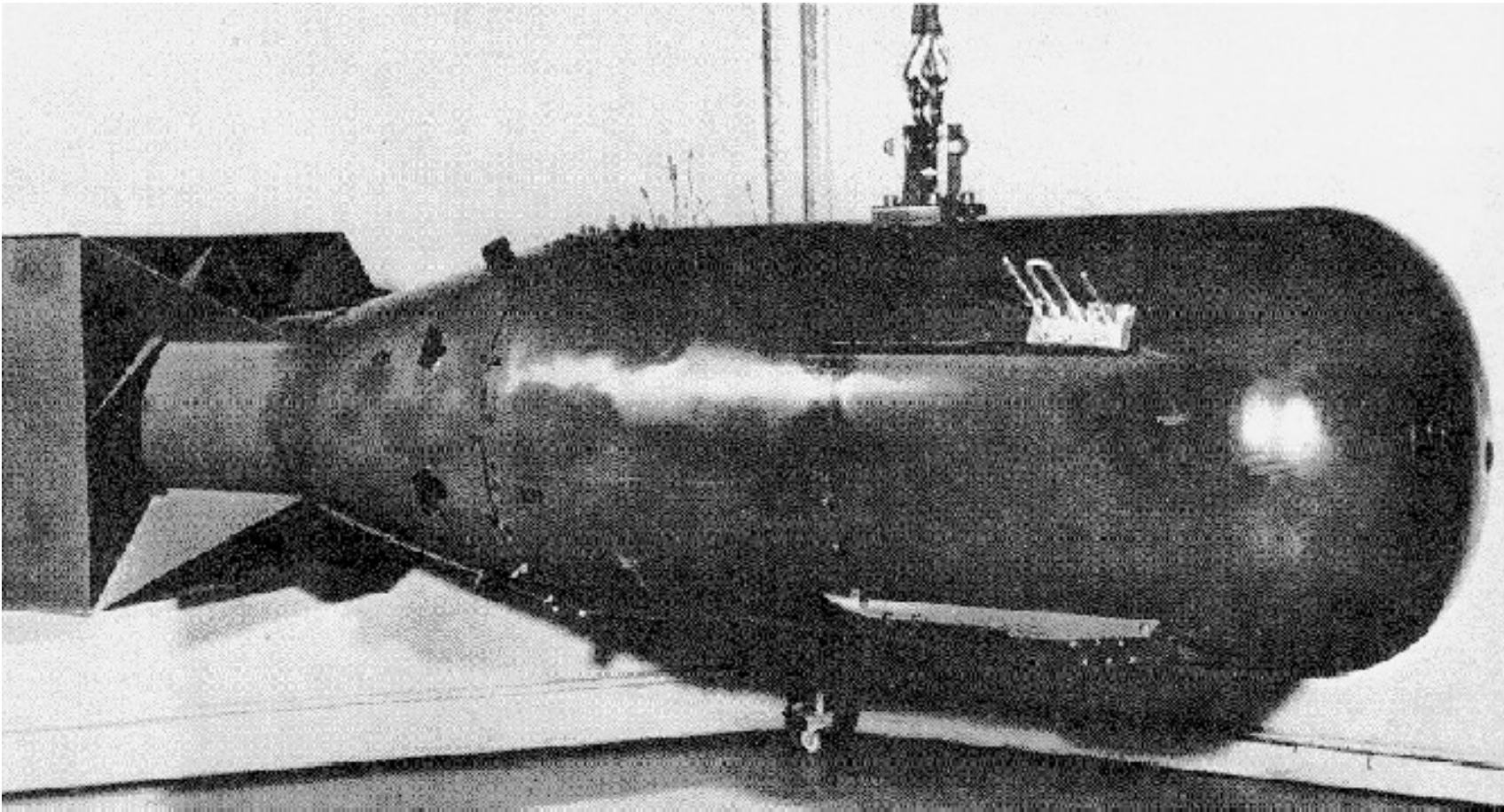
- Theoretical maximum yield-to-weight ratio: 25  
kt TNT from 1 lb. of fusion material  
(~ 3 times as much per lb. as fission weapons)
- There is no fundamental limit to the size of a  
thermonuclear weapon



# Fission Weapons – Gun Type

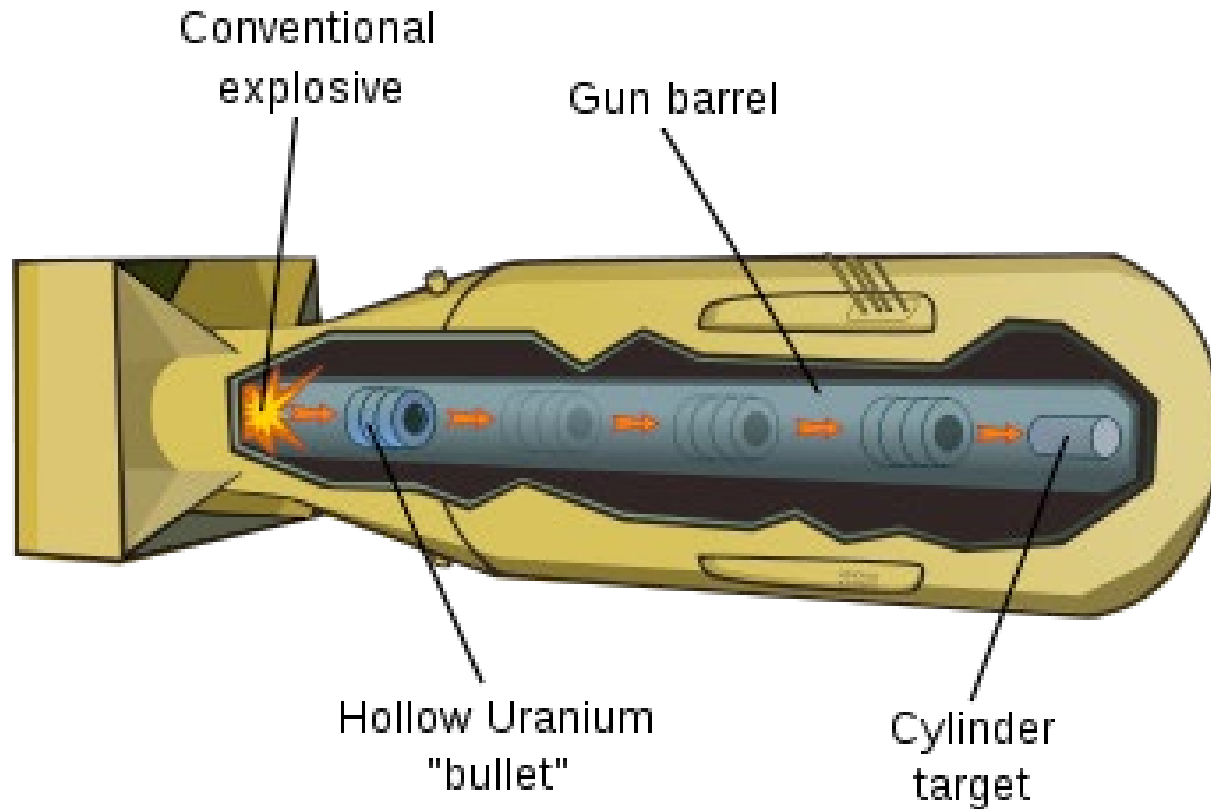
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## Little Boy



# Fission Weapons – Gun Type

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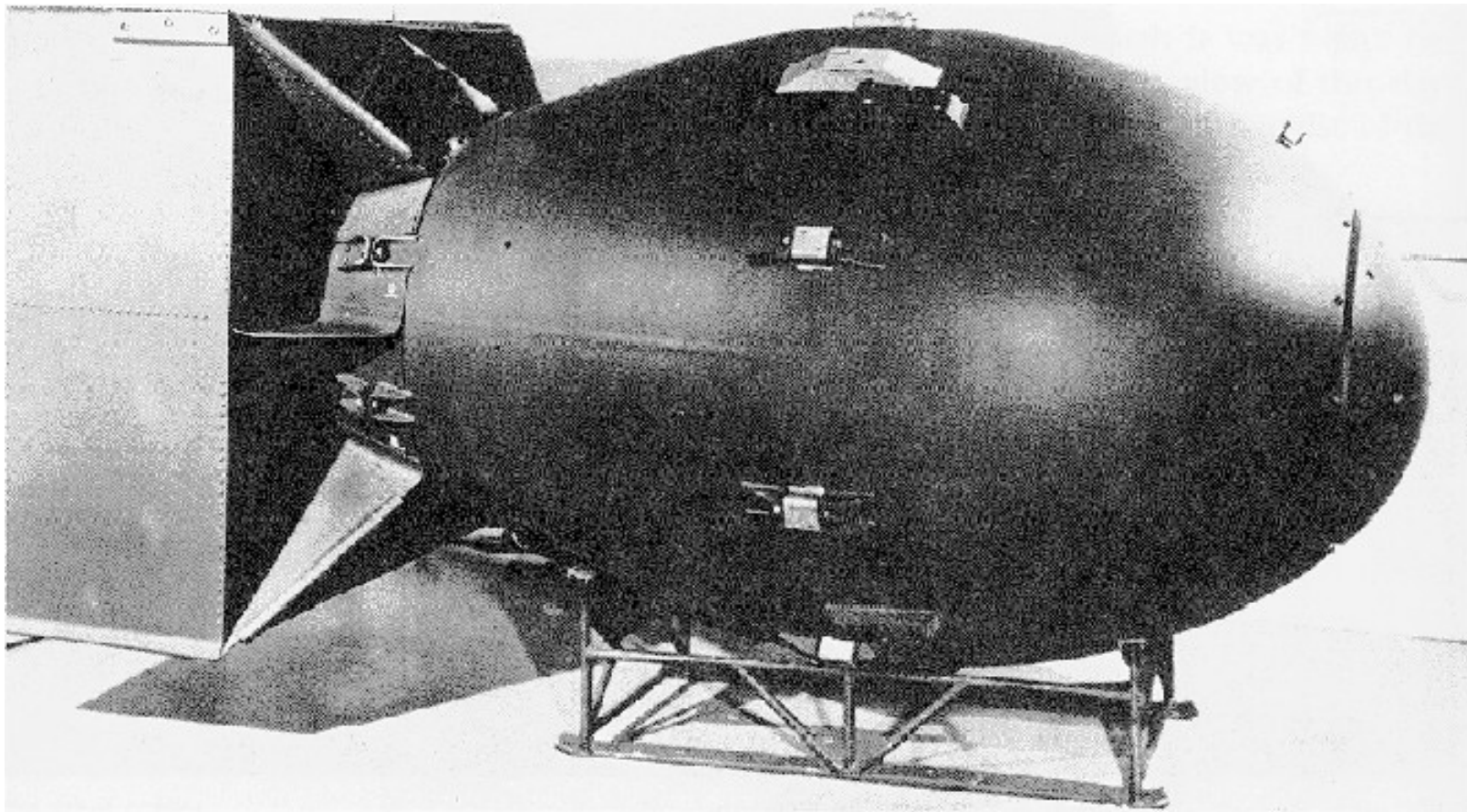


Works only with HEU  
(relevant today mostly for non-state groups)

# Fission Weapons – Implosion Type

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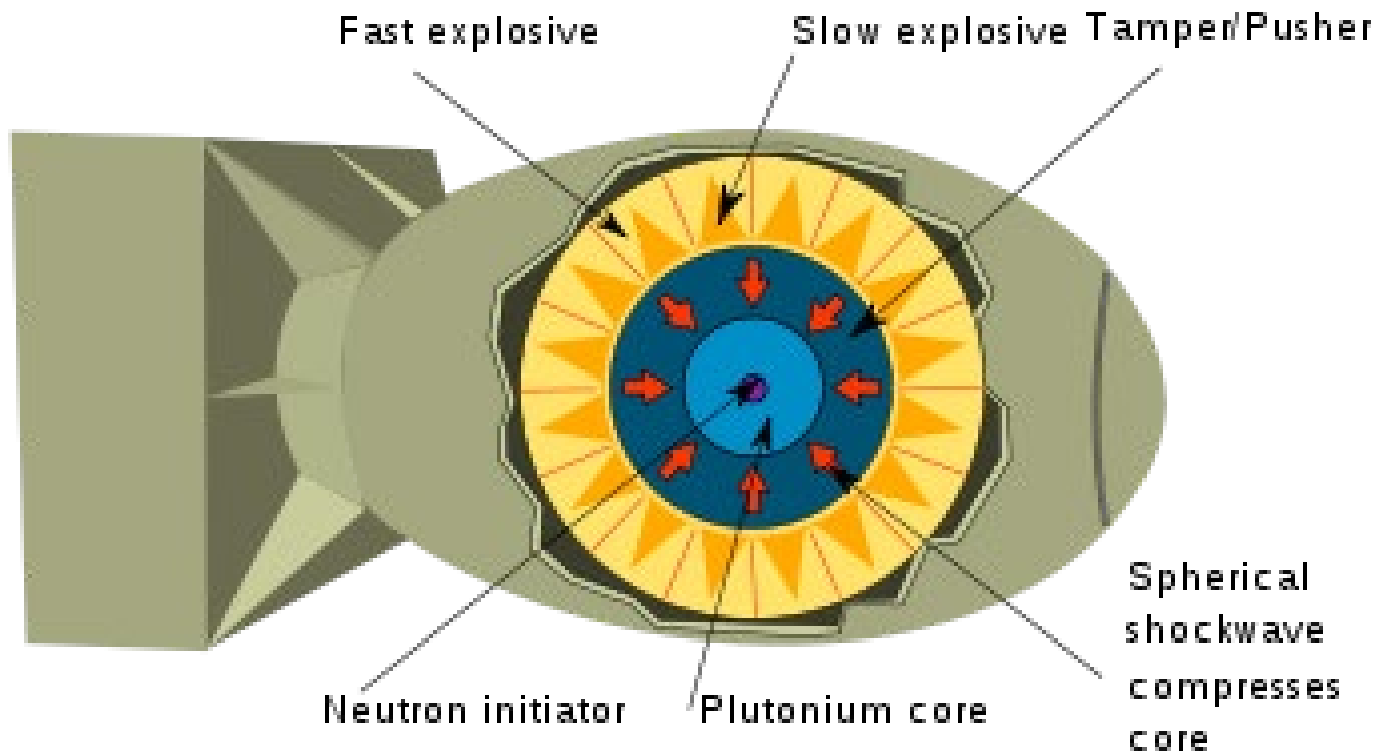
## Fat Man





# Fission Weapons – Implosion Type

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# Fission Weapons – Implosion Type

---

## Plutonium Sphere (“Pit”)



# Initiating a Fission Explosion – 1

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

# Initiating a Fission Explosion – 2

---

Timing is everything —

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

# Physics of Nuclear Weapons

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## Thermonuclear Weapons (“H-Bombs”)

# Fusion Nuclear Reactions (Basics)

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*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)

# Physics/Global Studies 280: Session 7

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## Plan for This Session

### Announcements/Questions

→ RE2v2 due today 2-5 at 10 pm by online submission  
paper copy in class on Thursday

→ peer reviewed papers available at

<http://courses.physics.illinois.edu/phys280/secure/assignments/RE2v1-review/>

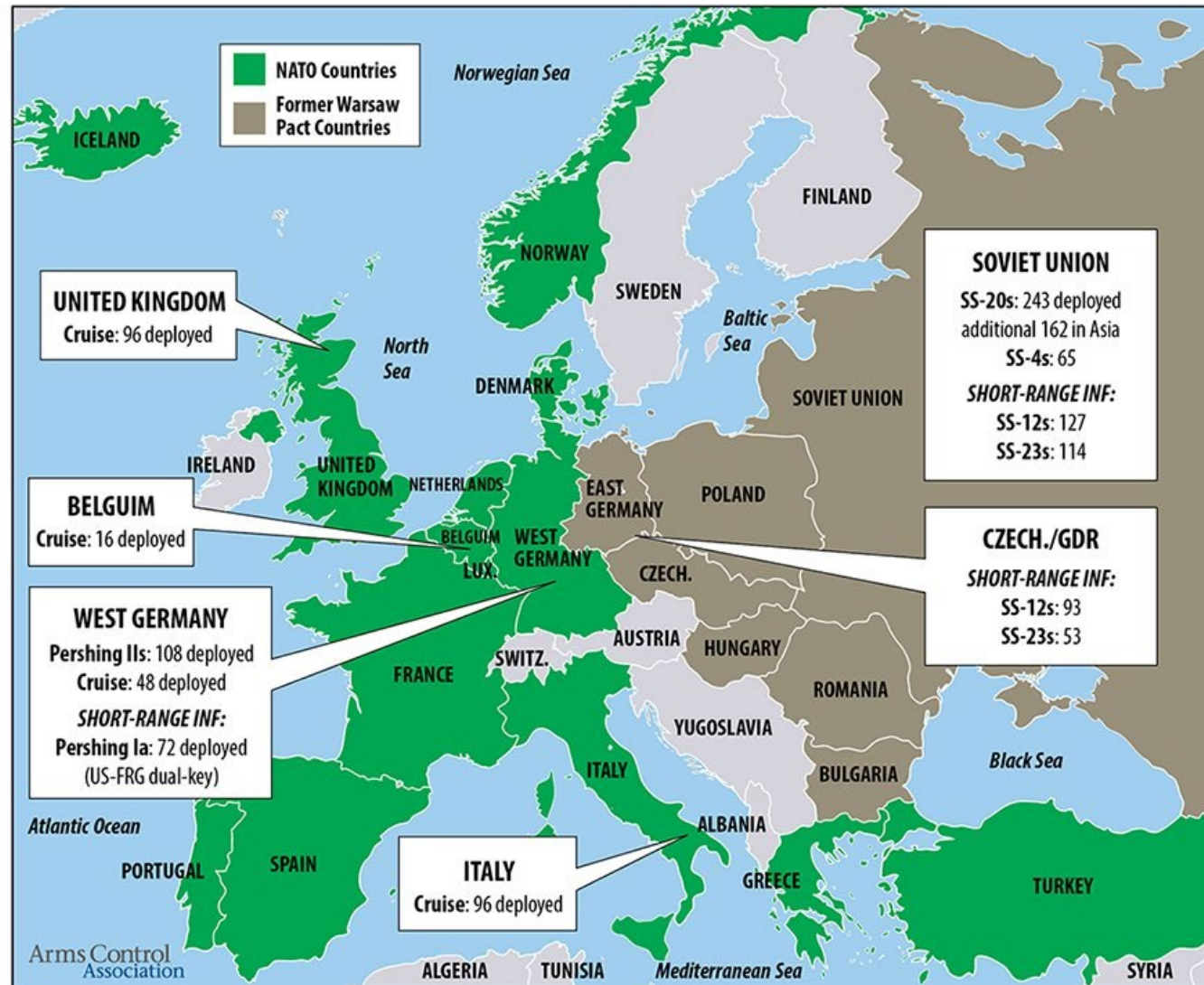
Grading peer review: peer review is worth 10% of RE2v1

### News

Module 2: Nuclear weapons (conclusion)

# News: INF Treaty Cancelled by the USA and Russia

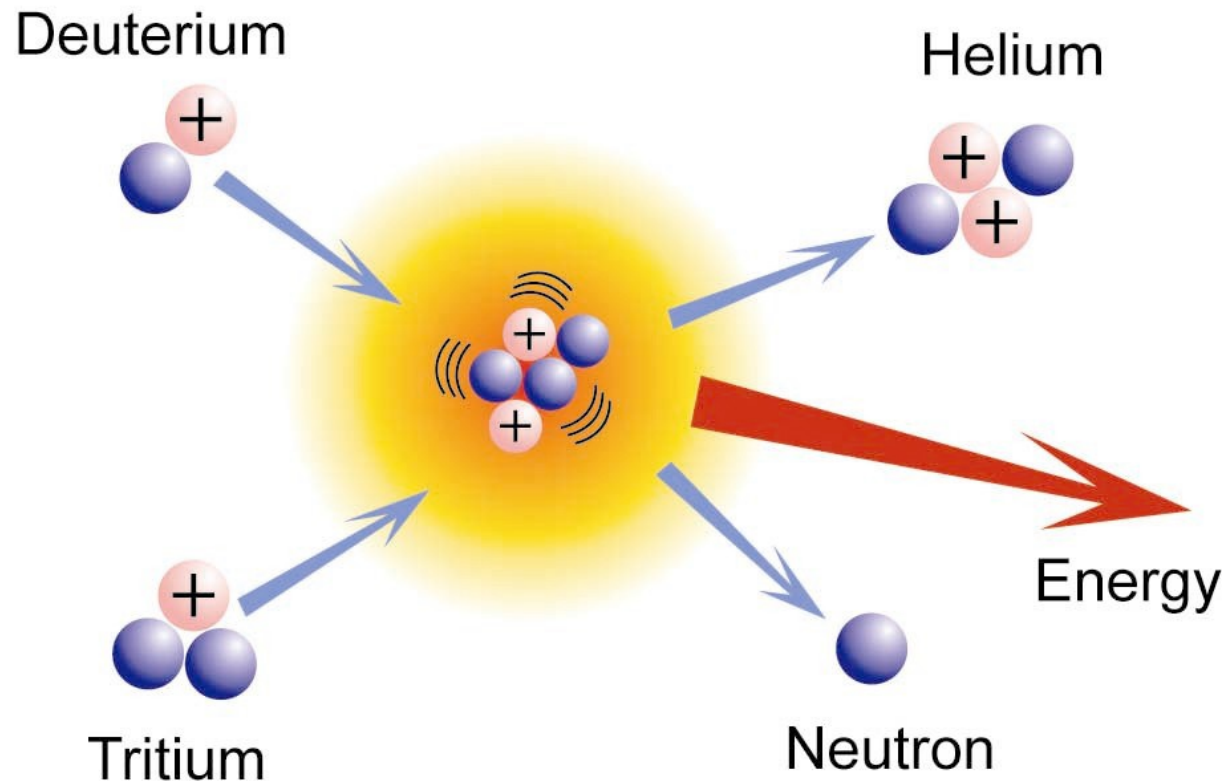
*Missile Deployments Eliminated by the INF Treaty*





# Example Fusion Nuclear Reaction

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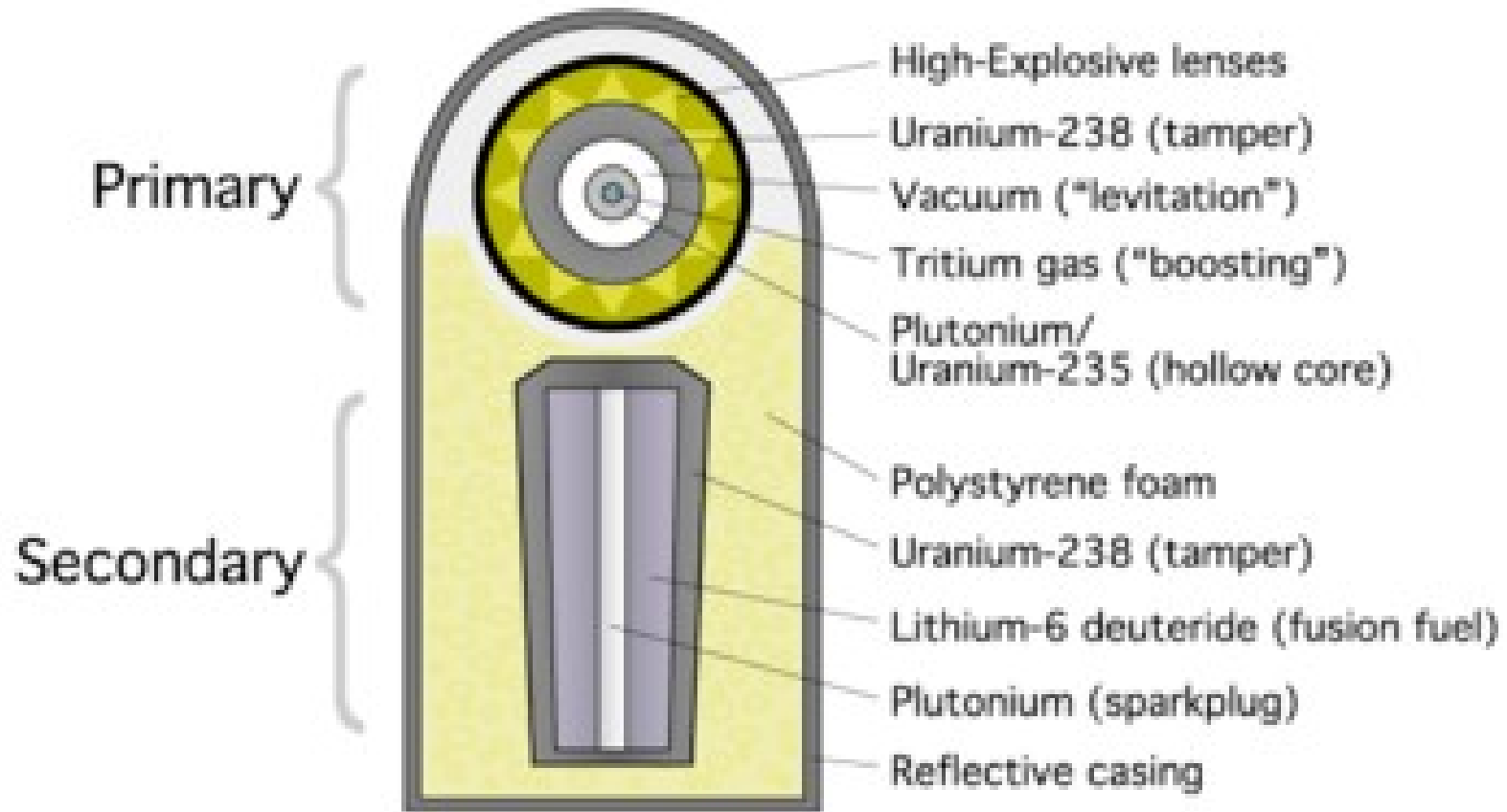


# Two-Stage (Thermonuclear) Weapons – 1

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

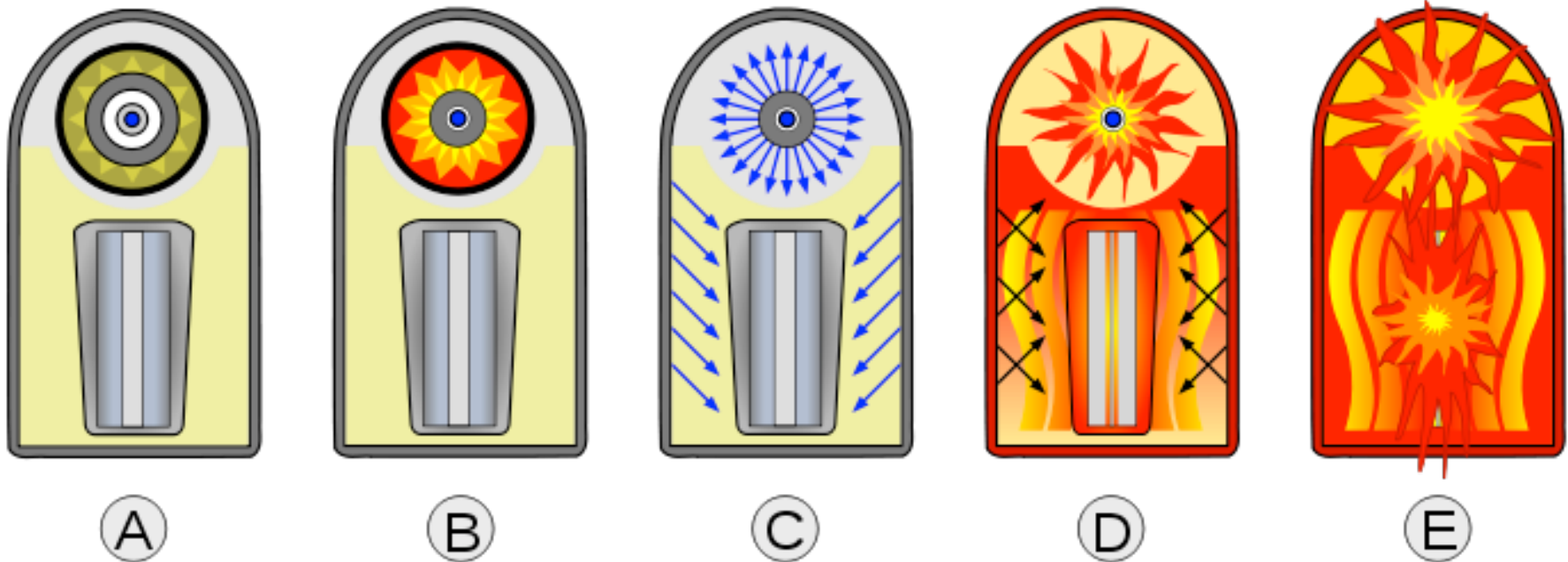
# Two-Stage (Thermonuclear) Weapons – 2



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

# Two-Stage (Thermonuclear) Weapons – 3

Sequence of events —



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

# Two-Stage (Thermonuclear) Weapons – 4

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- Modern thermonuclear weapons have two stages:
  - the primary (mostly fission)
  - the secondary (fusion+fission)

Fissions during the second stage are produced by high-energy neutrons from the fusion reactions and greatly increase the yield (“fission-boosted fusion”)

- The secondaries of deliverable bombs use  ${}^6\text{Li-D}$  to make T+D
- Burning grows quickly, but not geometrically (exponentially):  
the fusion burn is not a chain reaction

# Two-Stage (Thermonuclear) Weapons – 5

---

- X-rays from the 'primary' compress and heat the 'secondary', causing thermonuclear fusion of T + D
  - Radiation pressure is not important
  - Ablation (blow off) of surface material is the dominant heating and compressive effect
- There 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 – (Tsar test, October 30<sup>th</sup> 1960)
  - The U.S. concluded that this particular design was capable of releasing 100 Mt

# Two-Stage (Thermonuclear) Weapons – 6

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- Making a 50 Mt device makes no military/economic sense. Historic example served propaganda purposes.
- U.S. developed and fielded H-bombs with yields up to 9 Mt
- As ballistic missile accuracies improved, the maximum yield of deployed US weapons dropped to 1 Mt or less, allowing an increase in the area of death and destruction (explained later)
- All the States that developed fission bombs and sought to develop true thermonuclear bombs succeeded in doing so

# Two-Stage (Thermonuclear) Weapons – 7

---

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

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

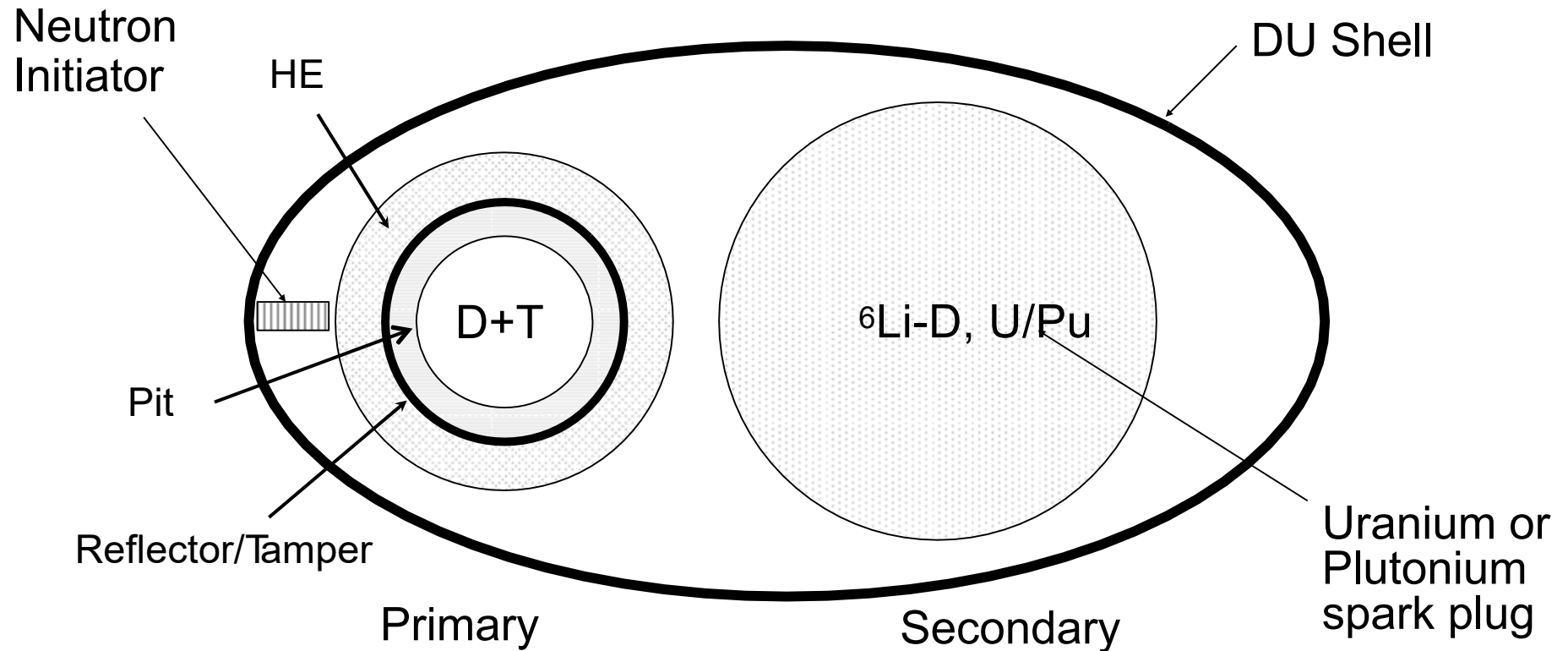


# Balance of Energy Release from Two-Stage Nuclear Weapons - 8

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- 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

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



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

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

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## Fission trigger —

- HE lenses + tamper + fissile core

## Fusion fuel packet —

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

## Uranium components —

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

# Lecture Question

---

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

- A) Under pressure and heat the Li nucleus fuses with the nucleus of the Deuterium, a Deuteron
- B)  ${}^6\text{Li}$  captures a neutron and splits into a Triton and a He nucleus. The Triton is the Tritium nucleus and fuses with a Deuteron.
- C) Under pressure and heat the Deuteron captures a neutron forming a Triton. The Triton fuses with a Deuteron.

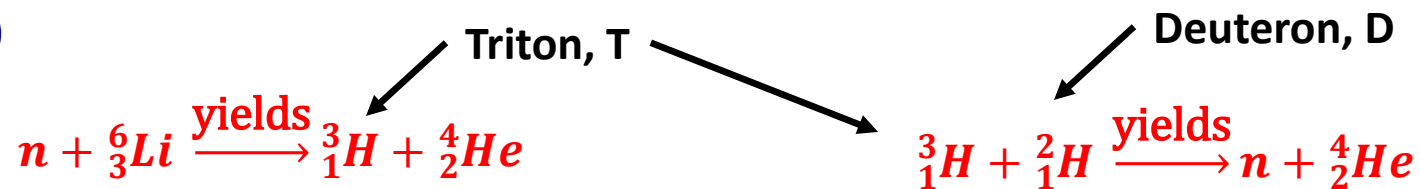
# Lecture Question Answer

---

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- C) Under pressure and heat the Deuteron captures a neutron forming a Triton. The Triton fuses with a Deuteron.

${}^6\text{LiD}$



(I) preparation of fusion fuel

(II) fusion reaction

# Another Example for Important Reactions with Light Nuclides : Initiators

---

Example of a simple initiator —

- Mixture of Polonium (Po) and Lithium (Li)
  - Polonium has several radioactive isotopes
    - Po-218  $\rightarrow$  Pb-214 +  $\alpha$
    - Po-216  $\rightarrow$  Pb-212 +  $\alpha$
    - Po-210  $\rightarrow$  Pb-206 +  $\alpha$
  - 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

# Technologies Needed for “Weaponizing” a Nuclear Device

---

Technologies needed to make a nuclear *weapon* —

- Technology to produce nuclear-explosive material (NEM)
- 

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

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

# Additional Materials and Knowledge Needed to Make a Two-Stage Nuclear Weapon

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- The basic materials required for the 'secondary' (Li-6 and D) are widely available
- The geometry of the 'secondary' is not critical
- Compression and ignition of the 'secondary' is described by *radiation-hydrodynamics* —
  - Electromagnetic radiation moves at the speed of light
  - A uniform distribution of radiant energy is quickly achieved
  - All the matter behaves as a fluid at the high temperatures and pressures involved and hence is described by hydrodynamics
  - Large, fast computers are required to simulate the explosion accurately



# B-61 Bomb

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

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## Physics and Engineering Requirements

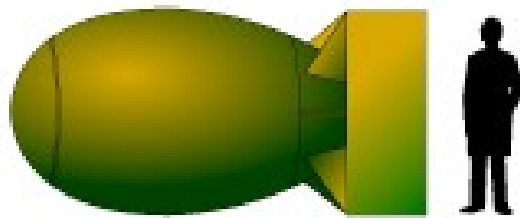
The physics package, fusing, and re-entry shroud must be —

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

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

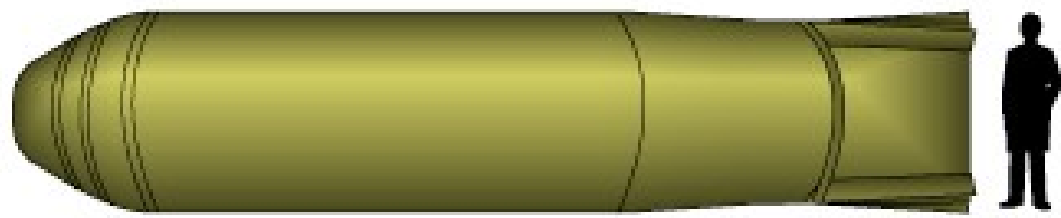
## Miniaturizing Massive Death and Destruction

### FIRST FISSION BOMBS



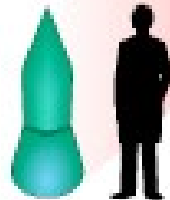
MK IV (Fat Man), 20kt (1945)

### FIRST FUSION BOMBS

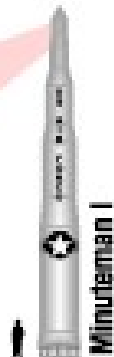


MK-17 (Bravo), 15Mt (1955)

### SINGLE WARHEAD DEVELOPMENT



W-59, 1Mt (1962)

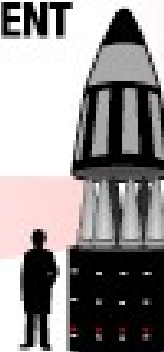


Minuteman I

### MULTIPLE INDEPENDENT RE-ENTRY VEHICLE (MIRV) DEVELOPMENT



W-87, 475kt (1986)



Peacekeeper MX

# Lecture Question

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

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

# Lecture Question Answer

---

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# Lecture Question

---

What is the biggest technology challenge in making nuclear weapons?

- A) **Critical assembly and related technologies (eg. high speed explosives)**
- B) **Ballistic missile technology**
- C) **Production of NEM**
- D) **Super computer technology for simulations of nuclear explosions and ballistic missile flight**
- E) **Production of fusion fuel**

# Lecture Question Answer

---

What is the biggest technology challenge in making nuclear weapons?

- A) Critical assembly and related technologies (eg. high speed explosives)
- B) Ballistic missile technology
- C) Production of NEM**
- D) Super computer technology for simulations of nuclear explosions and ballistic missile flight
- E) Production of fusion fuel

# Production of Nuclear Explosive Material

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***Enrichment*** of U-235

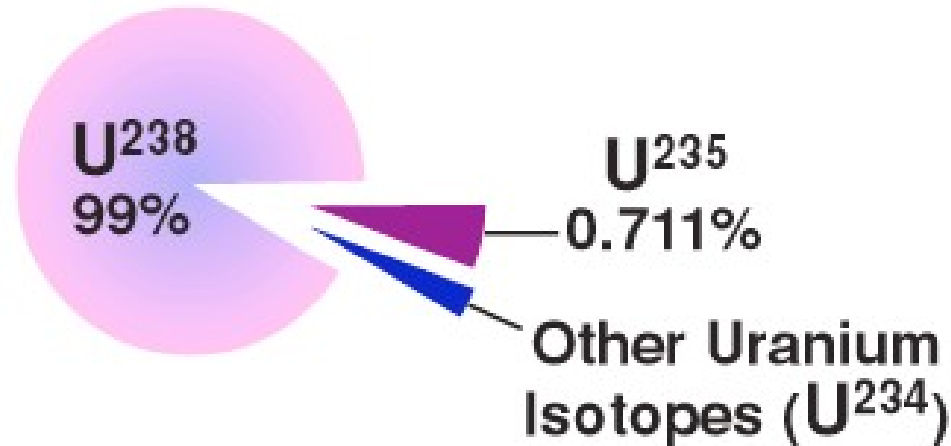
***Creation*** and ***Separation*** of Pu-239



# Enrichment of Uranium Is Required to Make a Nuclear Bomb

---

- Natural uranium is
  - 99.3% U-238 (which is fissionable but not fissile)
  - 0.7% U-235 (which is fissile)



# Enrichment of Uranium Is Required to Make a Nuclear Bomb

---

- Natural uranium must be *enriched* in U-235 to make a nuclear explosion (but not for use in some nuclear reactors).
- A nuclear explosion can be produced by uranium enriched to 20% or more U-235. Such uranium is called “weapons-usable”.
- Uranium enriched to more than 80% U-235 is called “weapons-grade”.
- Uranium enriched to more than 90% U-235 is preferred for nuclear weapons.

# Enriching Uranium – Overview

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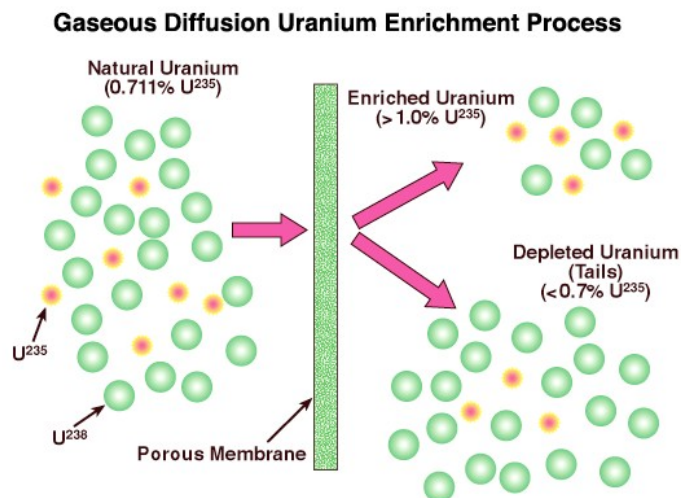
There are 4 main uranium enrichment techniques:

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

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

# Enriching Uranium – Details 1

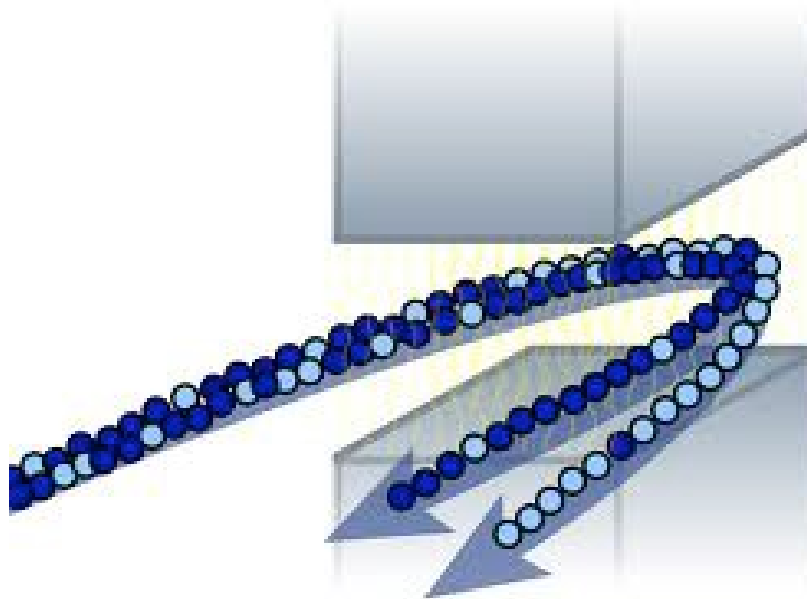
- Gaseous diffusion isotope separation
  - Developed at Oak Ridge National Laboratory, TN during WW II Manhattan Project
  - Uses high pressures to drive diffusion of uranium hexafluoride ( $\text{UF}_6$ ) gas through semi-permeable membranes
  - Thousands of stages are required: the enrichment factor in a single stage is typically  $\sim 1.004$



# Enriching Uranium – Details 2

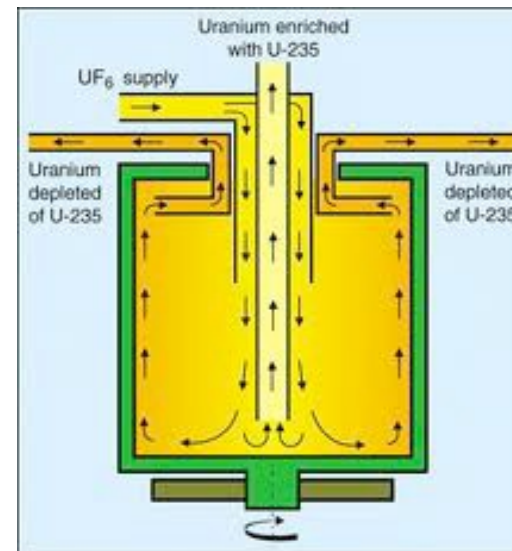
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- Electromagnetic isotope separation
  - Calutrons (California cyclotrons)
  - Manhattan Project
  - Basically a high-throughput mass spectrometer that sorts atoms by their charge to mass ratios ( $q/m$ ); 2–3 stages are adequate



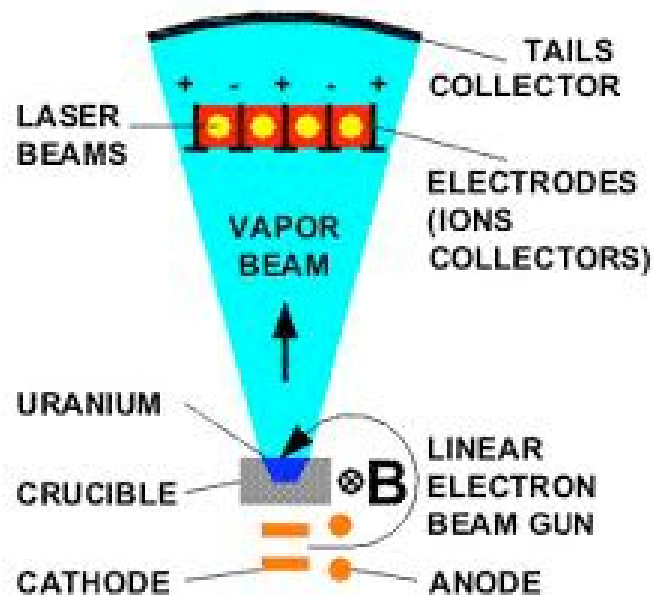
# Enriching Uranium – Details 3

- Gas centrifuge isotope separation
  - Massive version of centrifuges used in science and medicine
  - Feed stock is uranium hexafluoride ( $\text{UF}_6$ ) gas
  - Compact, easy to hide, and energy efficient; 40-90 stages
  - Requires high strength materials (Al, Fe)
  - Has become bomb proliferators' technology of choice



# Enriching Uranium – Details 4

- Molecular laser isotope separation
  - High-tech and compact (only 1 to 3 stages required)
  - Based on (very small) differences of molecular energy levels of  $\text{UF}_6$  for U-238 vs. U-235
  - End of Cold War and nuclear reactor industry initially killed the market for this technology but it is now being revived
  - Even more of a proliferation danger than gas centrifuges



# Plutonium Is Created in Nuclear Reactors

---

The fissile nuclide Pu-239 can be created by bombarding U-238 with neutrons in a nuclear reactor —

- U-238 + n → Pu-239 (via a two-step process)  
(non-fissile) (fissile)



N Reactor, Hanford, WA



Reactor, Yongbyon, NK



# Plutonium Must Then Be Chemically Separated from Uranium and Other Elements



224-B Plutonium Separation Plant, Hanford, WA, 1985



Plutonium Separation Plant Rawalpindi, Pakistan, Feb 2002

Plutonium is extracted from the uranium fuel rods by first dissolving the rods to form a slurry and then extracting the trace amounts of plutonium in the slurry by chemically processing the slurry.

# Producing a Nuclear Explosion Using Plutonium – 1

---

- **Virtually any combination of plutonium isotopes can be used to make a nuclear weapon.**
- Not all combinations, however, are equally convenient or efficient.
- Pu-239 is produced when the most common isotope of uranium, U-238, absorbs a neutron and then quickly decays to plutonium.
- Pu-239 is the most useful isotope for making nuclear bombs. It is produced in varying quantities in virtually all operating nuclear reactors.

# Producing a Nuclear Explosion Using Plutonium – 2

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- As fuel in a nuclear reactor is exposed to longer and longer periods of neutron irradiation, heavier isotopes of plutonium build up, as some of the plutonium absorbs additional neutrons, creating Pu-240, Pu-241, and so on.
- Pu-238 also builds up from a chain of neutron absorptions and radioactive decays starting from U-235.
- Plutonium with substantial quantities of Pu-238, Pu-240, Pu-241, Pu-242 is called “high burn-up” or “reactor-grade” plutonium.
- High burn-up plutonium can approach ~ 40% Pu-239, ~ 30% Pu-240, ~ 15% Pu-241, and ~ 15% Pu-242.

# Producing a Nuclear Explosion Using Plutonium – 3

---

**Producing a nuclear explosion is much easier if the plutonium is “weapon-grade” (defined as more than 93% Pu-239).**

Producing a nuclear explosion is more difficult using reactor-grade plutonium —

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

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

# Producing a Nuclear Explosion Using Plutonium – 4

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- Because of the preference for relatively pure Pu-239 for making bombs, **when a reactor is used specifically for creating weapons plutonium, the fuel rods are removed and the plutonium is separated from them after a relatively brief period of irradiation.** The resulting “low burn-up” plutonium has a higher concentration of Pu-239.
- However, brief irradiation is very inefficient for power production. Hence, **in power reactors the fuel is left in the reactor much longer, producing “high burn-up” (“reactor grade”) plutonium, which is less suitable for bombs.**

# A Nuclear Explosion Can Be Produced Using Reactor-Grade Plutonium – 1

---

Use of reactor-grade plutonium complicates bomb design for several reasons. One of the most important is that Pu-240 has a high rate of spontaneous fission and therefore will continually produce many background neutrons.

- In a well-designed nuclear explosive using weapons-grade plutonium, a pulse of neutrons is released to start the chain reaction at the optimal moment, but there is some chance that a background neutron from spontaneous fission of Pu-240 will set off the reaction prematurely. This is called "pre-initiation".
- With reactor-grade plutonium, the probability of pre-initiation is very large. Pre-initiation can substantially reduce the explosive yield, since the weapon may blow itself apart earlier, cutting short the chain reaction that releases energy.



# A Nuclear Explosion Can Be Produced Using Reactor-Grade Plutonium – 2

---

- However, calculations demonstrate that ***even if pre-initiation occurs at the worst possible moment*** (when the material first becomes compressed enough to sustain a chain reaction), ***the explosive yield of even a relatively simple device similar to the Nagasaki bomb would likely be about 1—3 kilotons.***
- While this yield is referred to as the "fizzle yield", a 1-kiloton bomb would still have a radius of destruction roughly one-third that of the Hiroshima weapon, making it a horrendous weapon.
- Regardless of how high the concentration of troublesome isotopes is, the yield would not be less than this. With a more sophisticated design, weapons could be built with reactor-grade plutonium that would be assured of having higher yields.

# A Nuclear Explosion Can Be Produced Using Reactor-Grade Plutonium – 3

---

*In short, it would be quite possible for a potential proliferator to make a nuclear explosive from reactor-grade plutonium using a simple design that would be assured of having a yield in the range of one to a few kilotons, or more if a more advanced design were used.*

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



# Categories of Nuclear Explosive Materials (Very Important)

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- Uranium —
  - LEU:  $< 20\%$  U-235
  - Weapons-usable HEU:  $> 20\%$  U-235
  - Weapons-grade HEU:  $> 80\%$  U-235
- Plutonium —
  - Reactor-grade:  $< 80\%$  Pu-239 (e.g., light-water )
  - Fuel-grade:  $80\%$  to  $93\%$  Pu-239
  - Weapons-grade:  $> 93\%$  Pu-239

# Nuclear Weapon Design

---

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

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