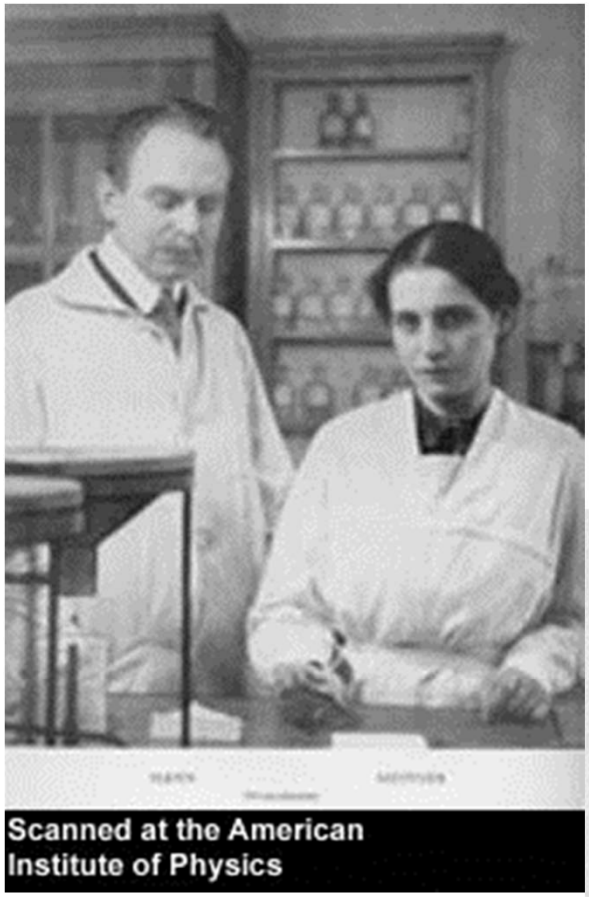
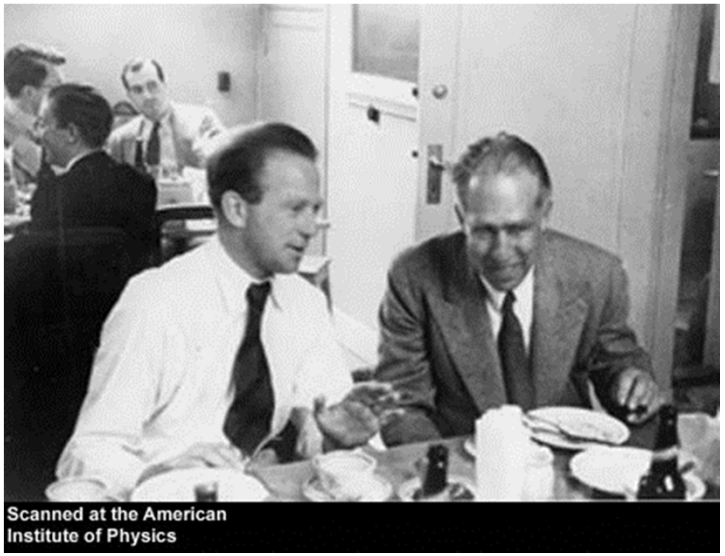
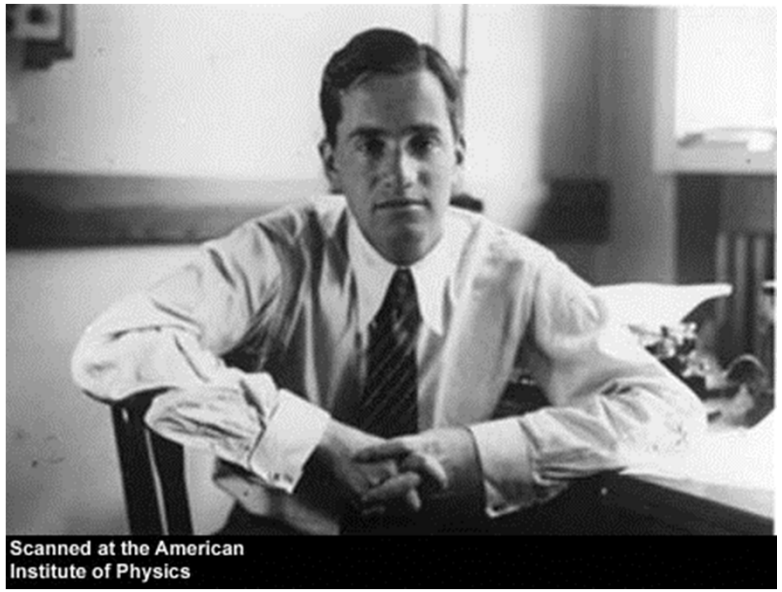
The Discovery of Fission







Overview

- **Where are we?**
  - By 1930, we have arrived at a new space-time description of physical events (relativity) and a new description of the interactions in nature (quantum mechanics).
  - Next step: combine the results of these two 20th century revolutions into a single theory which describes the interactions of the fundamental building blocks of nature.
- **Timeline:**
  - By 1930
    - There is an understanding of atomic behavior in terms of quantum mechanics.
    - There were a series of observations regarding atomic structure and radioactivity.
    - There was still not a fundamental understanding of radioactivity or the nucleus.

Pierre and Marie Curie

- Began work on the new radioactivity.
- Discovered Radium and Polonium.
- Marie is the only person to win two Nobel Prizes in two different scientific fields.

Frederic and Irene Joliot-Curie

- Discovered Artificial Radioactivity.
- Missed fission.

$$^{27}Al + {}^{4}\alpha \rightarrow {}^{30}P + {}^{1}n$$

Enrico Fermi

- Bombarded almost every element in the Periodic Table with neutrons.
- Also missed fission.
- Defected to the US when he accepted the Nobel Prize.

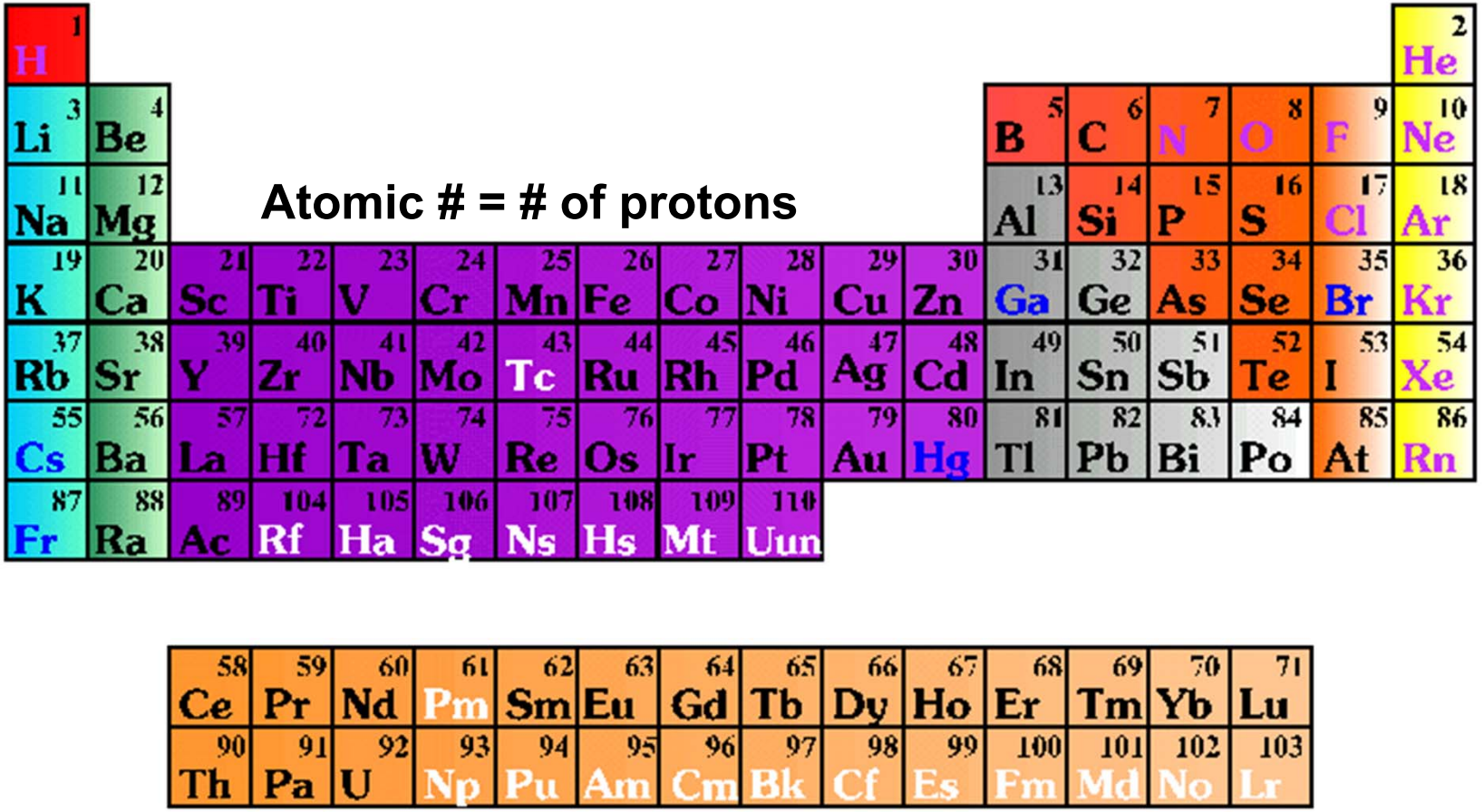
Lise Meitner, Otto Hahn, Fritz Strassman

- Meitner and Hahn and had worked together for several years on various aspects of radioactivity.
  - They also were bombarding uranium with neutrons trying to make transuranic elements.
- Meitner was Jewish and fled Germany in 1938.
  - She first went to Holland, then to Copenhagen where Niels Bohr worked, and ultimately to Sweden.
- Meitner and Hahn were in daily contact through the mail and continued to collaborate.

- **In one experiment, Hahn and Strassman were trying to isolate a new element they thought would be similar to barium by trying to co-precipitate the new element with barium carbonate.**
  - **At the end of a paper they stated that the element appeared to be barium.**
  - **The paper was picked up on Dec. 22, 1938 by Paul Rosbaud and published Jan. 6, 1939.**

Uranium to Barium?

- Expected: $^{238}U \rightarrow {}^{230}Ra + 2\alpha$
- Observed: $^{238}U \rightarrow {}^{144}Ba + ?$ (36p, 58n unaccounted?)



Otto Frisch

- Lise Meitner's nephew who worked with Bohr.
- On Xmas Eve, 1938, he and Meitner figured out that Hahn and Strassman had split the uranium atom.
- They recognized the huge amount of energy that was released.
- Frisch told Bohr…

Fission

- **The "most" stable nucleus is iron**
  - ^{56}Fe = 26 protons, 30 neutrons
- **Nuclei heavier than iron will give up energy when split.**
  - Details depend upon mass and final state particles.

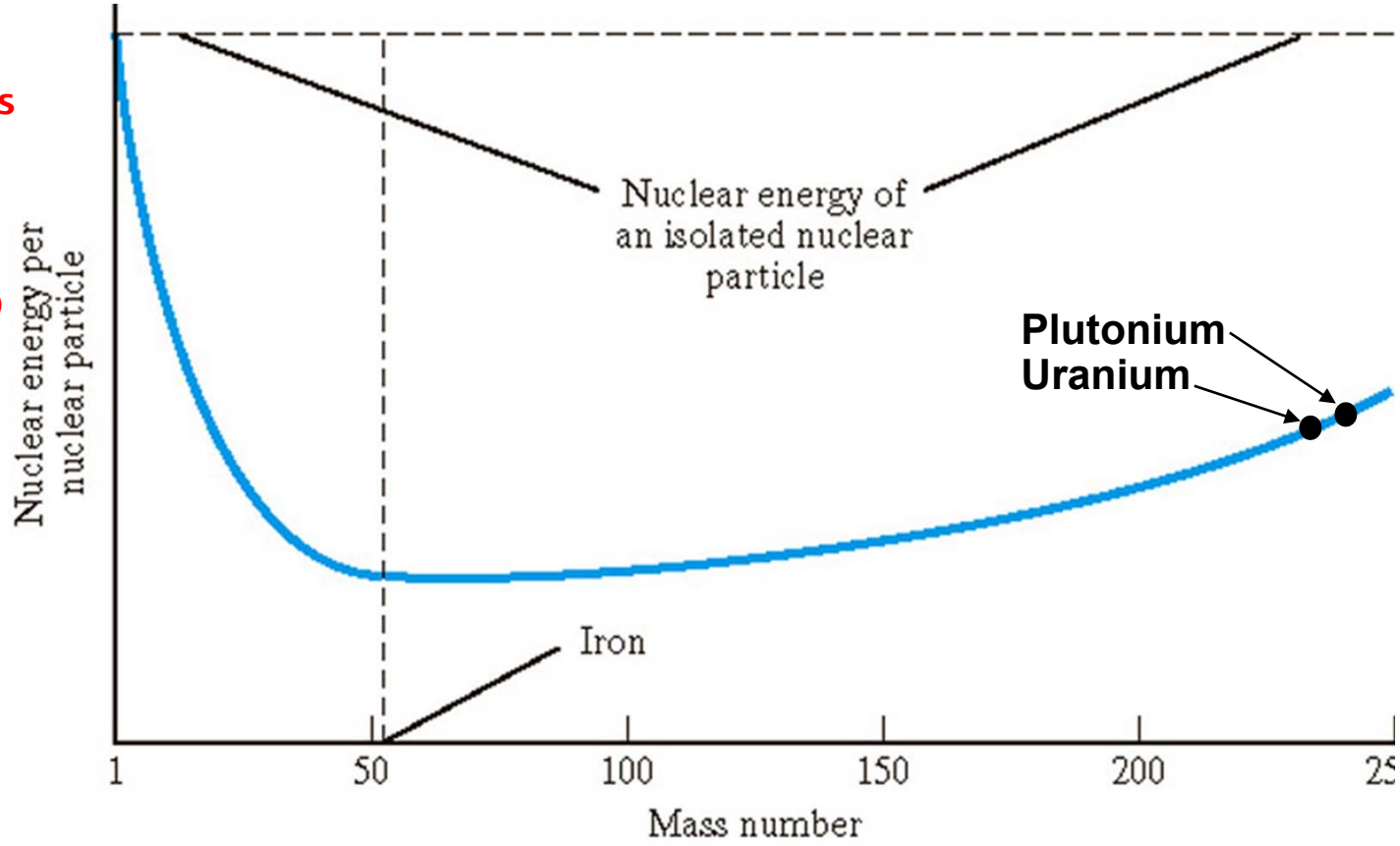
Energy difference is mass difference:

- $E=mc^2$

Example:

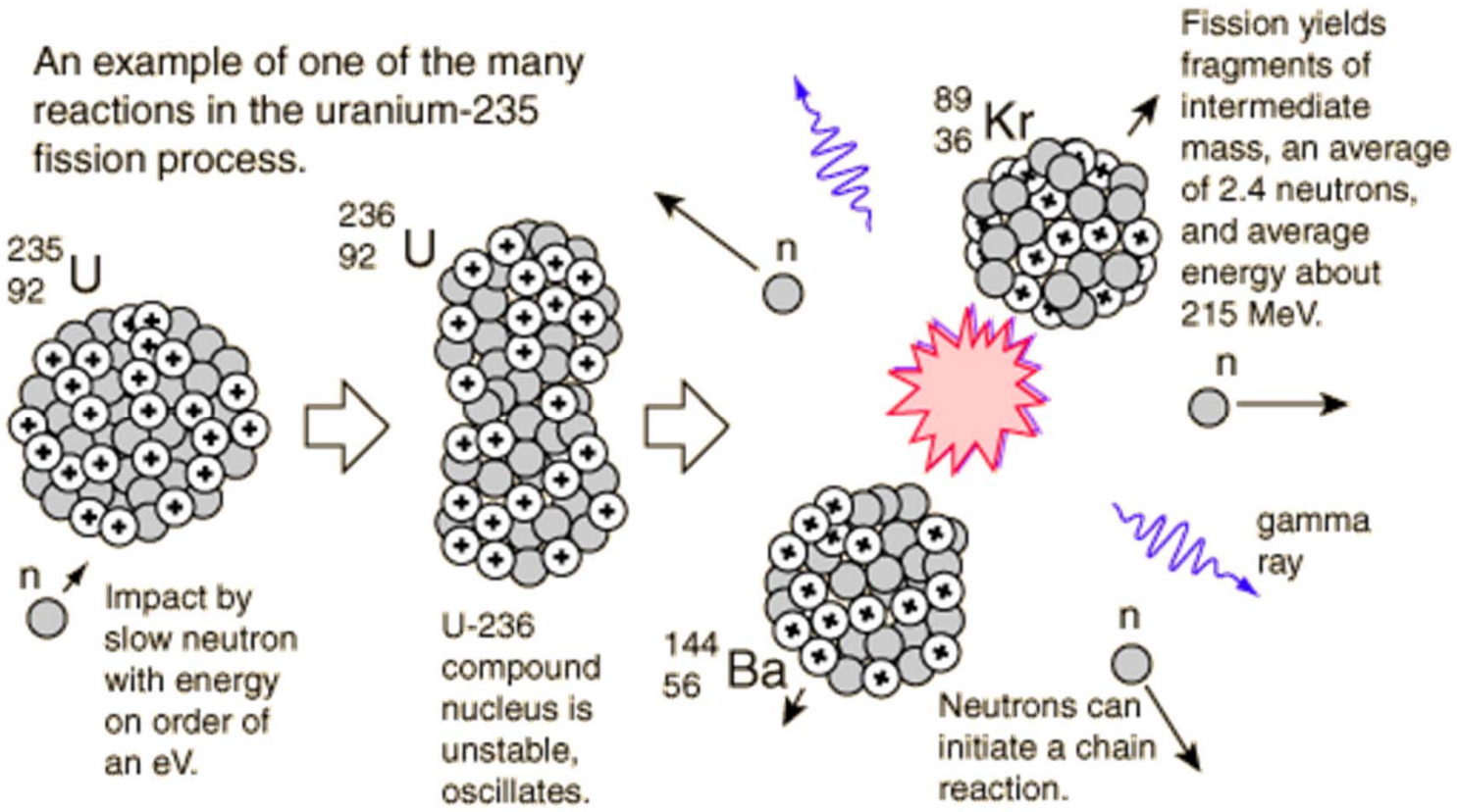
$m(^{56}Fe)+m(^{56}Fe)<m(^{112}Te)$

52 protons
60 neutrons
In both cases!



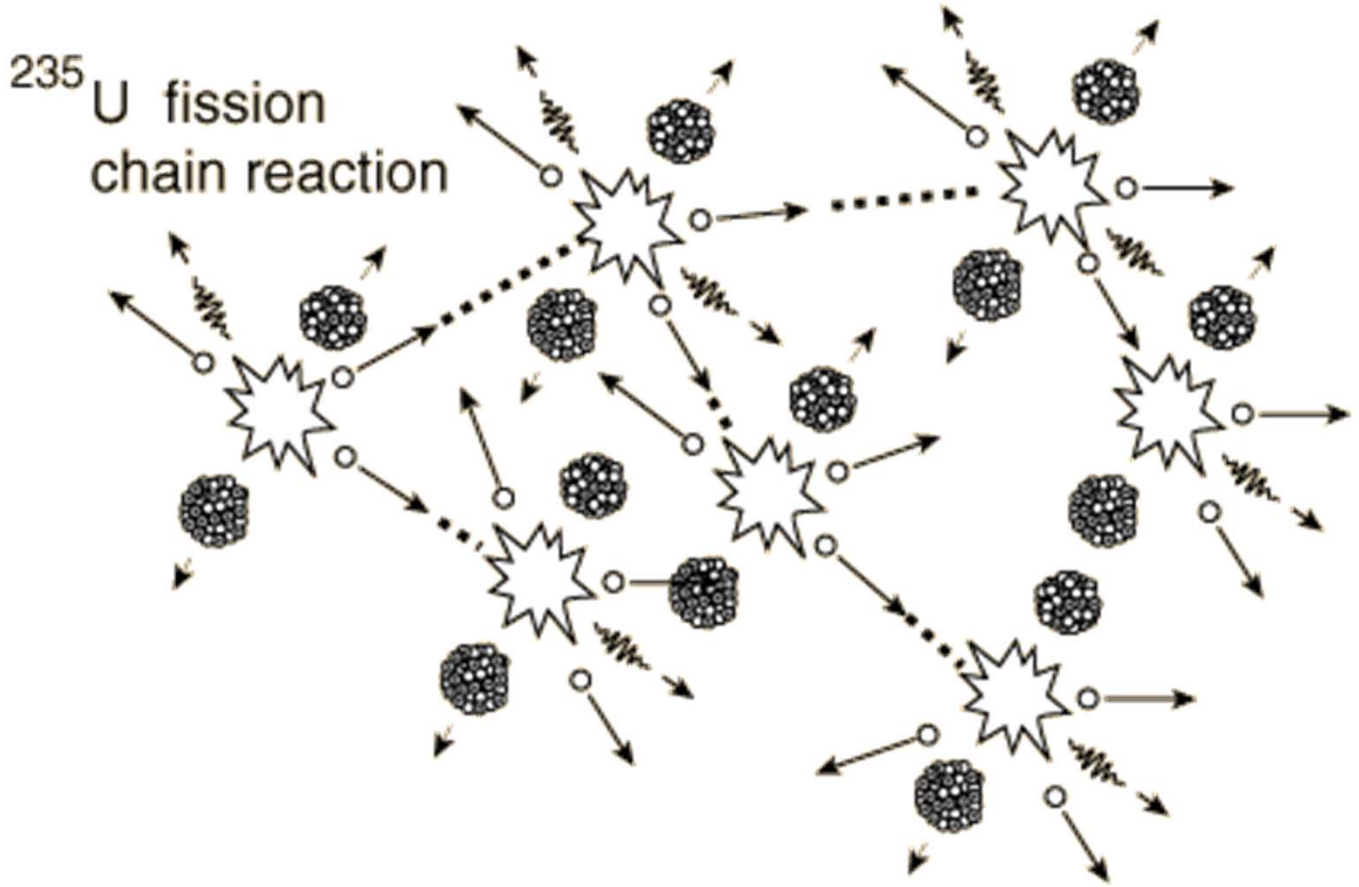
^{235}U Fission

- **Slow neutron hits ^{235}U nucleus**
  - **^{235}U splits into ^{89}Kr and ^{144}Ba**
  - **Also releases gamma rays (energy) and neutrons**



Chain Reaction

- **Neutrons from ^{235}U fission become trigger neutrons for additional fissions.**
  - **For ^{235}U, get enough neutrons per fission to sustain the chain reaction. This is why uranium and plutonium are desirable fission materials.**

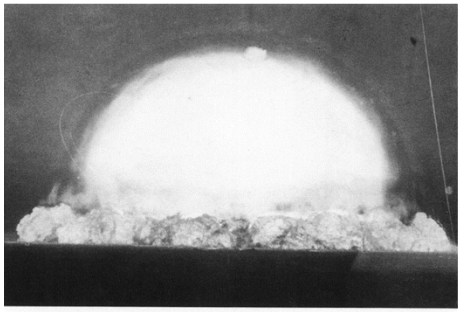


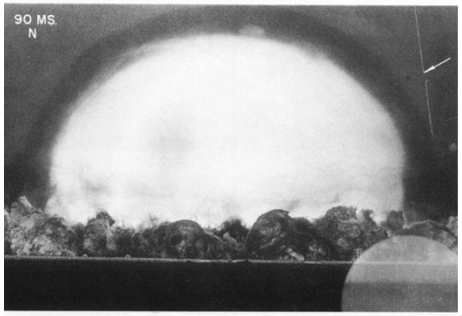
  - **Doesn't work as well for ^{238}U, which is the abundant isotope…**

Niels Bohr

- Brought news of fission to the US at the Fifth Washington Conference on Theoretical Physics.
- Several researchers went back to their labs and confirmed the work and reported back before the conference was over.

The Power of the Nucleus





Trinity 1945
20 kilotons

Enewetak 1952
10 megatons

Leo Szilard and Albert Einstein

- Szilard Composed a letter to Franklin Roosevelt.
- Einstein signed the letter dated Aug. 2, 1939.
- This letter leads ultimately to the Manhattan Project which began in 1942.

Glenn Seaborg

- Discovered plutonium at U.C. Berkeley, Feb. 23, 1941.
- ^{239}Pu also undergoes fission and is made from ^{238}U.

Plutonium Production

$$^{238}U + {}^{1}n \rightarrow {}^{239}U$$

$$^{239}U \rightarrow {}^{239}Np + \beta \qquad t_{1/2} = 23.5 \text{ min}$$

$$^{239}Np \rightarrow {}^{239}Pu + \beta \qquad t_{1/2} = 2.35 \text{ days}$$

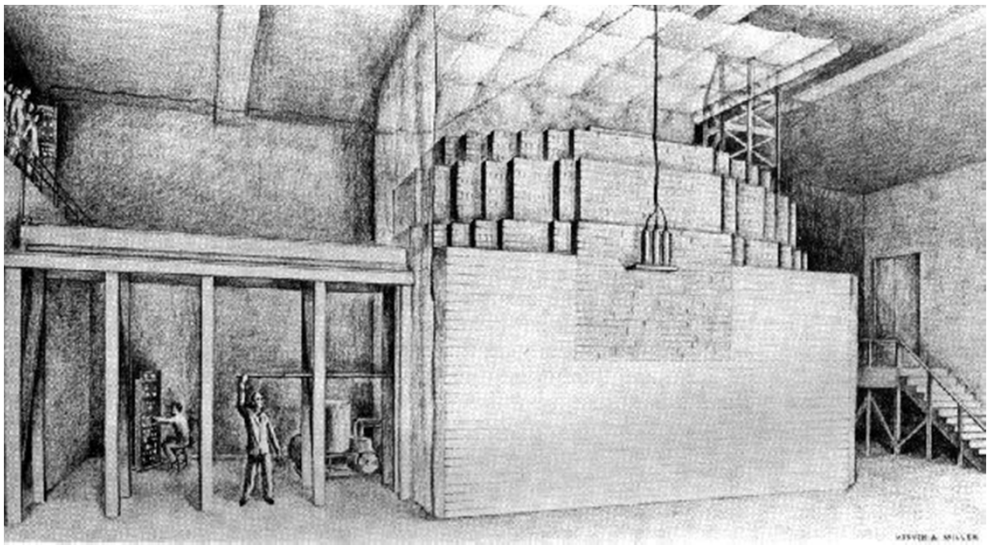
Some History

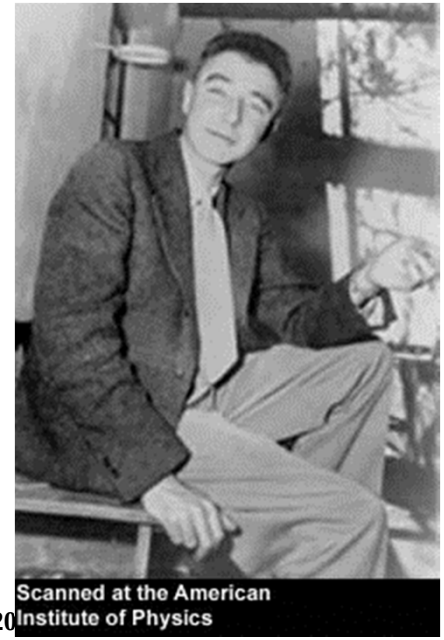
- **Late 1938**
  - Hahn and Strassman discover uranium fission
- **August 2, 1939**
  - Szilard and Wigner go to Einstein and ask him to write a letter to President Roosevelt telling him about the possibilities of uranium being used in a weapon.
  - Einstein's letter (written with Szilard) warns Roosevelt that the Germans are pursuing fissile uranium. link
- **September 1, 1939**
  - Germany invades Poland, World War II begins.
- **October 11, 1939**
  - Einstein's letter reaches Roosevelt
  - Roosevelt appoints a "Uranium Committee" with budget of $6k
- **December 6, 1941**
  - U.S. begins large scale atomic project (later to be named Manhattan Project)
- **December 7, 1941**
  - Pearl Harbor, U.S. enters World War II

Fission Chain Reaction

- **December 2, 1942**
  - Fermi creates the first chain reaction (controlled) in Chicago

- 80,590 lbs uranium oxide
- 12,400 lbs uranium
- 771,000 lbs graphite
- Cadmium rods used as moderator (absorb neutrons to control chain reaction)

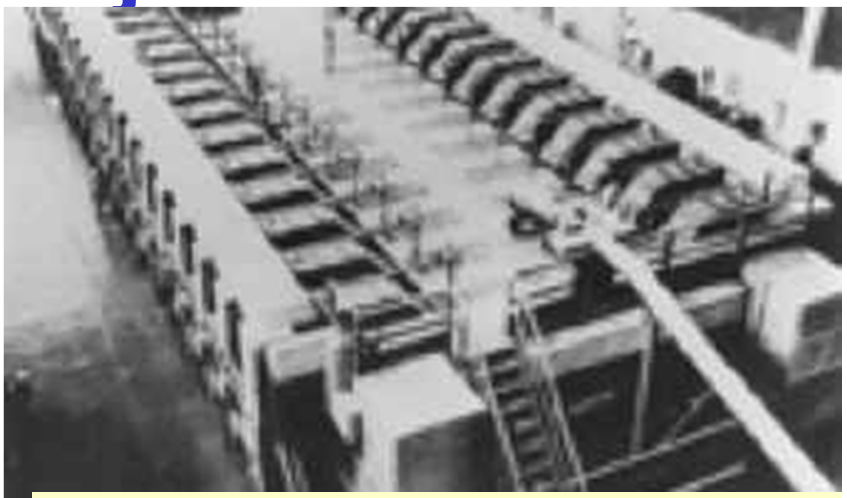




- **mid-1942**
  - Leslie Groves becomes head of Manhattan Project
  - Groves picks Oppenheimer as scientific director

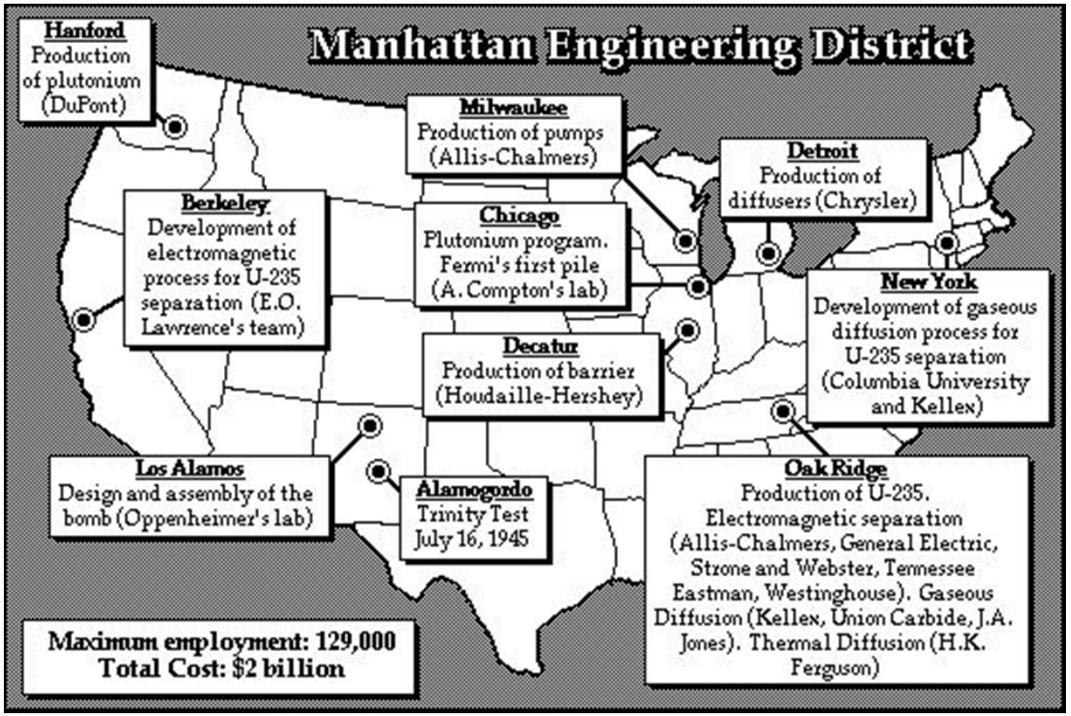
Manhattan Project

- Incredible 3-year undertaking
  - Cost ~$20B in 1996 dollars
- Many challenges
  - Uranium isotope separation
  - Plutonium production
- Many US scientists involved in Manhattan project or radar development



Y12 Calutron plant

K25 gaseous diffusion plant



Oak Ridge

X-10

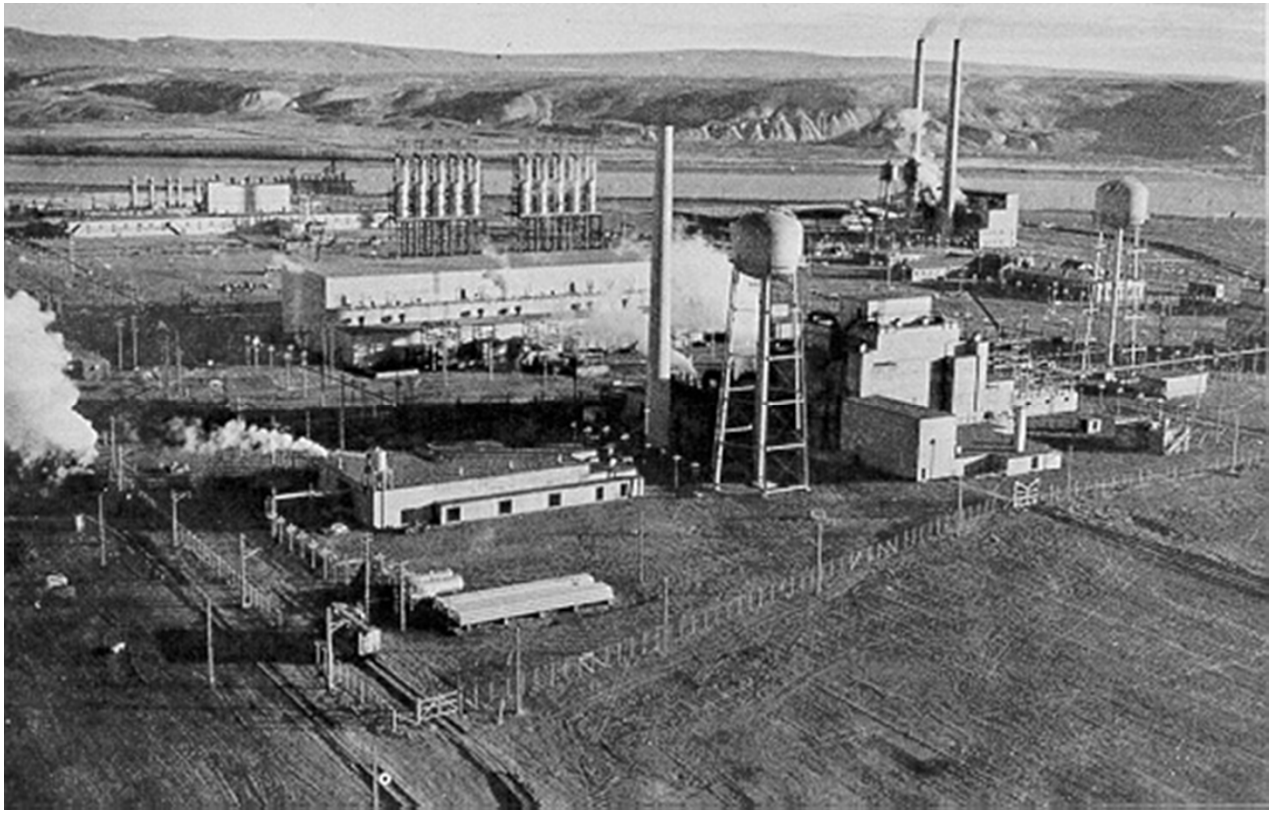
- Secret City on the Clinch River near Knoxville, Tennessee.
- Primary purpose was to enrich ^{235}U.
- Also built a graphite reactor at X-10 to study the production of plutonium.

Y-12

- Magnetic separation of ^{235}U from ^{238}U at Oak Ridge.
- The work was overseen by E. O. Lawrence from U. C. Berkeley.

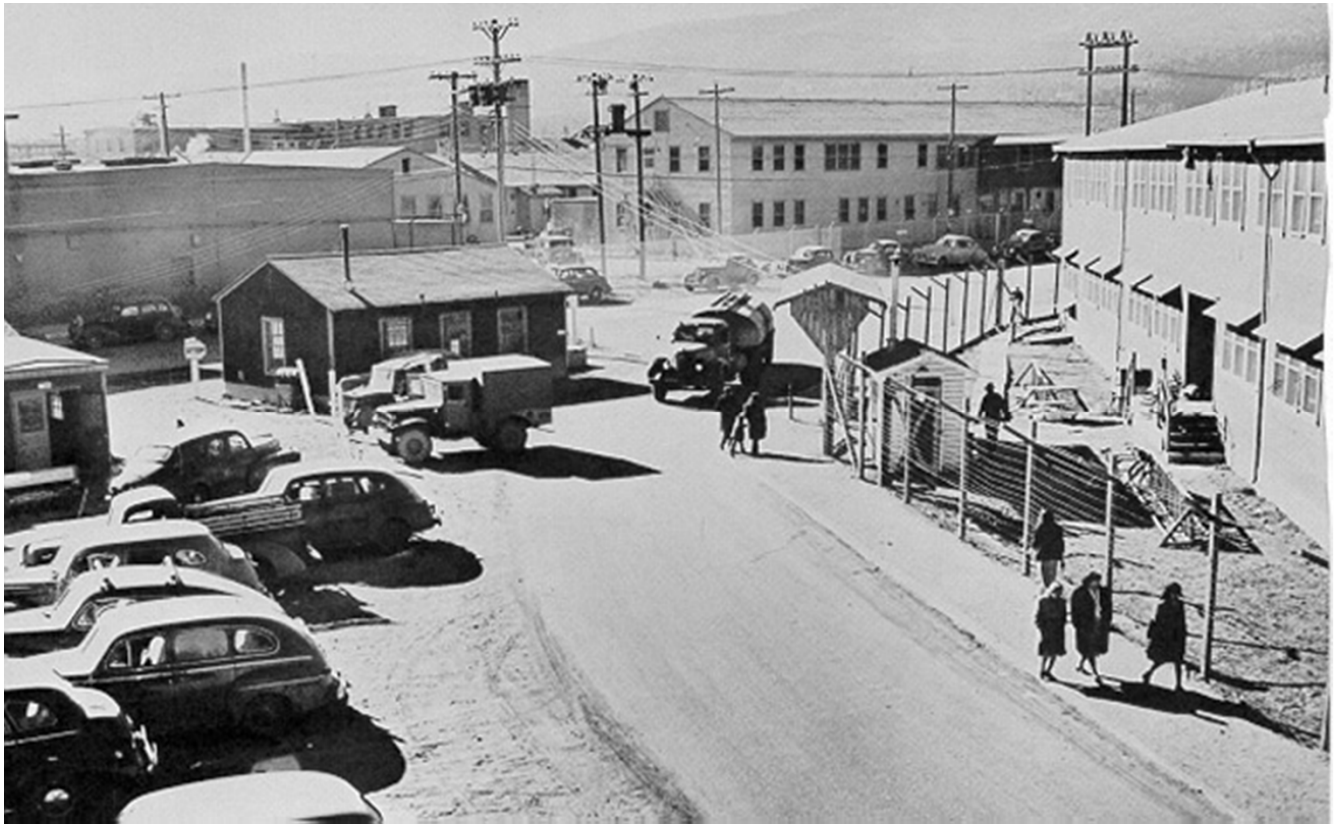
K-25

- Gaseous diffusion plant at Oak Ridge for enrichment of ^{235}U.
- Based on Graham's Law of Effusion and the oddity that UF_6 is a gas.



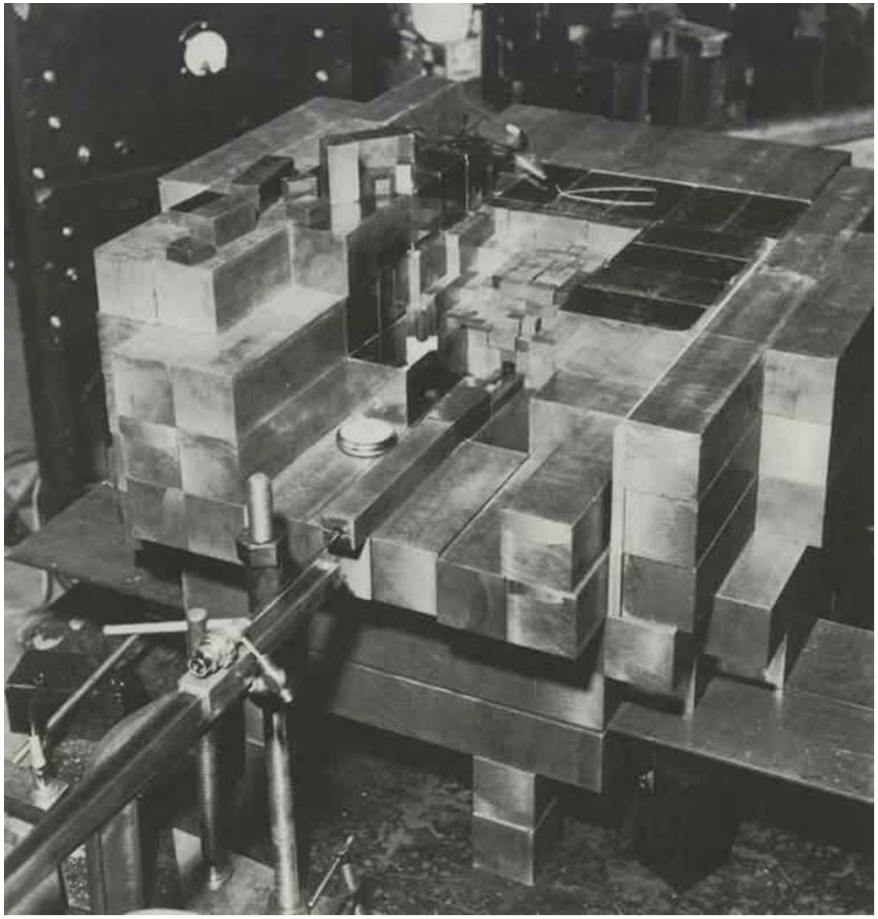
Hanford

- Secret City on the Columbia River in Washington State.
- A series of nuclear reactors designed to produce plutonium.
- A chemical plant to purify plutonium.



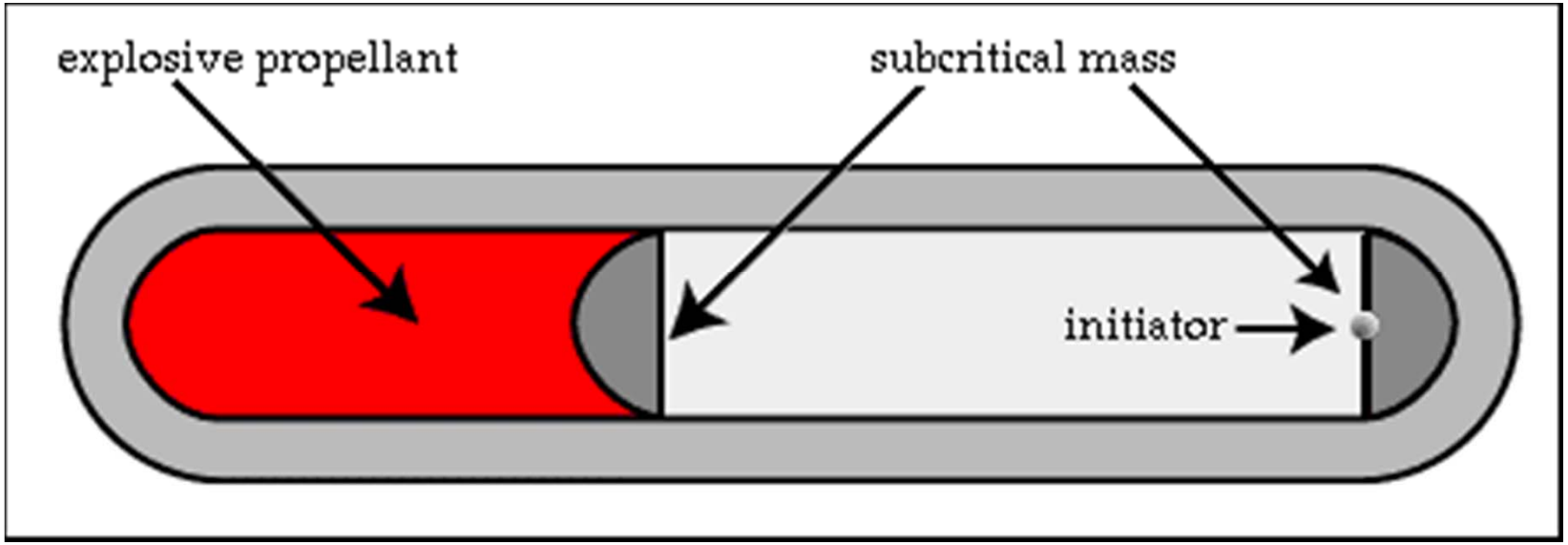
Los Alamos

- Secret City in the Sangre de Christo Mountains in New Mexico.
- The purpose was to design and build the bombs.



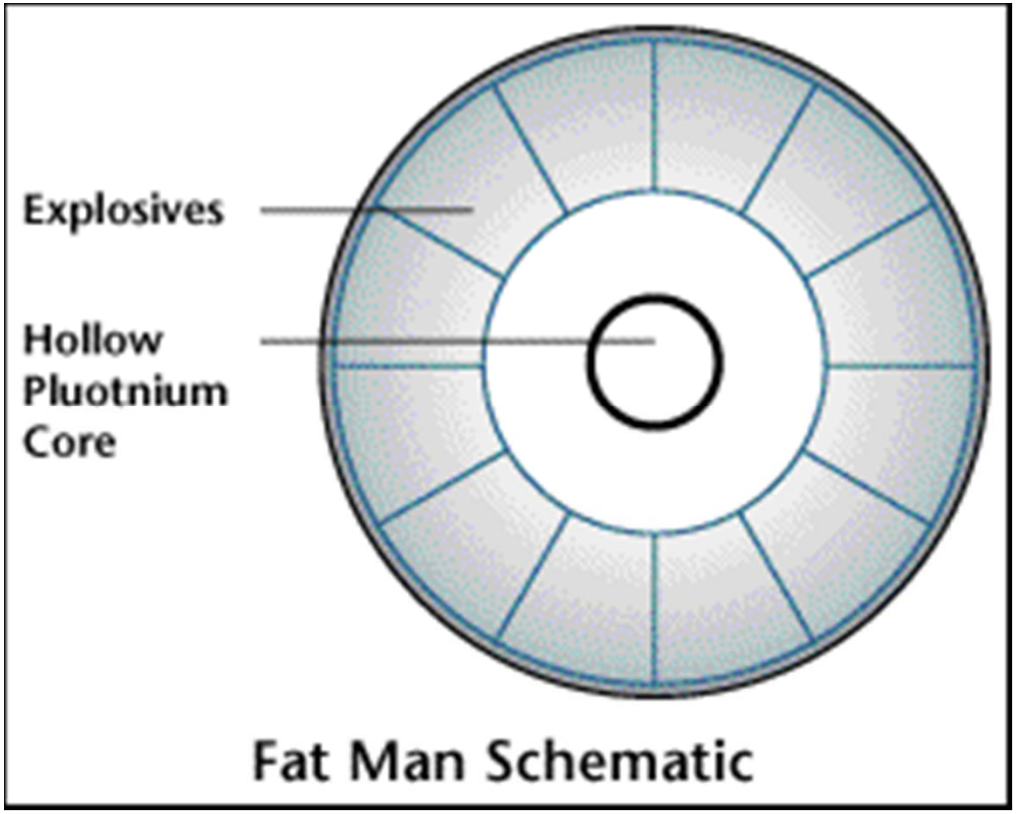
Tickling the Tail of the Dragon

- The exact size of the critical mass was determined by Otto Frisch at Los Alamos.



Gun Design

- This design worked with uranium.
- A 2000 lb TNT Blockbuster bomb was used as the “trigger”.



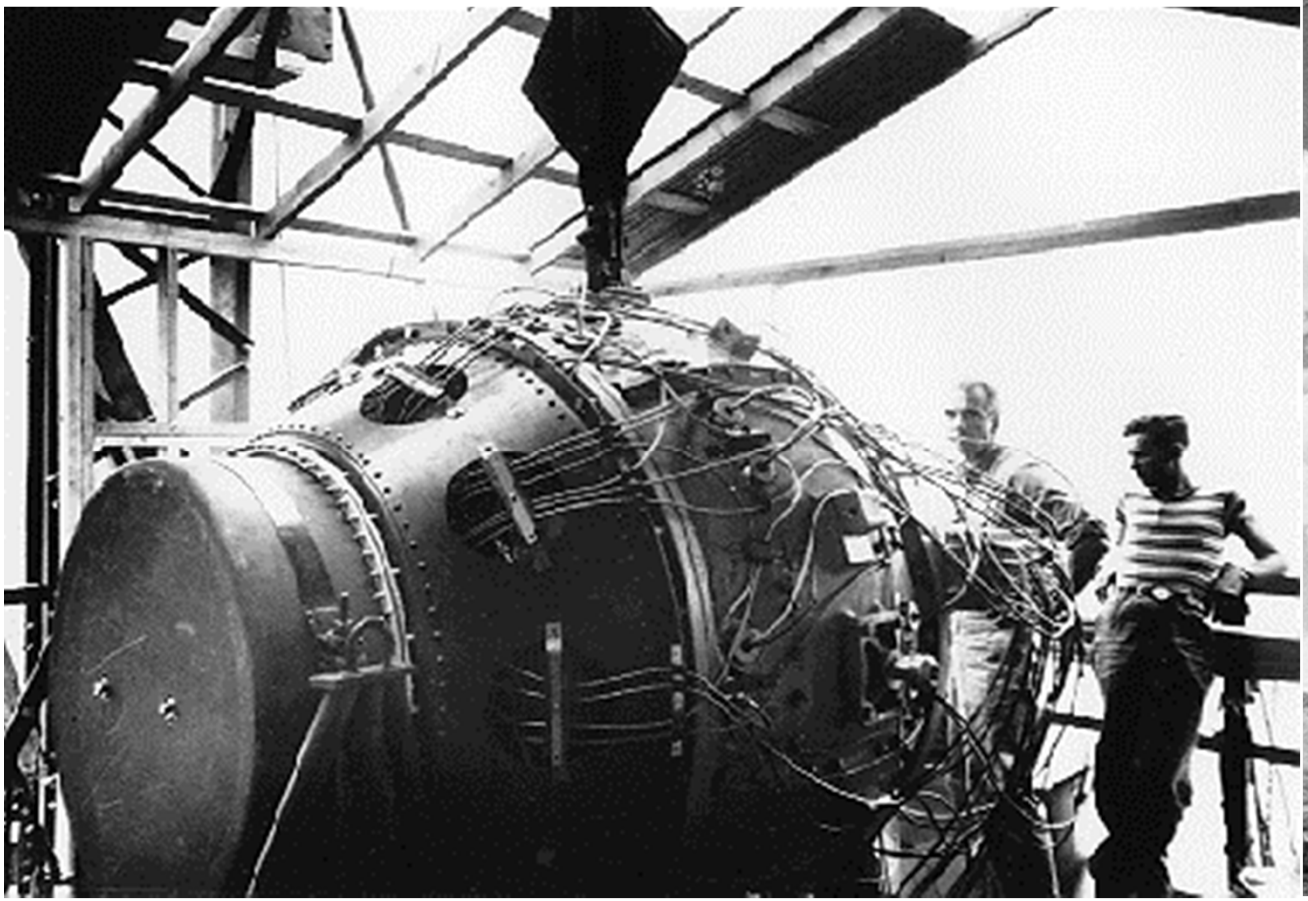
Implosion Design

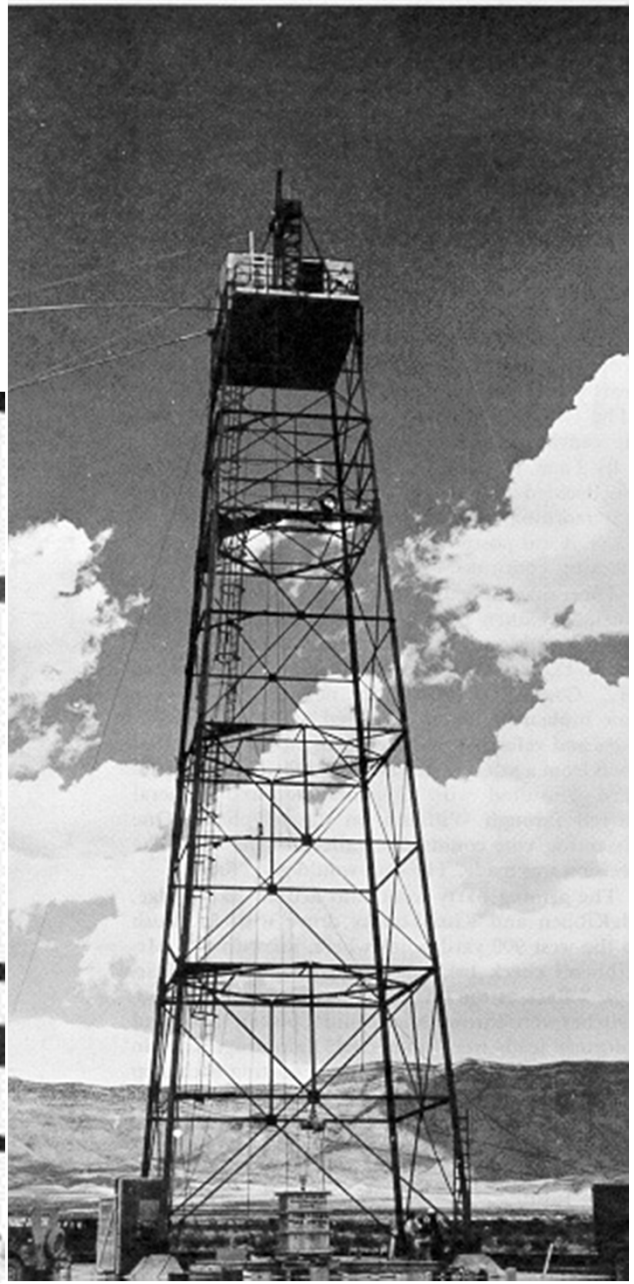
- This design was required for plutonium.
- Impurities of ^{240}Pu would release too many neutrons and cause premature detonation in the gun design. This would lower the yield.

Trinity Site

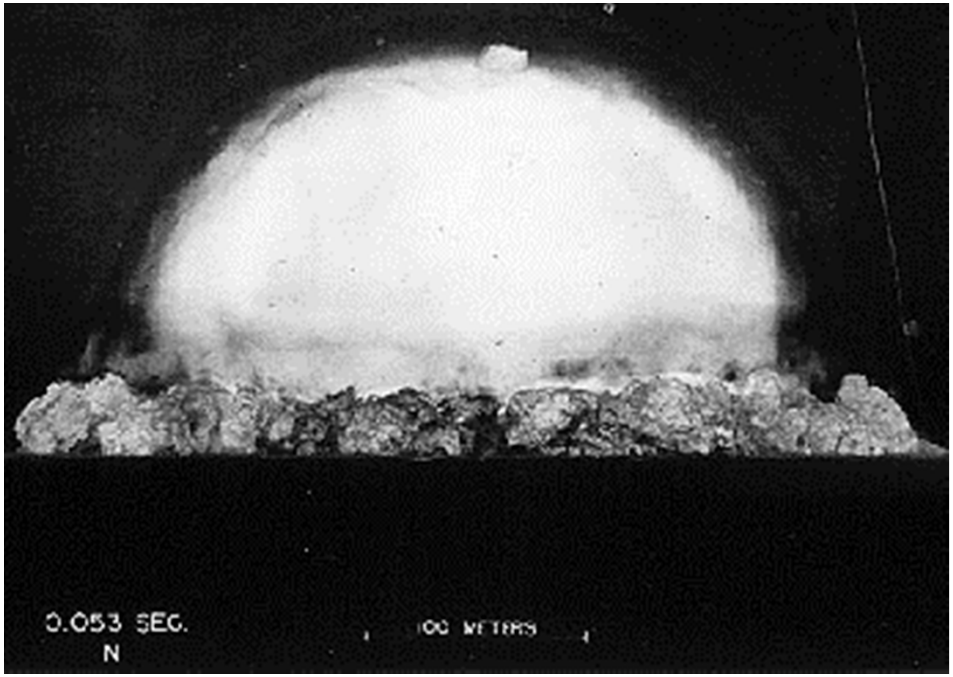
- The gun design was simple and the scientists did not feel that testing was necessary.
- The implosion device was much more complicated and needed to be tested.
- The chosen site was in the Jornado del Muerto Valley near Alamogordo New Mexico and code named Trinity.

Gadget





The Dawn of the Nuclear Age

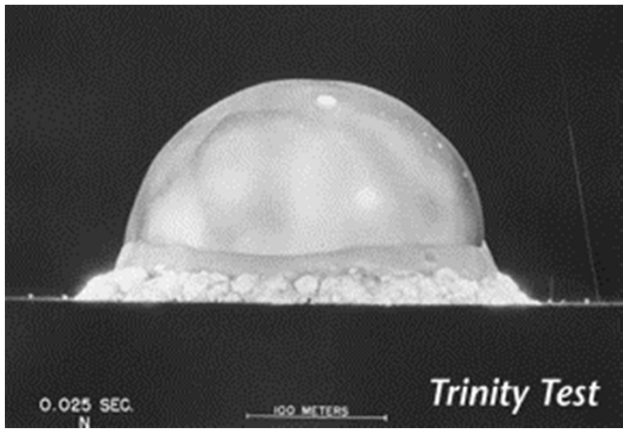


- The first nuclear explosion occurred at 5:29:45 am on July 16, 1945 at Trinity.

- Edward Teller described wearing double welders glasses and was not impressed until he removed his hands from around the glasses.
- Fermi was holding pieces of paper in his hand and waited for the shock wave to estimate the output. He later commented on missing both fission and the first nuclear explosion.

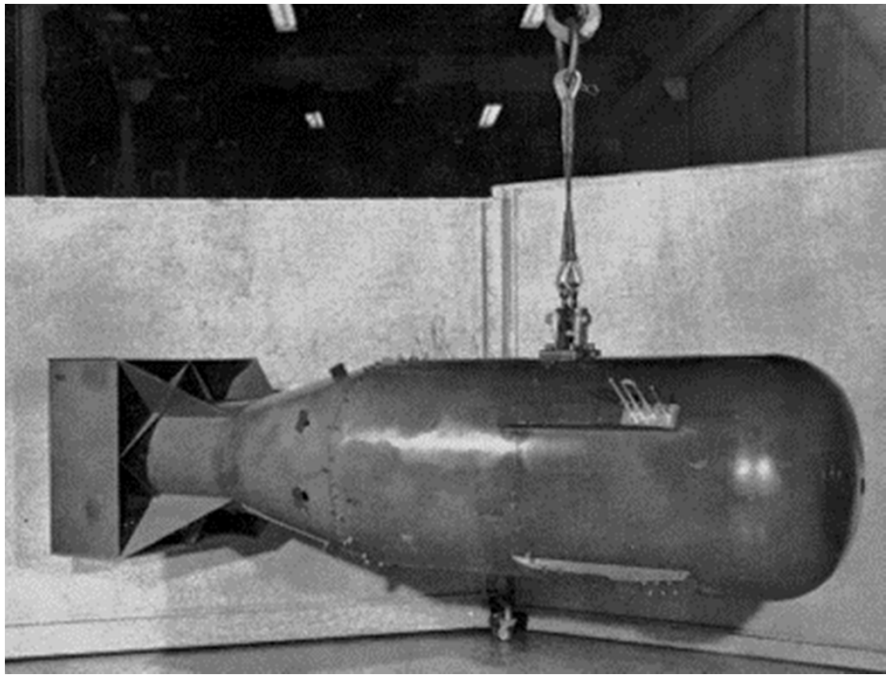
Fat Man and Little Boy

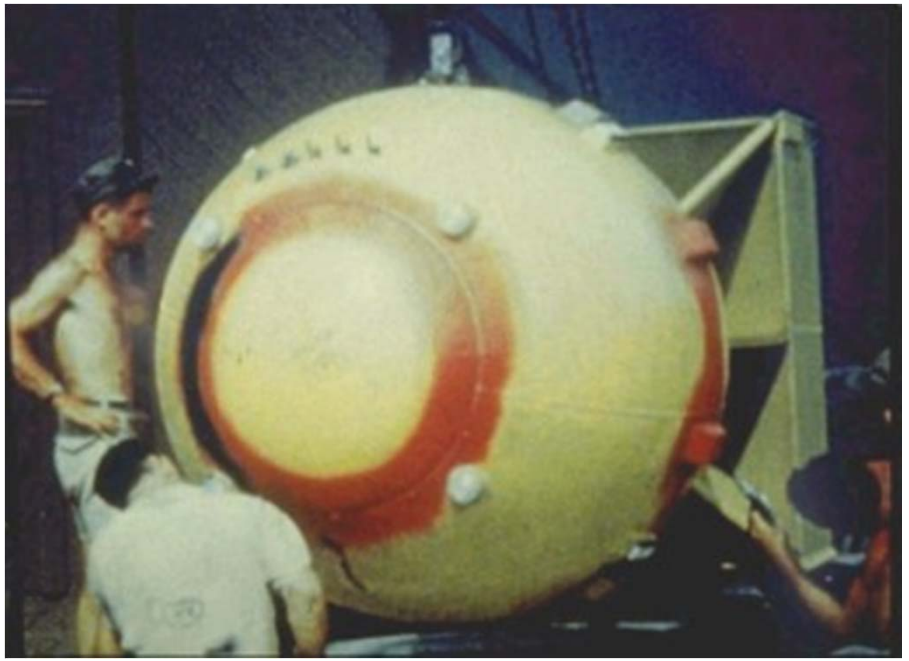
- May 8, 1945
  - Germany surrenders, their bomb program had not gotten far
- July 16, 1945
  - Trinity test, first atomic bomb ever detonated
  - Plutonium implosion device
  - ~20,000 tons of TNT



- August 6, 1945
  - Uranium gun device "Little Boy" dropped on Hiroshima
  - Detonated about 2000 ft above ground
  - 140,000 killed by end of 1945, ~200,000 total
- August 9, 1945
  - Plutonium implosion device "Fat Man" dropped on Nagasaki
  - About 70,000 killed.
- August 14, 1945
  - Japan surrenders

Little Boy and Fat Man





Sociological Issues

- **Should the US have used nuclear weapons?**
  - This is an ongoing debate.
    - Pro: It saved 0.5-1 million US lives (Japan invasion)
    - Con: Japan was preparing to surrender anyway.
  - Paul Olum: "I can see both sides of the debate to use the first bomb. Truman had an incredibly difficult decision to make. To me, what was totally unnecessary was the second bomb."

- **How did this affect the role of scientists in society?**
  - Two simultaneous (at-odds) views:
    - The scientists were the saviors.
    - The scientists were responsible for the doomsday device.
  - Many of the Manhattan project scientists were the first ones to appreciate how this would change the world.

To Use or Not to Use

- With the end of the war in Europe on May 8, 1945, discussion began on whether or not to use the bombs.
- Japan had never been a threat to develop a bomb.
- Groves definitely wanted to use the bombs.
- Szilard started a petition, signed by many of the scientists involved in the project, to not drop the bombs. The petition was never delivered to Truman.

Hiroshima

- Aug. 6, 1945, Little Boy was dropped by the Enola Gay piloted by Col. Paul Tibbets.
- Equivalent to 12-15 kilotons of TNT.
- 70,000 immediate deaths, 140,000 by the end of the year.

Nagasaki

- August 9, 1945, Fat Man was droped by Bocks Car piloted by Maj. Charles Sweeney.
- Equivalent to 21 kilotons of TNT.
- 40,000 immediate deaths, 70,000 by the end of the year.

VJ-Day

- Japan surrenders unconditionally on Aug. 14, 1945.
- Surrender signed in Tokyo Harbor aboard the USS Missouri on Sept. 2.

Fusion

- **The "most" stable nucleus is iron**
  - ^{56}Fe = 26 protons, 30 neutrons
- **Nuclei lighter than iron will give up energy when fused.**
  - Details depend upon mass and final state particles.
  - For very light nuclei, get more energy than with fission

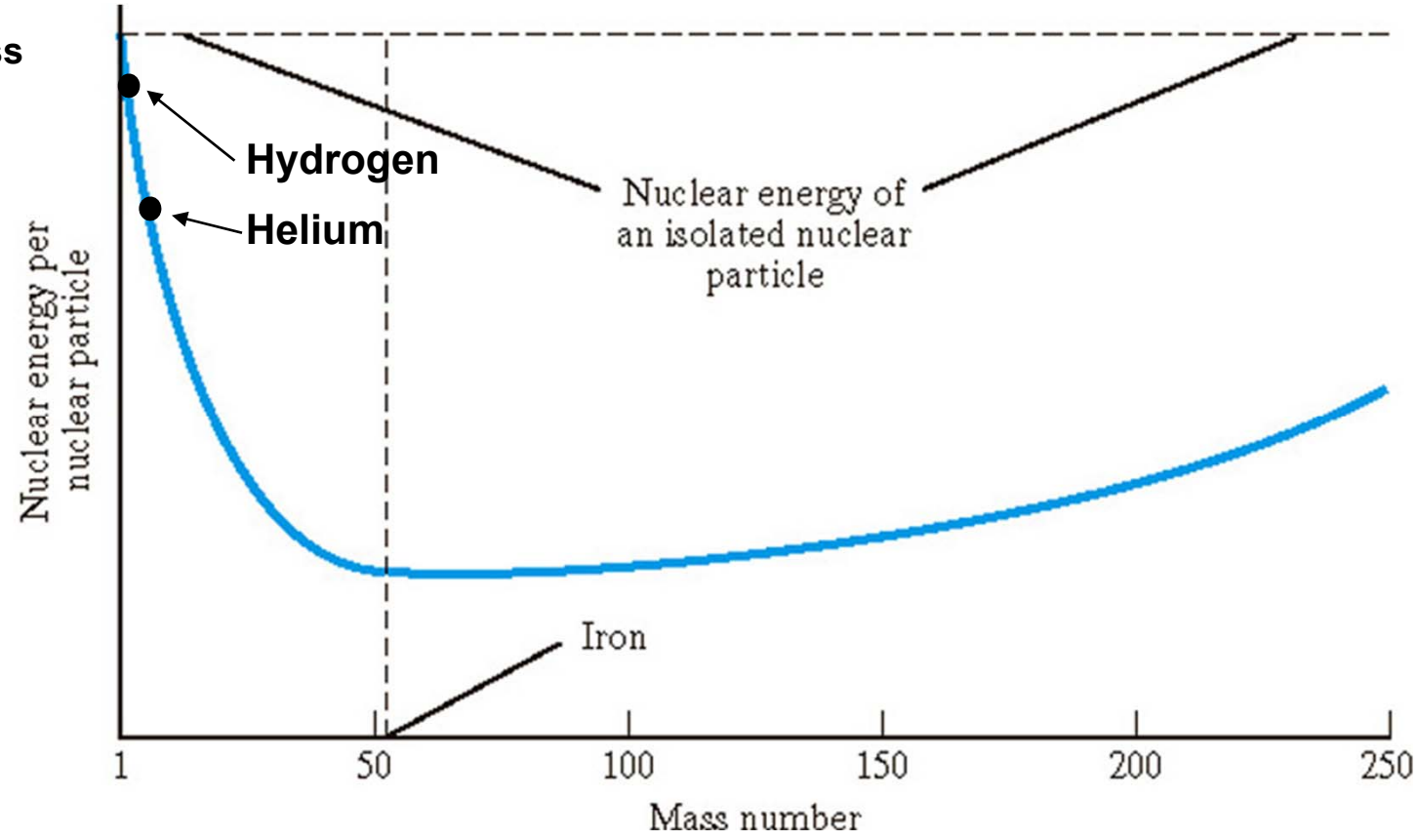
•Energy difference is mass difference:

• $E=mc^2$

•Example:

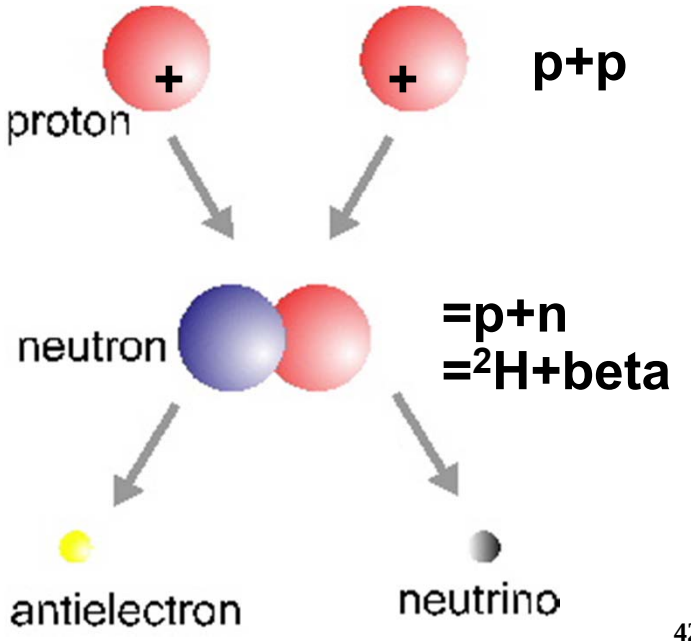
$m(^2H)+m(^2H)>m(^4He)$

2 protons
2 neutrons
In both cases!



Fusion

- **Fusion is the nuclear reaction that powers stars.**
  - Hydrogen and Helium abundant in the universe.
  - Recall, heavy elements only created in supernovae, so Uranium and Plutonium quite rare.
- **Pros**
  - Fusion fuel is easy to come by.
  - Energy released is much greater than by fission.
  - Fission tends to produce secondary radioactivity (radioactive waste) while fusion does not.
- **Challenge**
  - Need a large amount of energy to begin fusion process. Nuclei must overcome electrostatic repulsion to get close enough to fuse.

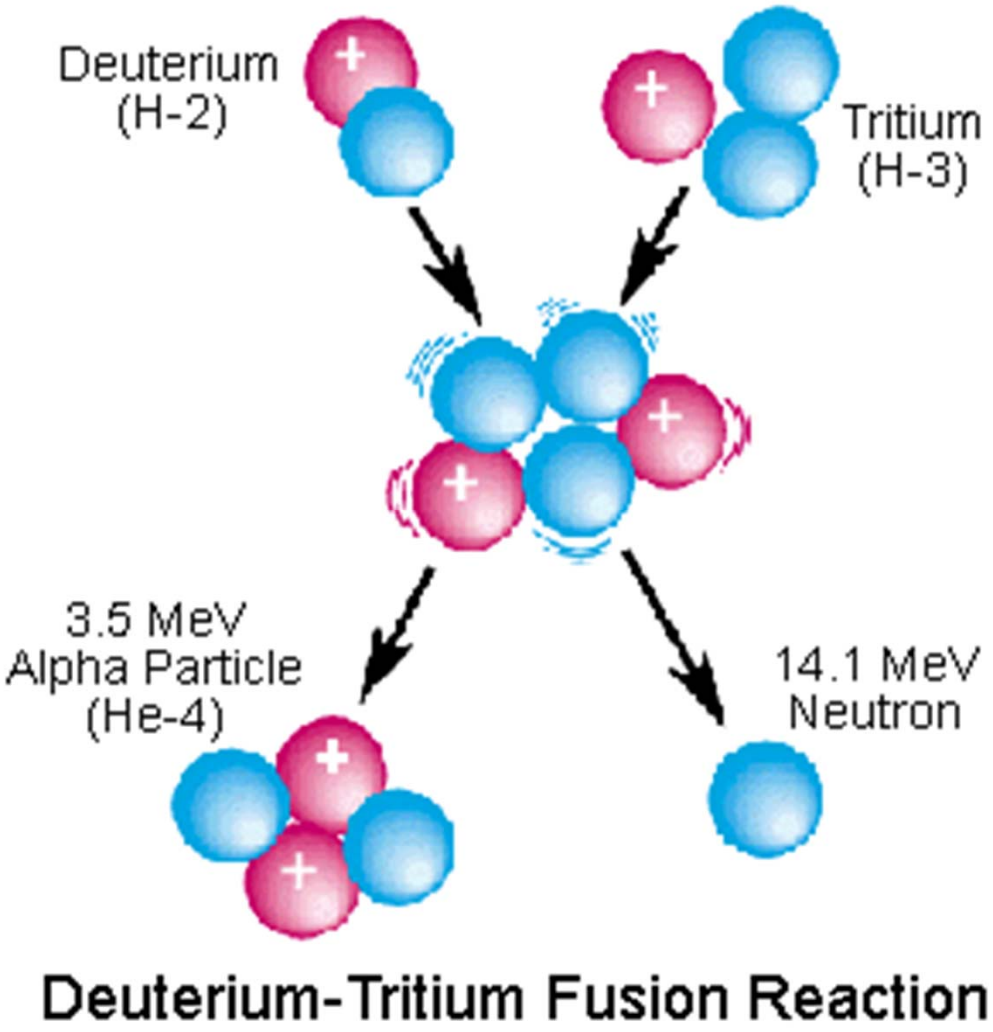


Edward Teller

- Edward Teller pushed for further work on a fusion based bomb.
- Known as the Father of the Hydrogen Bomb.

Stanislaw Ulam

- Recognized that radiation could create the pressure that would cause fusion.
- Led to the design of a staged thermonuclear device.



Deuterium-Tritium Fusion Reaction

The Fusion Reaction

- Requires a plutonium bomb as a trigger.

Mike

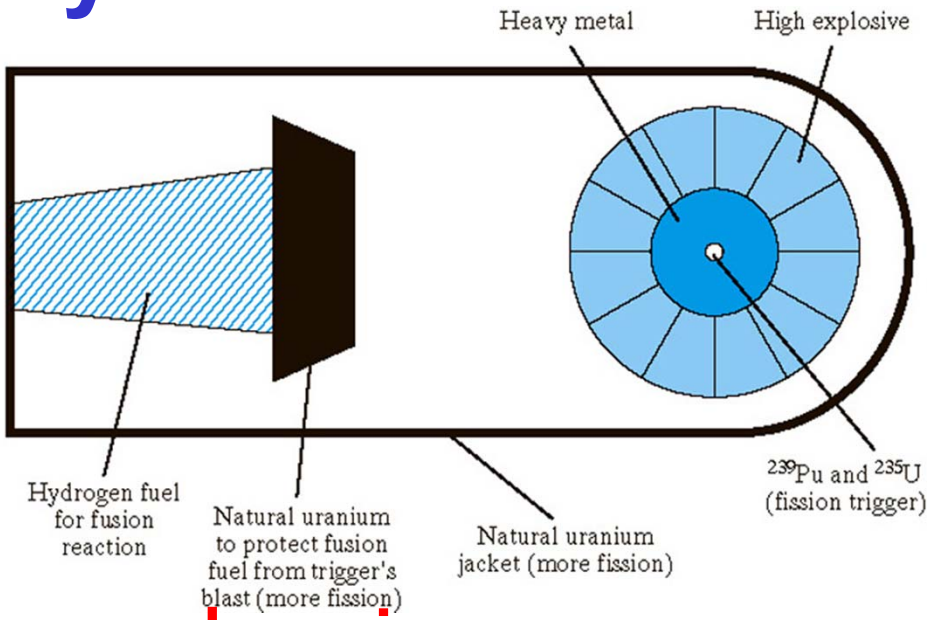
- First staged fusion explosion occurred on Eniwetok Atoll on Oct. 31, 1952.
- Mike used liquid deuterium as a fuel.
- The output of 10.4 megatons of TNT exceeded all of the explosives used in WW II including both atomic bombs.

Fusion

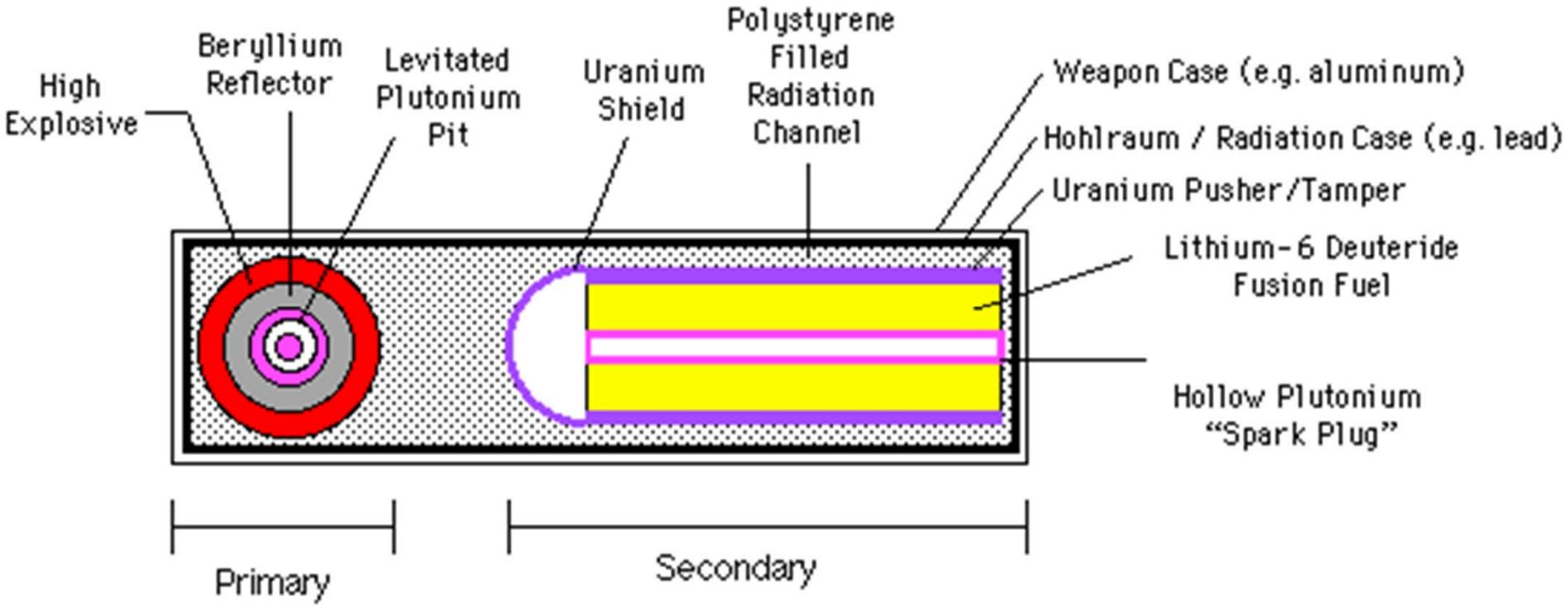
- **Nuclei must be very close together for fusion to occur.**
  - This can happen through pressure or temperature.
- **Alternatives to initiate fusion**
  - In stars, fusion initiated by gravitational pressure. The mass of the star provides enormous gravitational forces, bringing the nuclei close together.
  - In bombs, it's initiated by high temperatures. The high temperature is caused by a fission device.
    - Hydrogen (fusion) bombs are triggered by fission bombs.
  - In fusion reactors, the plan is to generate high temperatures to start the process, and then use techniques to maintain it.
    - Inertial confinement (lasers)
    - Tokamak (toroid magnet) confinement

History

- 1952 The Ulam-Teller "Super" is detonated as the first ever Hydrogen bomb.
  - It is 1000 times more powerful than the Hiroshima bomb.
  - It is triggered by a fission bomb.



- 1954 US launches first nuclear submarine.
- 1955 The Soviet Union detonates their first hydrogen bomb.
  - U.S. believed that the Soviets were decades behind in the race to a fusion device.
- The nuclear arms race begins.
  - At the height of the cold war, it is estimated that the US and USSR had ~20,000 nuclear weapons each. These nukes are all hydrogen bombs, much more powerful than the fission devices used in WWII.



Modern Thermonuclear Warhead

- Modern weapons use LiD as a fuel.
- As many as 20 warheads may sit on a single ICBM.

Nuclear Weapons Today

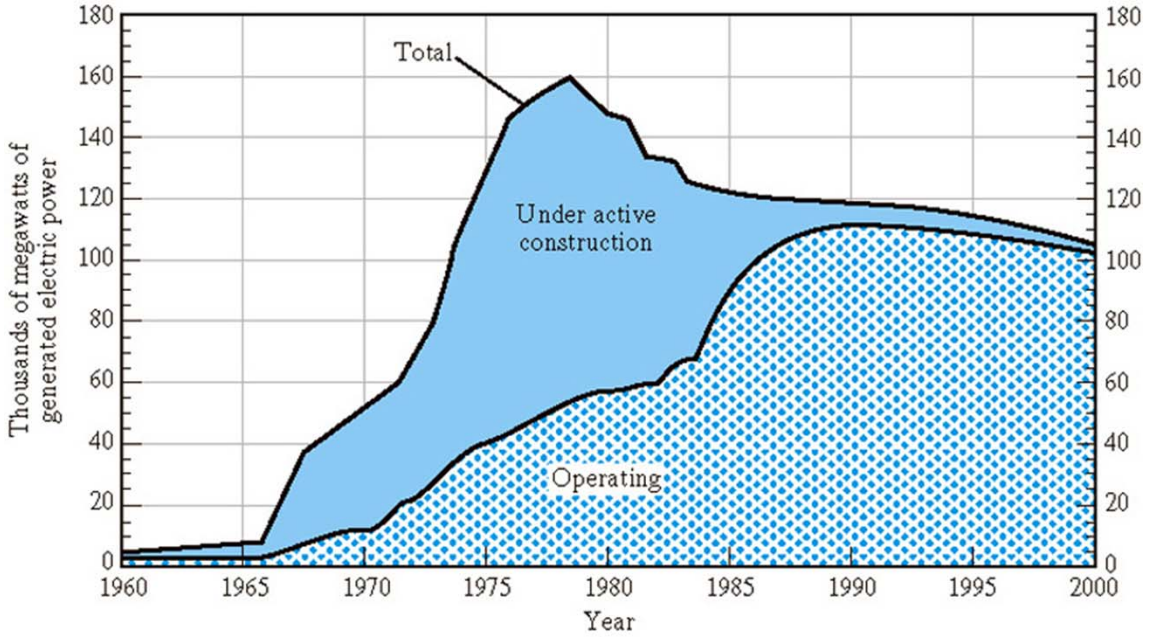
- The nuclear club
  - US, Russia, China, France, Great Britain, India, Pakistan
  - Likely: Israel, Ukraine, North Korea
- Other countries have the technology, but are not developing nuclear weapons.
  - Most signed a non-proliferation treaty.
    - example: Canada
    - South Africa dismantled their bombs
    - Other former USSR countries returned their bombs to Russia
- Countries attempting to gain nuclear capability (Iran) are after fission devices
  - Uranium enrichment and/or plutonium production is the biggest challenge
  - Iran was found to have an enrichment program.
  - In 1991/1992, Iraq was found to have an enrichment program
- Other key aspect is method of delivery.

Nuclear Fuels

- **Fission bombs need either:**
  - Plutonium [produced by breeder reactors]
  - 90% enriched ^{235}U
- **Nuclear submarines**
  - 20-45% enriched ^{235}U
  - Necessary for compact reactor size.
- **Commercial power plants**
  - 4% enriched ^{235}U
  - Incapable of generating a nuclear explosion
  - Can melt-down and spread radiation.
- **Naturally occurring Uranium**
  - 1% enriched in ^{235}U
- **Fusion bombs need:**
  - A fission device
  - deuterium (^{2}H)
  - tritium (^{3}H) half-life 12.3 years!

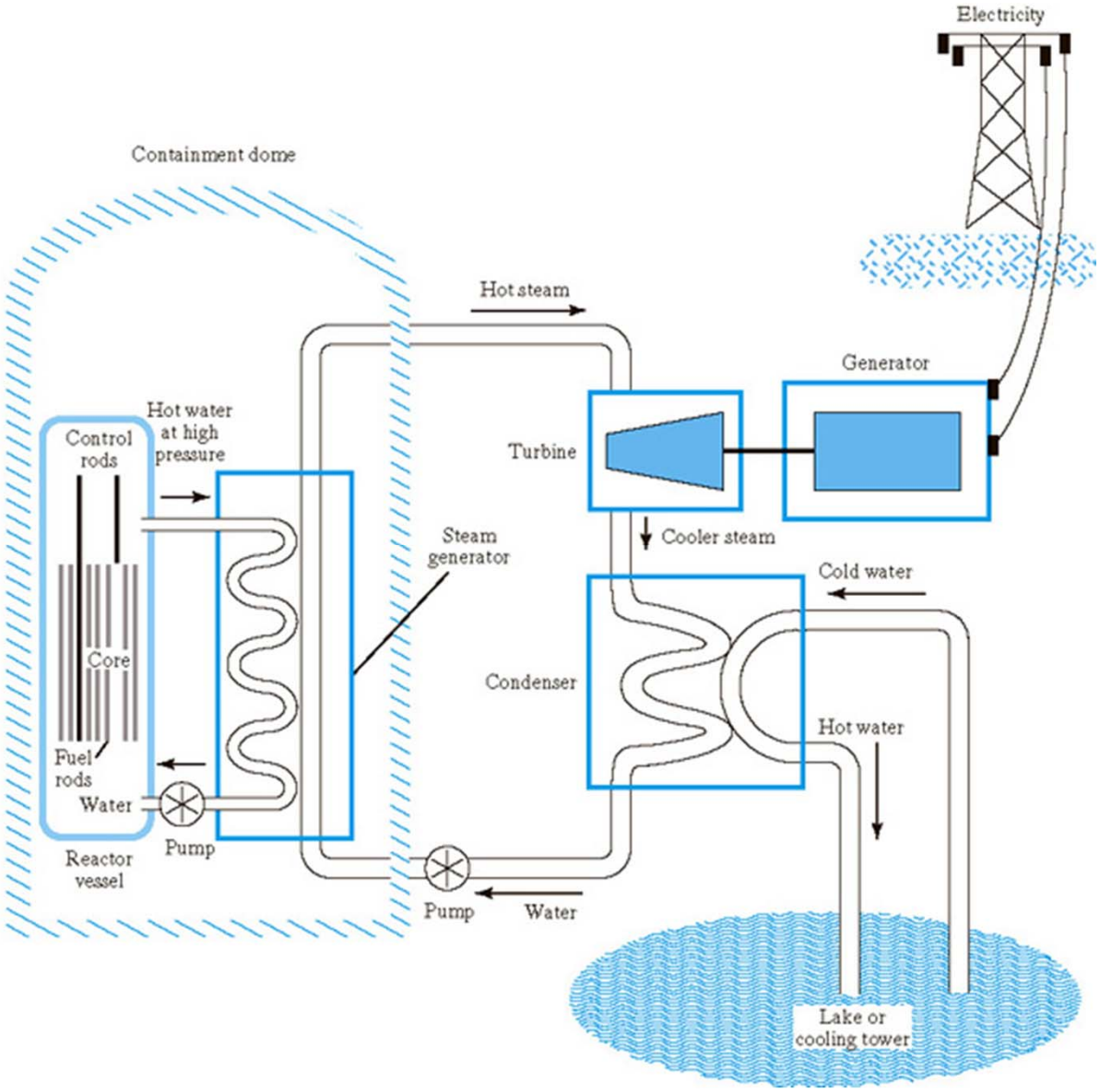
Nuclear Energy Production

- 1955-57
  - First nuclear power plants generate electricity for public consumption.
- 1979
  - 3 Mile Island
    - US nuclear power initiatives decline
- 1986
  - Chernobyl
- Today
  - 443 commercial nuclear power plants (11 in Illinois)
    - Accounts for <5% of the world's energy consumption.
  - These are all fission (uranium/plutonium) reactors.
    - Concerns: radiation safety and radioactive wastes.
  - Sustained fusion has not been achieved.



Nuclear Energy

- **General idea**
  - Use vast energy from nuclear reactions to heat large quantities of water.
  - Use steam to turn turbines which generate electricity.
- **Heat source could be fission or fusion reactor.**
  - Same idea for coal powered electricity.



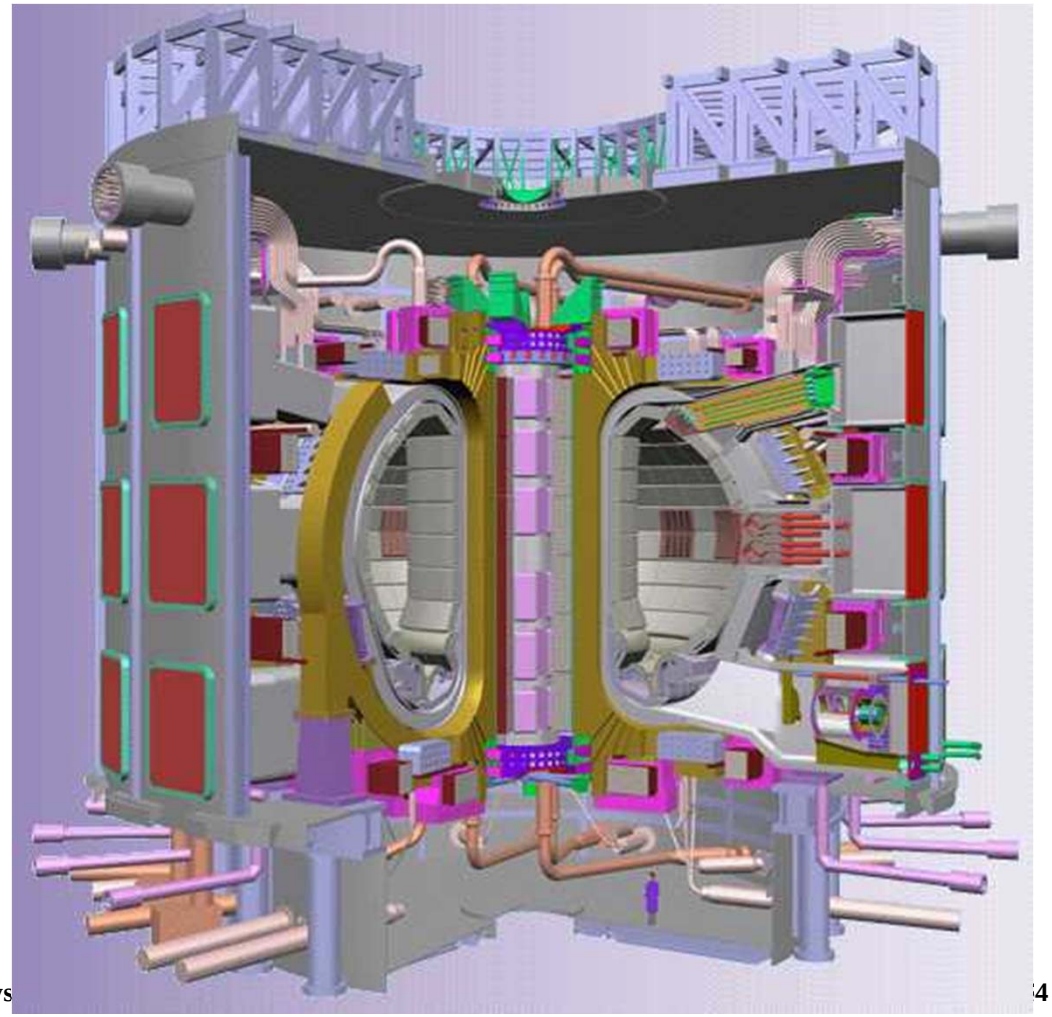
ITER

- **International Thermonuclear Experimental Reactor (ITER) is designed to achieve scientific break-even.**
  - **As much energy out as energy put in.**
  - **This has never been achieved in a controlled fusion system before.**

Construction cost of $2.8 B

8 years from start of

construction to first plasma.



Summary

- The nucleus possesses vast amounts of energy
- This energy is released in fission reactions
  - Uranium & plutonium fission bombs
  - Nuclear power plants
- This energy is released in fusion reactions
  - Stars
  - Hydrogen bombs
- The genie was let out of the bottle in 1945
  - Mankind will have to deal with peaceful and non-peaceful uses of nuclear power forever.