The Beginning of the Nuclear Age
"Because of the danger that Hitler might be the first to have the bomb, I signed a letter to the President which had been drafted by Szilard. Had I known that the fear was not justified, I would not have participated in opening this Pandora's box, nor would Szilard. For my distrust of governments was not limited to Germany."
Rumors or Reality?

American and British nuclear physicists felt they needed to start an A-bomb project to avoid falling behind their German counterparts. They feared Hitler's forces would be the first to have use of atomic arms. This evaluation was based on a number of considerations:

• The pre-war stop of uranium export
• The high caliber of German theoretical and experimental physicists like Otto Hahn, Paul Harteck, Werner Heisenberg, Fritz Strassmann, and Carl-Friedrich von Weizsäcker;
• German control of Europe's only uranium mine after the conquest of Czechoslovakia;
• German capture of the world's largest supply of imported uranium with the fall of Belgium;
• German possession of Europe's only cyclotron with the fall of France;
• German control of the world's only commercial source of heavy water after its occupation of Norway.
nuclear reaction processes

A(a,a)A
A(a,a’)A*

(in-) elastic scattering
¬ particle energy
¬ X-ray radiation
¬ γ-ray radiation

A(a,b)B  
A(a,γ)C  
A(a,C)D

nuclear reaction processes
¬ γ-radiation
¬ particle break-up
¬ fission
Some background

The probability for a reaction to occur is the cross-section $\sigma$!

probability for incoming beam to hit a target nucleus with radius $R$: $\sigma \approx \pi R^2$

Typical radius of nucleus $\approx 10^{-12}$ m

cross section $\approx$ area, unit barn:
$1$ barn $= 1 \cdot 10^{-24}$ cm$^2$
Total probability for reaction \( \approx \text{Yield} \)

If target has thickness \( d \), and target material has \# nuclei/volume: \( n_0 \) [part./cm\(^3\)]

\[ Y = \sigma \cdot n_0 \cdot d \]

The yield gives the intensity of the characteristic signal from the reaction process per incoming particle with the cross section \( \sigma \)! It also gives the number of reaction products per incoming particle!
Fission based explosions

Trigger $^{235}\text{U}$ fission through neutron bombardment each fission process generates 3 neutrons (- neutron losses)

Required for the success of explosion is:

- High neutron capture probability $\sigma_{\text{fiss}}$ (cross section)
  (measurements with neutron beams on fissionable material)
- Maintaining high neutron flux $n_n$
  (measurement of neutron production reactions)

\[
Y_{\text{fiss}} = \sigma_{\text{fiss}} \left[ \text{barn} \right] \cdot n_{^{235}\text{U}} \left[ \text{part} \right] \cdot n_n \left[ \text{s}^{-1} \text{cm}^{-2} \right]
\]

\[
E_{\text{fission}} = \varepsilon \cdot Y_{\text{fiss}}
\]

Efficiency factor
1/v law of neutron capture

Neutrons have no charge! Neutron capture cross sections are inverse proportional with neutron velocity since no deflective Coulomb barrier is involved. As lower the velocity as higher the reaction probability!

Introduces the need for “moderating” neutrons to low “thermal” velocities
Fission cross section

Experimental results from fission studies
Moderators

Example: neutron capture probability for 5 MeV neutrons from reaction is \( \sim 1 \) barn (1 barn = \( 10^{-24} \) cm\(^2\)). What is the capture cross section for thermal neutrons (E=0.026 eV)

\[
\sigma(E) \propto \frac{1}{v} \propto \frac{1}{\sqrt{E}}; \quad \sigma(E_{\text{therm}}) = \sqrt{\frac{E_{\text{fast}}}{E_{\text{therm}}}} \cdot \sigma(E_{\text{fast}})
\]

\[
\sigma(0.026) = \sqrt{\frac{5 \cdot 10^6}{0.026}} \cdot 1 \text{ barn} = 1.4 \cdot 10^4 \text{ barn}
\]

Four orders of magnitude improvement by slowing down the neutrons!!! **What is the best slow down mechanism?**
Scattering and Energy Loss

Best neutron moderators are light mass materials because of large energy transfer in scattering event: Graphite C, heavy water $\text{D}_2\text{O}$ (low absorption cross section is crucial!)
Moderators

**Graphite**: easy to originate from carbon, obvious first choice

Easy to machine for industrial purposes!

**Heavy Water** is dideuterium oxide, or D$_2$O or $^2$H$_2$O. Gilbert N. Lewis isolated the first sample of pure heavy water in 1933.
Walter Bothe, the leading experimental nuclear physicist in Germany, did the crucial experiment and concluded that carbon in the form of graphite would not work. In America, Enrico Fermi did a similar experiment and concluded that graphite was marginal. He suspected that an impurity in the graphite was responsible for the problem. Leo Szilard, who was working alongside Fermi, had studied chemical engineering before going into physics. He remembered that electrodes of boron carbide were commonly used in the manufacture of graphite. It was known that one atom of boron absorbs about as many slow neutrons as 100 000 atoms of carbon. Very small boron impurities would "poison" the graphite for use as a nuclear reaction moderator. Szilard therefore went around to the American graphite manufacturers and convinced one of them to make boron-free graphite. Using this pure graphite as the moderator, the American group achieved a chain reaction on 2 December 1942.

The German team, however, needed to use heavy water, D₂O. Ordinary water contains heavy water at a rate of about 1 part in 10 000. The two can be separated by repeated electrolysis, which requires large amounts of electric power in close proximity to a water source. The Germans had this at a hydroelectric plant in occupied Norway, and they set up a separation facility there.

*Hans Bethe in Physics Today Vol 53 (2001)*
Comparison of cross sections

Neutron absorption on Boron

Neutron scattering on Carbon
The first commercial heavy water plant was the Norsk Hydro facility in Norway (built 1934, capacity 12 metric metric tons per year).

Plant was attacked by the Allies to deny heavy water to Germany. Attacks between 1941 and 1943 failed!

However, D₂O supply destroyed by partisan sabotage when German government tried to ship it to Germany.
Uranium $^{235}$U separation

Natural uranium contains only 0.7% of the $^{235}$U isotope. The remaining 99.3% is mostly the $^{238}$U isotope. To achieve fission of large amounts of $^{235}$U separation techniques are required. Reactors operate at 3-4% enrichment, weapons require 90% enrichment.

Three methods have been developed:

1. Separation by diffusion through porous membrane; diffusion rate $\sim 1/M^2$ (circular separation)
2. Electromagnetic separation in “cyclotrons”
3. Centrifugal separation (developed in 1940, but only applied in 60ties).
Plutonium

Seaborg discovered plutonium at U.C Berkeley, Feb. 23, 1941.

$^{239}$Pu also undergoes fission and can be made from $^{238}$U.

The “breeding process” requires the exposure of $^{238}$U to high neutron flux!

- $^{238}_{92}$U + $^1_0$n $\rightarrow$ $^{239}_{92}$U neutron capture reaction
- $^{239}_{92}$U $\rightarrow$ $^{239}_{93}$Np + $\beta$\textsuperscript{-} $t_{1/2}$ = 23.5 min
- $^{239}_{93}$Np $\rightarrow$ $^{239}_{94}$Pu + $\beta$\textsuperscript{-} $t_{1/2}$ = 2.35 days

He was discoverer of plutonium and all further transuranium elements through element 102!
Groves projected three sites for the development of nuclear weapon production with the goal of:

1. Enrichment of $^{235}\text{U}$
2. Generating $^{239}\text{Pu}$
3. bomb assembling and testing

The Manhattan Project

In response to the perceived German threat the United States initiated its own program for the development of an “Atomic Bomb” under the Army Corps of Engineers in June 1942.

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Basic goal was to probe and utilize all of the available technical possibilities!
After graduating from Harvard in 1925 and studying (unsuccessfully) at Cambridge under Ernest Rutherford, he obtained his PhD in Göttingen, Germany. In 1929 he returned to the United States to positions at Berkeley and Cal Tech. He was appointed by General Groves in 1942 as the Scientific Director of the Manhattan Project.

Groves said of Oppenheimer, "He's a genius. A real genius...Why, Oppenheimer knows about everything. He can talk to you about anything you bring up. Well not exactly. I guess there are a few things he doesn't know about. He doesn't know anything about sports."
The basic research for understanding fission properties was performed at the University of Chicago. For this purpose Enrico Fermi built the first nuclear reactor, CP-1, in a squash court under the football stadium. The first sustained nuclear reaction occurred on Dec. 2, 1942!
The Pile

Practical use of this data is made in the design of thermal columns. A column of graphite with base of dimensions $l \times l$ is placed against a nuclear pile which is a source of fast neutrons. At distances greater than a few feet from the pile, the neutrons in the graphite will be thermal.

Assuming $\rho = 0$ except in this small layer near the pile and using Eq. 19, the equation for $n(r)$ is

$$\nabla^2 n - \frac{\rho}{a} = 0$$

The approximate boundary conditions are

\[ n = 0 \text{ at } \begin{cases} x = 0 \text{ and } y = 0 \text{ and } z = 0 \\ y = 0 \end{cases} \]

Let

\[ m(z) = \sum_{j, k = 1}^{\infty} m_{j, k}(z) \sin \frac{\pi j x}{l} \sin \frac{\pi k y}{l} \]

\[ \frac{d^2 m_{j, k}}{dz^2} - \left[ \frac{\pi^2 (j^2 + k^2)}{l^2} + \frac{1}{a^2} \right] m_{j, k} = 0 \]

\[ m_{j, k}(z) = C e^{-\frac{z}{b_{j, k}}} \quad \text{where} \quad \frac{1}{b_{j, k}} = \sqrt{\frac{1}{a^2} + \frac{\pi^2 (j^2 + k^2)}{l^2}} \]

$b_{j, k}$ is maximum for the $(1,1)$ mode.

\[ \frac{1}{b_{1, 1}} = \sqrt{\frac{1}{a^2} + \frac{\pi^2}{l^2}} \]

For $l \gg a$, $b_{1, 1} \approx a$

\[ \frac{1}{b_{n}} = \sqrt{\frac{1}{a^2} + \frac{\pi^2}{l^2}} \]

and for $l \ll a$, $b_{n} \approx \frac{l}{\sqrt{\pi a}}$ is the effective diffusion length.

Thus $b_{n}$ can reach its maximum value ($a$) by increasing $l$.

The object is to get thermal neutrons out past the region of the nascent and higher energy neutrons which already reach out on the order of 50 cm ($\sqrt{\mu n} \approx 50$ cm). Thus $l > a$ is a condition for building a thermal column.
The CP-1 used 235 enriched uranium metal from Iowa State.

As moderator for slowing down the neutrons to thermal velocities the reactor used high purity graphite.

As control rods, for absorbing neutrons and preventing the reactor to become critical CP-1 used Cadmium rods. (Other neutron absorbing materials are e.g. Boron).

Moderators need high neutron scattering cross section, Absorbers require high neutron capture cross section.
Accelerator based radiation and material test facilities

Wisconsin: neutron production to test material fissibility
Notre Dame: high energy electron beam to test radiation

1941-1952
In a remote area near Knoxville, Tennessee a secret city was built. The main reason for choice of site was the abundant availability of Tennessee water power.

Primary purpose of the Oak Ridge facility was to enrich $^{235}$U.

They also built a graphite reactor at site X-10 to study the production of plutonium. (Today site of ORNL)

Construction started in 1942
Chemistry is necessary for generating weapon grade plutonium!

**X-10 plutonium breeder reactor**

**Bismuth Phosphate Process for Recovery of Plutonium**

- Pu is found in low concentrations (<250 ppm) in reactor products.
- Weapons grade Pu must be chemically pure (<1 part in $10^7$ parts Pu).
- The Pu recovery for this process was 95% with <1 part impurity in $10^7$.

$$\text{Pu}(s) + X(s) \xrightarrow{\text{HNO}_3/\text{H}_2\text{SO}_4} \text{Pu}^{4+}(aq) + X^+(aq)$$

$$\text{Pu}^{4+}(aq) + X^+(aq) + \text{Bi}^{3+}(aq) \xrightarrow{\text{H}_3\text{PO}_4} \text{Pu}_3\text{(PO)}_4(s) + X^+(aq) + \text{BiPO}_4(s)$$

$$\text{Pu}_3\text{(PO)}_4(s) + \text{BiPO}_4(s) \xrightarrow{\text{HNO}_3/\text{oxid. agent}} \text{Pu}^{6+}(aq) + \text{Bi}^{3+}(aq)$$

$$\text{Pu}^{6+}(aq) + \text{Bi}^{3+}(aq) \xrightarrow{\text{H}_3\text{PO}_4} \text{Pu}^{6+}(aq) + \text{BiPO}_4(s)$$

$$\text{Pu}^{6+}(aq) \xrightarrow{\text{H}_2\text{O}_2/\text{reducing agent}} \text{PuO}_2^{2+}(aq) \xrightarrow{\text{reducing agent}} \text{Pu}(s)$$

$X(s)$ = fission products or uranium; $\gamma^+$ = oxidation state
Purpose of Y-12 plant:
Magnetic separation of $^{235}\text{U}$ from $^{238}\text{U}$.
The work was overseen by Lawrence.
Operated 1943-1946
(diffusion based separation was superior)
Magnetic Separation

\[ m \frac{v^2}{r} = e \cdot v \cdot B; \quad E = \frac{1}{2} m \cdot v^2 \]

\[ \frac{m \cdot v}{r} = e \cdot B; \quad \sqrt{2 \cdot E \cdot m} = e \cdot r \cdot B \]

\[ m = \left( \frac{e \cdot r \cdot B}{2 \cdot E} \right)^2; \quad \frac{m_1}{m_2} = \left( \frac{r_1}{r_2} \right)^2 \]

\[ m_1 = 238, \quad m_2 = 235, \quad r_1 = 10m \]

\[ r_2 = r_1 \cdot \sqrt{\frac{m_2}{m_1}} = 10 \cdot \sqrt{\frac{235}{238}} = 9.94m \]
Gaseous diffusion plant at Oak Ridge for enrichment of $^{235}\text{U}$ versus $^{238}\text{U}$.

Based on Graham’s Law of Effusion and the oddity that UF$_6$ is a gas when heated up to 135°F.
Graham’s Law of Effusion

Assume two gases of molecular masses $m_1$ and $m_2$ diffuse. The ratio of time it takes for equal amounts of gas to reach a given distance is:

$$\frac{t_1}{t_2} = \sqrt{\frac{m_1}{m_2}}$$

This results from the dependence of the velocity of a gas particle in a Maxwell Boltzmann distribution.

$$\frac{t_1}{t_2} = \sqrt{\frac{m_1}{m_2}} = \sqrt{\frac{235}{238}} = 0.99$$

Several subsequent diffusion separator stations necessary for gradual slow enrichment.
Secret City on the Columbia River in Washington State.

- A series of 9 nuclear reactors were designed to produce plutonium.
- A chemical plant to process material and purify plutonium
- Storage site for the resulting nuclear waste

Constructed in 1943 as follow up on X-10 in Oak Ridge as main site for industrial plutonium production shut-down in 1963! Represents a major nuclear waste problem
Plutonium-Production Cycle

Plutonium Production Cycle as It Existed throughout the Manhattan Project at the Hanford Site
Nuclear Waste

Solid waste:
burial grounds

Liquid waste:
retention basins,
reverse wells,
underground tanks
Columbia river

Gaseous waste:
$^{14}\text{N}(n,p)^{14}\text{C}$
toxic fumes
ventilation and
exhaust into the
atmosphere

The 618-10 Burial Ground... "consisted of trenches and rows of burial caissons known as "pipe fields." The caissons were made of 5 to 6 open-bottomed 55-gallon drums welded together and buried upright. From the mid-1950s until about 1960, solid radioactive wastes were collected from operations buildings in cardboard containers and then stored in lead pans known as "gunk catchers" and transported to 300 North [618-10] in shielded "load luggers." The cardboard waste containers then were dropped from the gunk catchers down the caissons, and the holes were filled with sand and dirt until radiation levels declined to a safe or "tolerance" reading. If radiation levels could not be reduced to tolerance ranges, concrete was poured down the hole until such levels were achieved." - Gerber 1993a, p. 59
Left-over

Hanford is arguably the most contaminated site in North America. Cleanup costs are projected in the tens of billions of dollars, and requiring a fifty-year effort.

The Hanford Nuclear Site in southeastern Washington state stores 54 million gallons of dangerous high-level radioactive waste containing hundreds of millions of curies from the nation's nuclear weapons production process.
Plutonium production at Hanford

Total Annual Production of Plutonium at the Hanford Site