This was recognized in 1939

plus

the fact that

$$n + U \rightarrow X + Y + \text{extra neutrons}$$

possibly could be used to initiate more fission

... the possibility of a self-sustaining chain reaction.

At first.. everyone thought: POWER SOURCE

then.. everyone thought: BOMB.

To understand the parameters, experiments were quickly mounted to:

- measure the absorption and fission cross sections for U isotopes.
- measure the energy spectrum of fission neutrons.

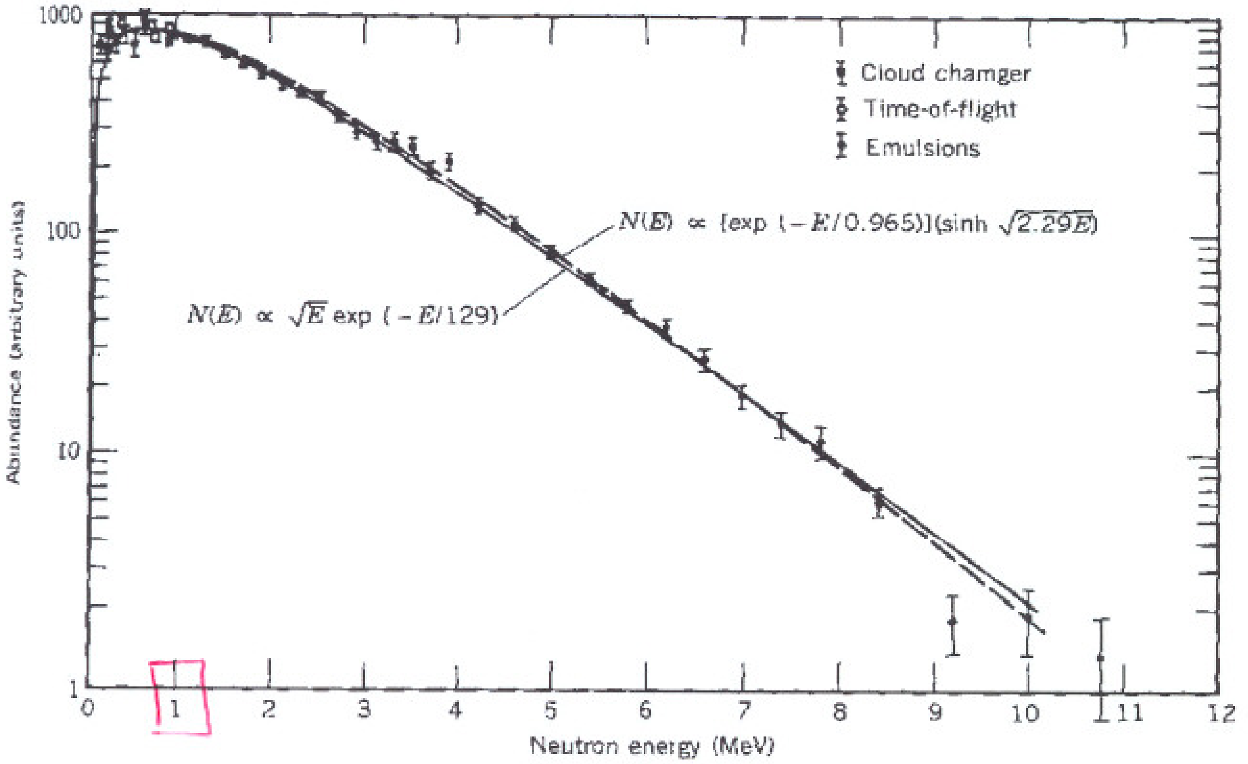


Figure 13.13 Energy spectrum of neutrons emitted in the thermal-neutron fission of ^{235}U. From R. B. Leachman, in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy*, Vol. 2 (New York: United Nations, 1956), p. 193.

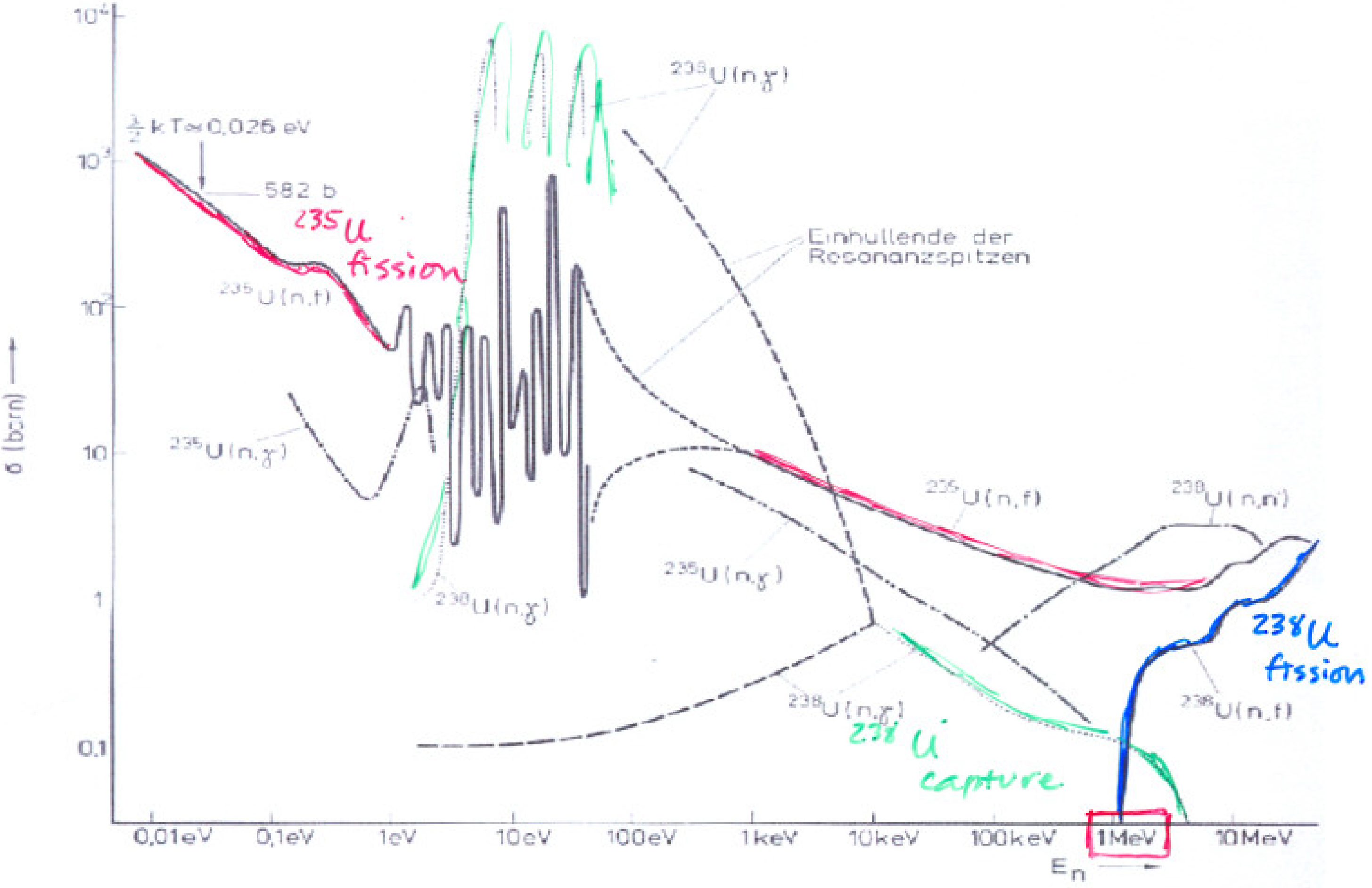


Fig. 124 Übersicht über die Wirkungsquerschnitte bei Reaktionen von Neutronen mit Uran. In den Bereichen dicht liegender Resonanzen können die Strukturen in der Zeichnung nicht wiedergegeben werden. Es ist daher nur die Einhüllende der Resonanzmaxima- und -minima eingezeichnet (gestrichelt). Ein Detail ist in Figur 107 wiedergegeben

Summary:

^{238}U will fission

only with neutrons above 1 MeV

^{235}U will fission

for all neutron energies

^{238}U will absorb neutrons

for almost all neutron energies below 1 MeV

and:

natural U is 99.3% ^{238}U

0.7% ^{235}U

⇒ must find a way to enhance ^{235}U

- can't be chemically.
- can be a variety of "mechanical" ways.

⇒ or find an alternative fuel

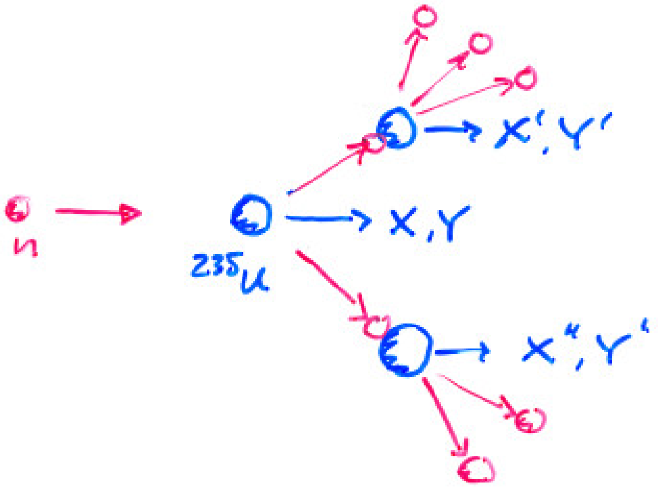
Neutron Economy.

Neutrons are useful for ^{235}U, but required in high fluxes, and efficient if at low energies

They can disappear by:

1. being absorbed by elements of reactor
2. lost to the outside. ✓

⇒ engineering the shape of the fissile material is important.



~2½ neutrons are produced per average fission

take $\underline{\underline{2}}$... and the 1 kg ^{235}U example.

$\sim 3\times10^{24}$ nuclei $\simeq (2)^{81}$, so 81 generations required to "fish" 1kg of ^{235}U @ 100% efficiency

"Criticality", K

in our example K = 2 -- sorta excessive to sustain a chain reaction

K = 1 ⇒ critical ... good for controlled fission

K > 1 ⇒ supercritical -- "good" for explosive fission.

K < 1 ⇒ subcritical

How much?

^{235}U : a sphere of ~ 18 cm diameter (7")

~ 53 kg is "critical mass"

The "other" material -- Plutonium, found in 1940.

^{239}Pu : ~ 18 kg is critical mass

Plutonium is produced by

$$n + {}^{234}U \longrightarrow {}^{239}U^{*} \longrightarrow {}^{239}Np + \beta$$

$$\hookrightarrow {}^{239}Pu + \beta$$

↑ natural uranium

History of Nuclear Power woven with history of nuclear weapons.

1938	1940	1942	1945	1955
fission U	Pu	Chicago "pile"	2 weapons used against Japan	first public power reactor

Germany began reactor research immediately

made technical choices:

1. not to try to extract ^{235}U from ^{238}U
2. to try to "convert" $^{238}U \rightarrow {}^{239}Pu$
3. moderator:
    - tried graphite & concluded it would not work — wrong
    - chose D_2O "heavy water" *

smoking gun was the Nazi occupation of Norway & its Ammonia production facility

... by product is D_2O.

* more neutron rich than H_2O. Also, H_2O will absorb neutrons.

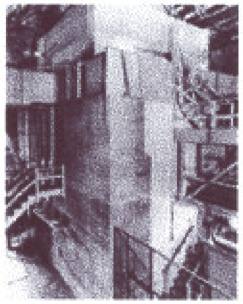
US also began immediately

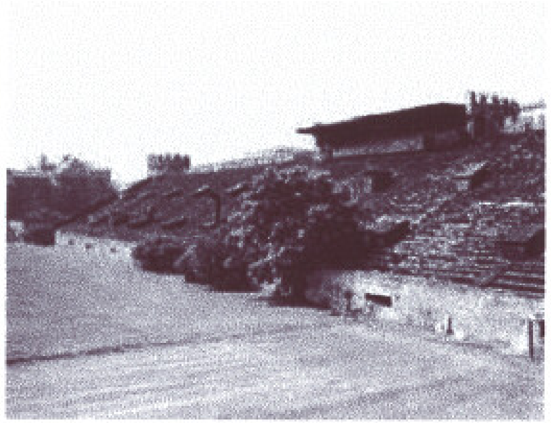
made technical choices:

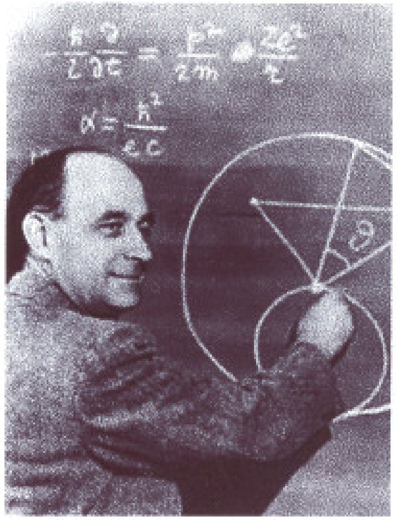
1. chose to attempt both:
    - extraction of ^{235}U from ^{238}U

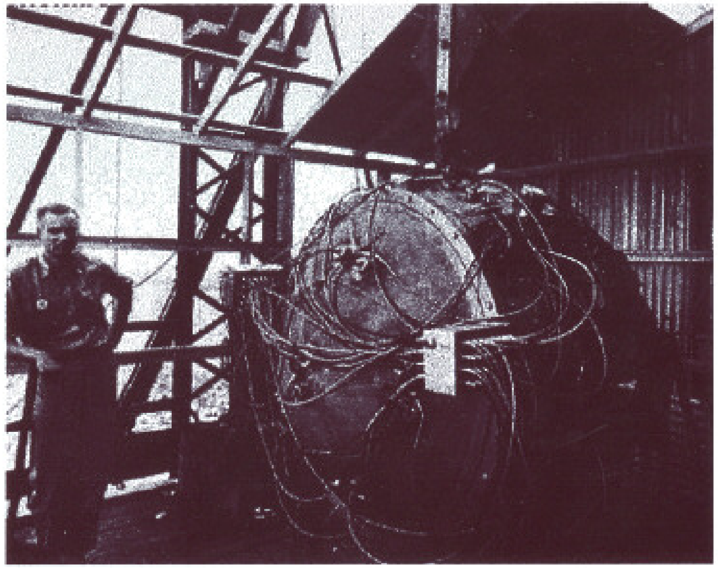
      and

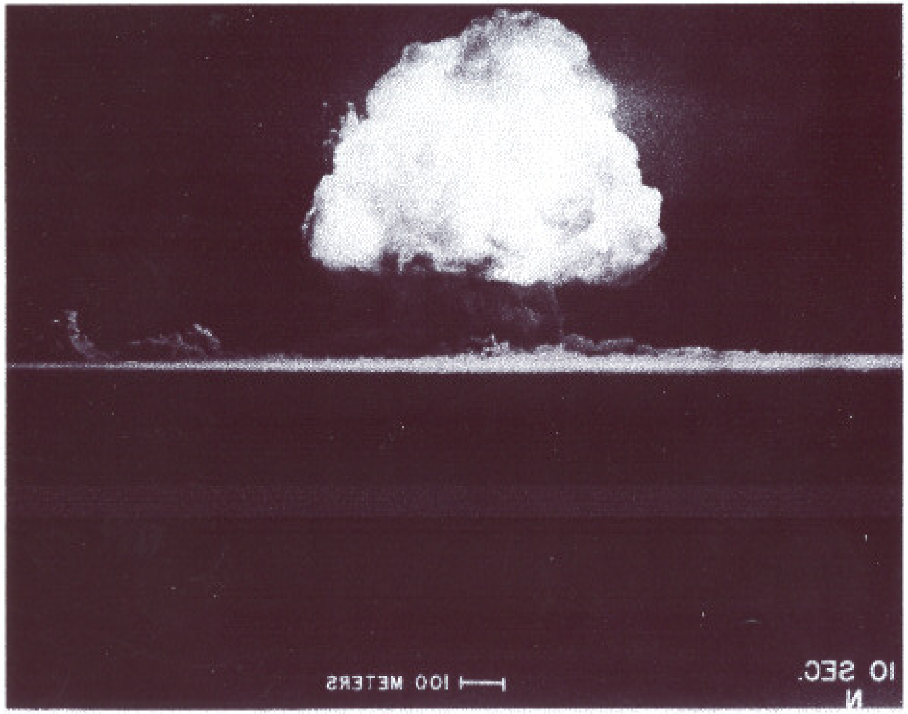
    - conversion $^{238}U \rightarrow {}^{239}Pu$
2. moderator:
    - Fermi correctly guessed that the German rejection of graphite was due to contamination
    - purified graphite and built the first controlled fission chain reaction in Chicago in 1942 using graphite moderator & ^{238}U fuel

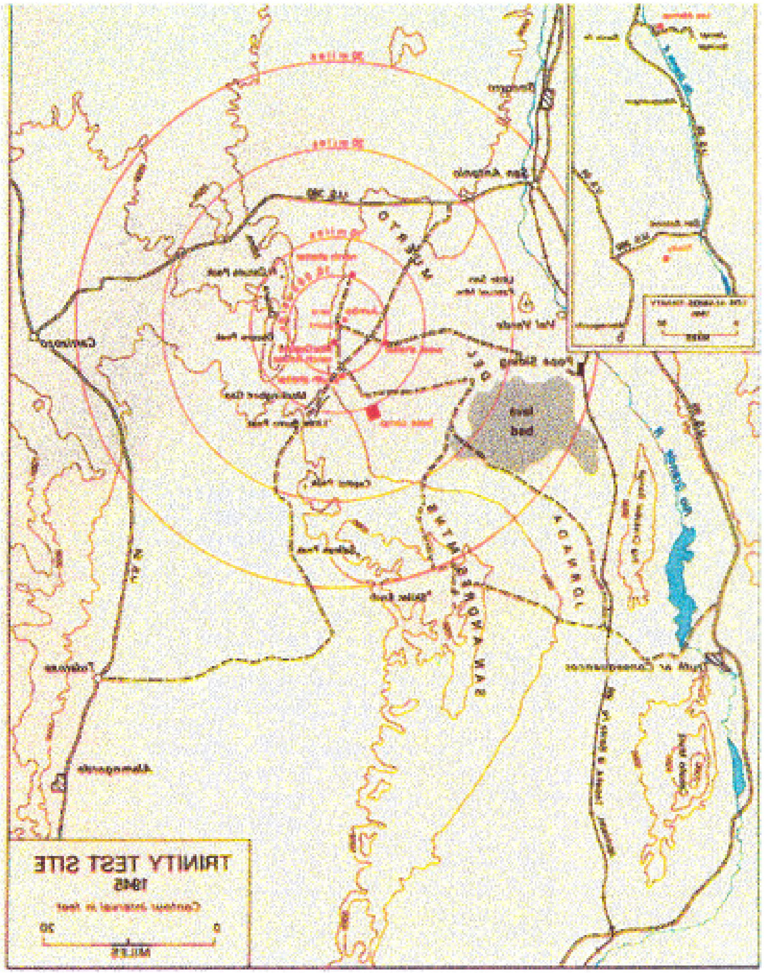


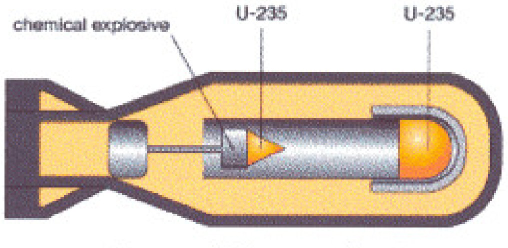




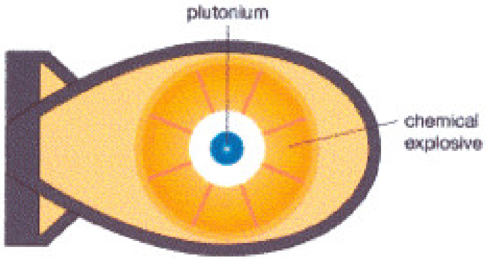



10 SEC.
N
100 METERS


TRINITY TEST SITE
1945
Contour interval in feet
20
0
MILES
SAN ANDRES MTNS
JORNADA DEL MUERTO

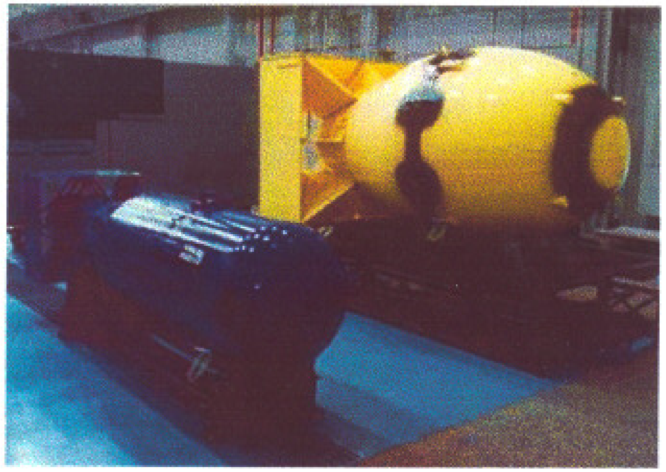


two non-critical masses will meet



single non-critical mass will be compressed

20kT, plutonium implosion device



13kT, uranium gun device

Raw Material specifications...

depends on the application...

Natural U is 99.3% ^{238}U
0.7% ^{235}U

TYPE	MAIN USES
natural ^{238}U	some power reactors military Pu production reactors
"low-enriched" uranium LEU .. 0.7–20% ^{235}U	most operating power reactors some research reactors French naval propulsion reactors
"highly-enriched" uranium HEU >20% ^{235}U	most research reactors US, British, Russian naval prop. nuclear weapons military Pu and T production r.
mixed plutonium-uranium oxide MOX	some reseach & ext. reactors some power reactors
Pu	nuclear reactors

"weapons grade" uranium is >90% ^{235}U

Enrichment is technically very challenging and expensive.

4 Kinds of Enrichment Techniques

1. Gaseous diffusion

   Manhattan Project @ Oak Ridge National Lab, TN

   diffuses UF_6 gas through semi-permeable membranes

   at high pressure $\propto \frac{1}{M^2}$

2. Electromagnetic isotope separation

   -- sort of a high-flux mass spectrometer

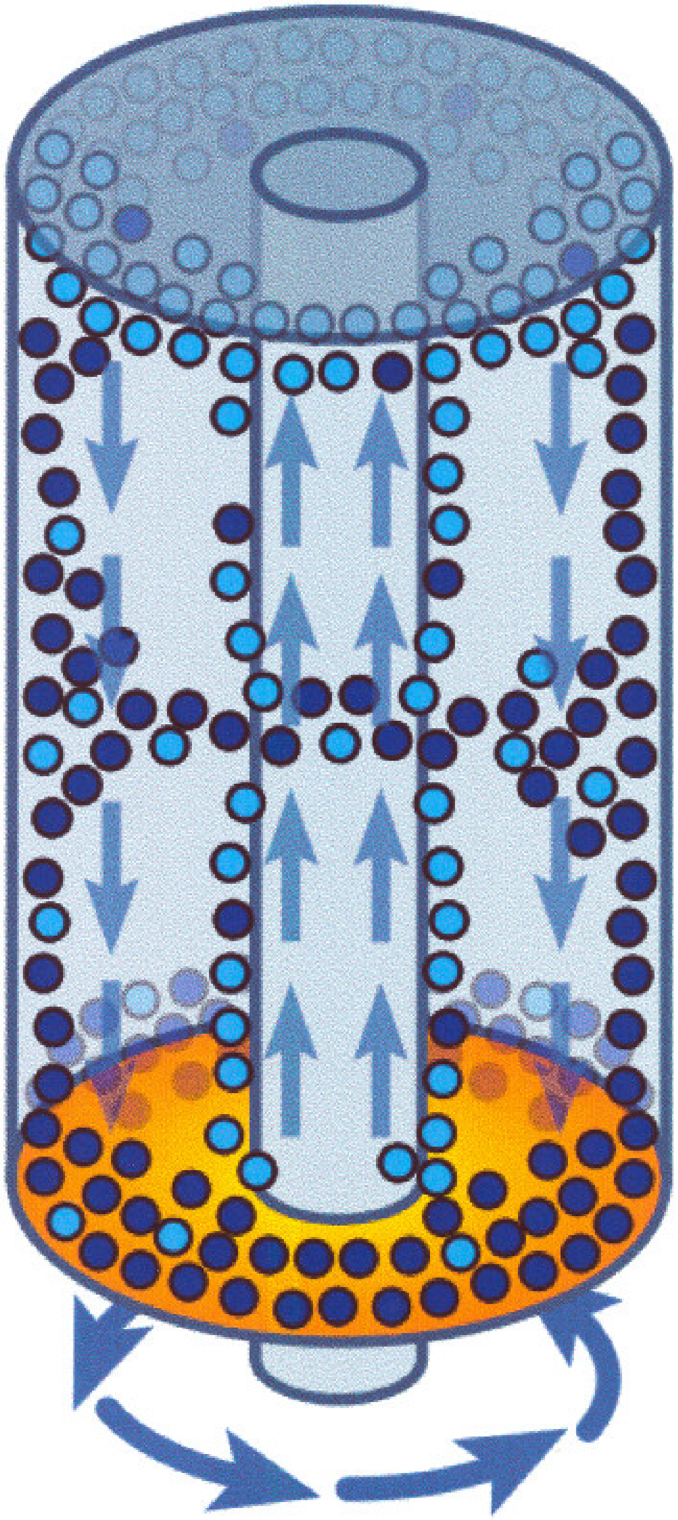
3. Gas centrifuge

   UF_6 separated through ~100 stages

   requires sophisticated metallurgical designs (Al, Fe)

4. Molecular laser isotope separation

   exploits the ~~nuclear~~ molecular energy level differences between ^{235}U and ^{238}U in UF_6.



Concerns for proliferation.-

Technology transfer..

Pakistan → Iran, N Korea, Lybia.

LEU facilities can be converted to HEU

Breeder reactors...

$n + {}^{238}U \rightarrow {}^{239}U^* \rightarrow {}^{239}U + \gamma$

↳ ${}^{239}Np + \beta + \bar{\nu}$

↳ ${}^{239}Pu + \beta + \nu$

↳ fission + 2.7 n

so actually breed the fuel ${}^{239}Pu$

to be used in another reactor...

leaving it going for a long time makes.

${}^{239}Pu + {}^{240}Pu$ okay for power.

↑

not fissile.

removing quickly makes

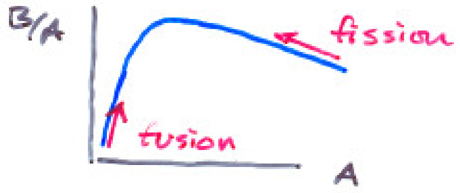
${}^{239}Pu$ + traces $< 7\%$ ${}^{240}Pu$ for weapons grade Pu.

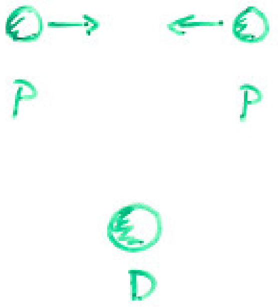
FUSION

About the same time that fission weapons were being engineered, Hans Bethe calculated how

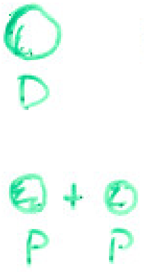
the sun works.

Light nuclei @ very high speeds can overcome the Coulomb repulsion... and fuse into heavier elements





can understand by liquid drop



smaller surface area than

→ so binds.

not enough heat in sun to provide K_p to fuse--

→ quantum mechanical tunneling again

Thermonuclear burning in the solar interior in chains:

Proton chain:

$^1H + {^1H} \rightarrow {^2H} + e^+ + \nu$ → there's a story here ×2

$^1H + {^2H} \rightarrow {^3He} + \gamma$ ×2

$^3He + {^3He} \rightarrow {^4He} + {^1H} + {^1H}$

$\Rightarrow \quad 6\,{^1H} \rightarrow {^4He} + 2\,{^1H}$

net: $4\,{^1H} \rightarrow {^4He}$

$\Rightarrow$ 24.7 MeV + 2 MeV (e^+e^-) = 26.7 MeV

slow... but heats star so that

carbon chain: $3\,{^4He} \rightarrow {^{12}C}$:

$^1H + {^{12}C} \rightarrow {^{13}N} + \gamma$
$\hookrightarrow {^{13}C} + e^+ + \nu$

$^1H + {^{13}C} \rightarrow {^{14}N} + \gamma$

$^1H + {^{14}N} \rightarrow {^{15}O} + \gamma$
$\hookrightarrow {^{15}N} + e^+ + \nu$

$^1H + {^{15}N} \rightarrow {^{12}C} + {^4He}$

On earth?

Controlled? not yet.

$^{2}H + ^{2}H \rightarrow n + ^{3}He$ $Q = 3.3$ MeV ?

$^{2}H + ^{2}H \rightarrow p + ^{3}H$ $Q = 4.0$ MeV ?

$^{2}H + ^{3}H \rightarrow n + ^{4}He$ $Q = 17.6$ MeV ?

most likely .. decades away.

Uncontrolled? hundreds of times.

$^{2}H + ^{3}H \rightarrow ^{4}He + n$

$n + ^{6}Li \rightarrow ^{4}He + ^{3}H$

$^{2}H + ^{2}H \rightarrow ^{3}He + n$

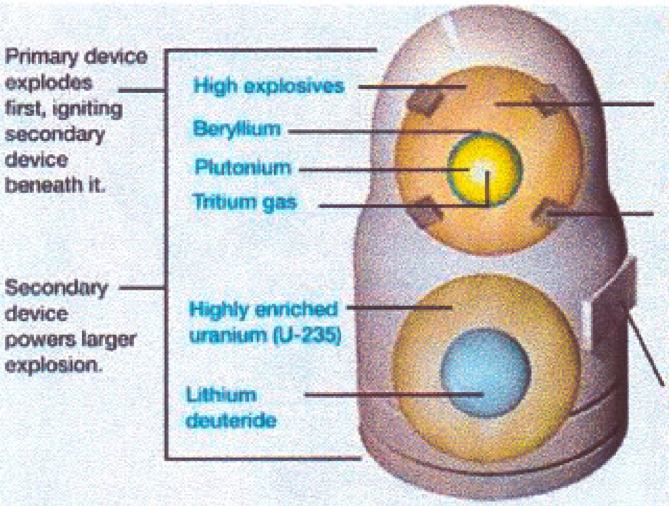
$^{2}H + ^{2}H \rightarrow ^{1}H$

used to boost fission weapons

LiD is a solid @ STP
(DT instead for
ERW)

Typical U.S. thermonuclear bombs ~ 1 Mt (- 9 Mt)

USSR deployed 20 Mt weapons

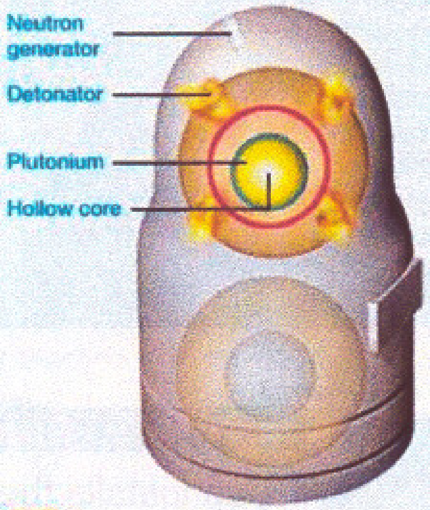


POSSIBLE IMPROVEMENTS

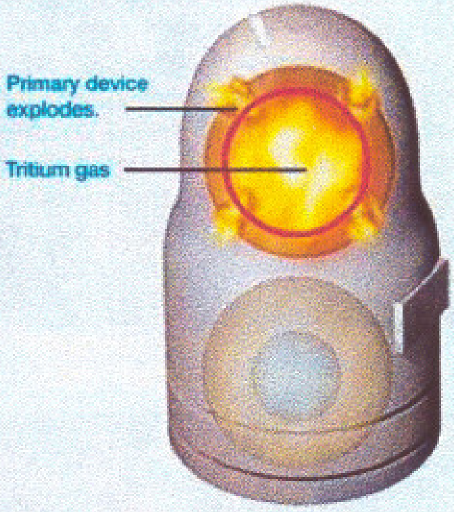
RELIABILITY: More plutonium or tritium to ensure secondary device is triggered.

SAFETY: Fire-resistant plutonium, insensitive high explosives, and "single-point-safe primaries" (which prevent an explosion if only one detonator fires) to guard against accidental detonation.

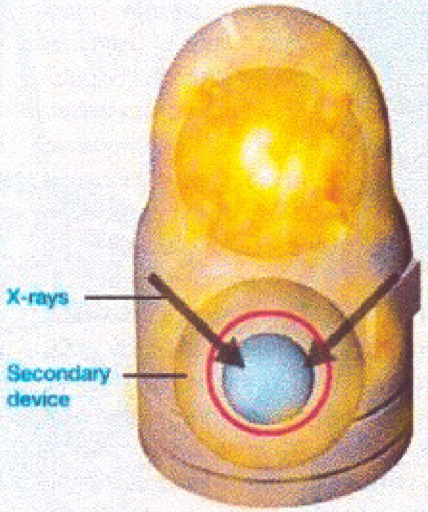
SECURITY: Encryption to prevent unauthorized activation of the device and safeguards that disable the bomb if the security system is breached.



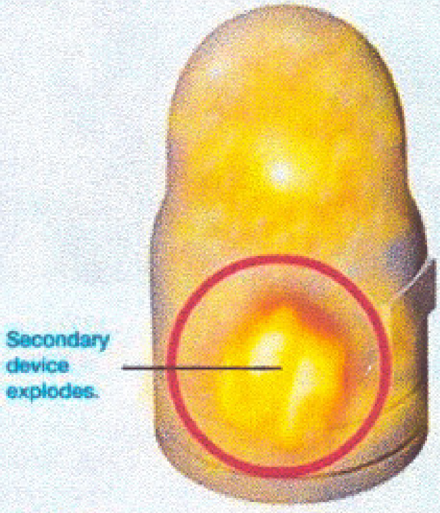
STEP 1
Detonators trigger a shell of high explosives, compressing the plutonium into a hollow core. The neutron generator then fires a stream of energetic neutrons into the plutonium, triggering a fission chain reaction.



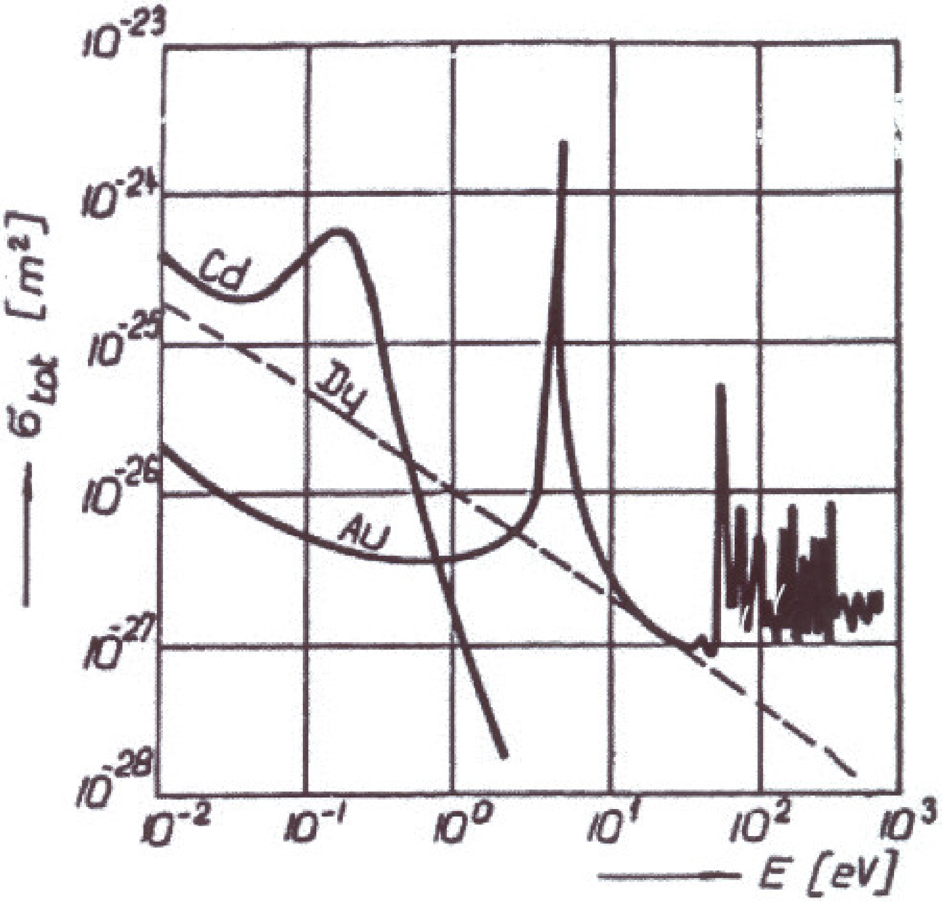
STEP 2
The energy from the fission reaction causes a fusion reaction in the tritium gas, magnifying the overall explosive power of the primary device.



STEP 3
A few millionths of a second later, high-energy X-rays reflect off the inside casting of the bomb, heating and compressing the secondary device.



STEP 4
The lithium deuteride inside the secondary device breaks down into a type of hydrogen, which undergoes thermonuclear fusion, releasing immense amounts of energy.


10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
σ_{tot} [m²]
Cd
Dy
AU
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
E [eV]

1000 bn