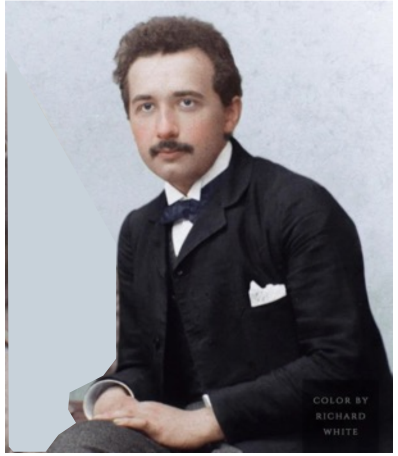
Historical Developments and Moments in Nuclear Astrophysics

Michael Wiescher
University of Notre Dame

Nuclear Physics before 1942
The Manhattan Project
The Big Bang Theory
The ignition of the atmosphere
From Superheavies to Supernova

The Scientific Basis –Formula

for the energy generation in bomb and stars



$$E = m \bullet c^2$$

Albert Einstein 1904

The nucleus as a quantum system, the birth of quantitative nuclear astrophysics

George Gamow 1928

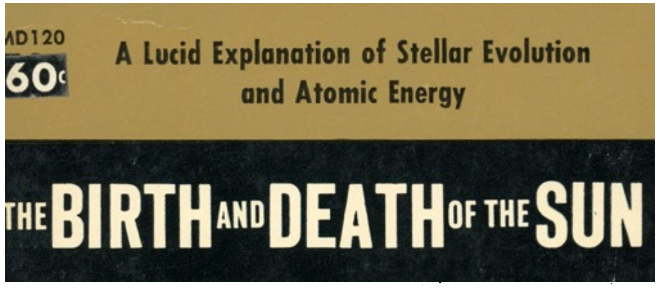
Arthur Eddington 1920

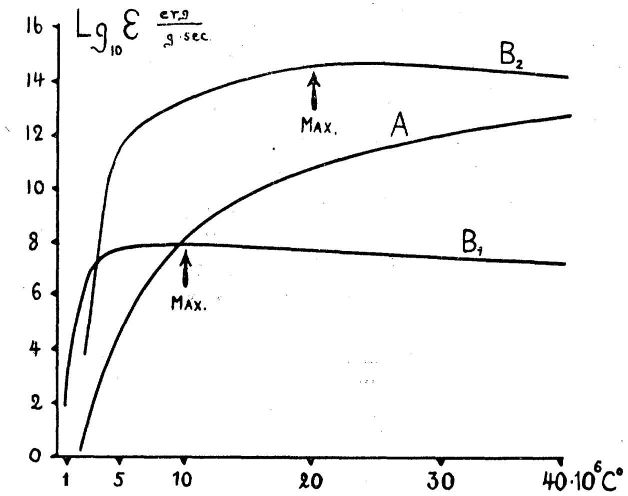
"What is possible in the Cavendish Lab may not be too difficult in the Sun"

The mass formula a conversion mechanism of mass to energy

Carl Friedrich von Weizsäcker 1934

From energy source to element origin





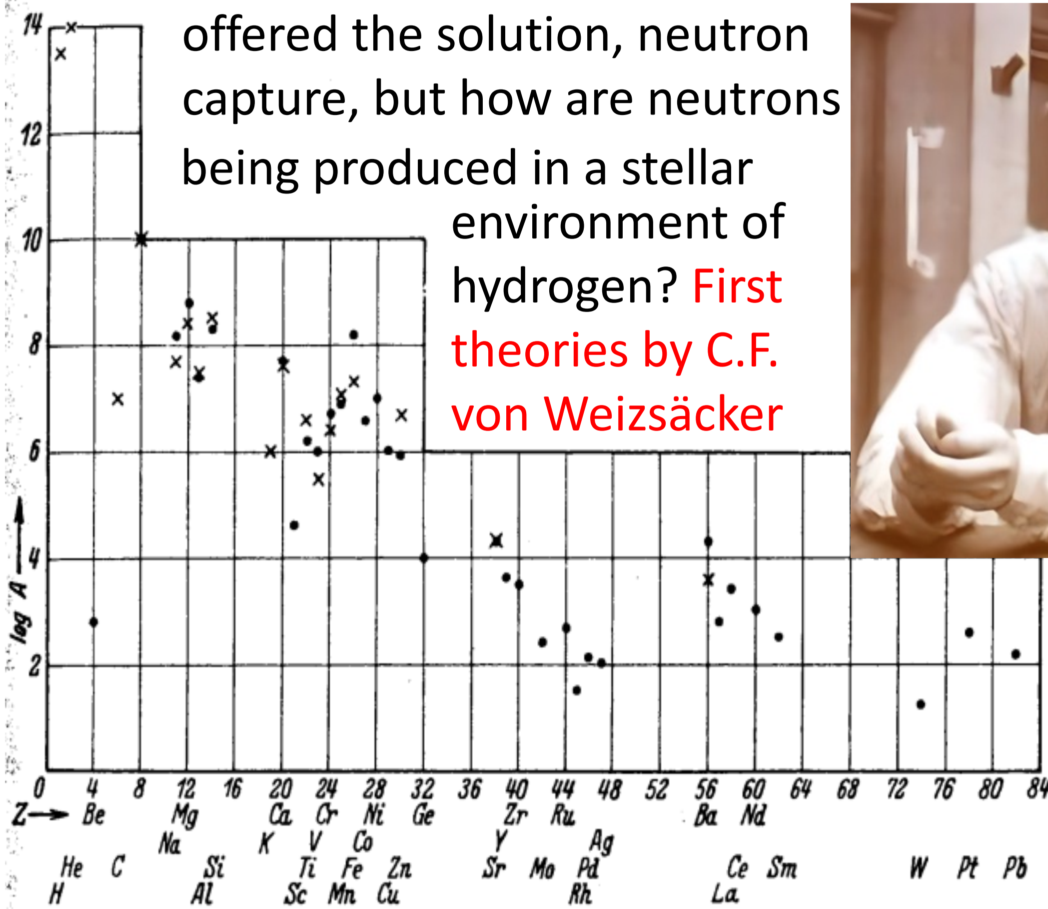
Stars are driven by the release of nuclear energy

G. Gamow and E. Teller, "The Rate of Selective Thermonuclear Reactions," *Phys. Rev.* 53 (1938): 608-609.

Observation of heavy elements in 1920-1930

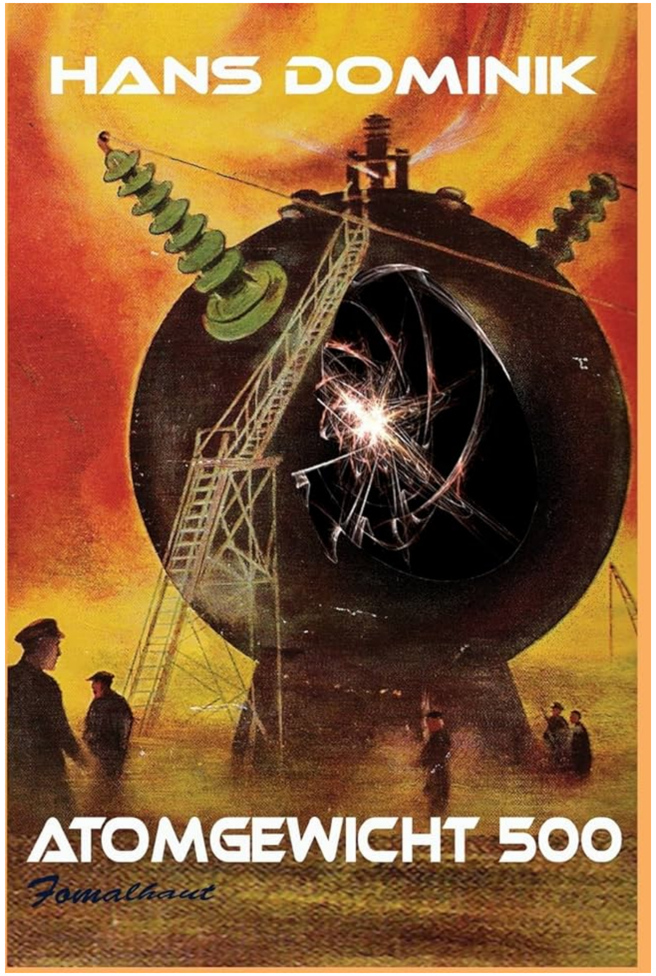
How have heavy elements been produced???

The discovery of the neutron in 1932 by James Chadwick offered the solution, neutron capture, but how are neutrons being produced in a stellar environment of hydrogen? First theories by C.F. von Weizsäcker

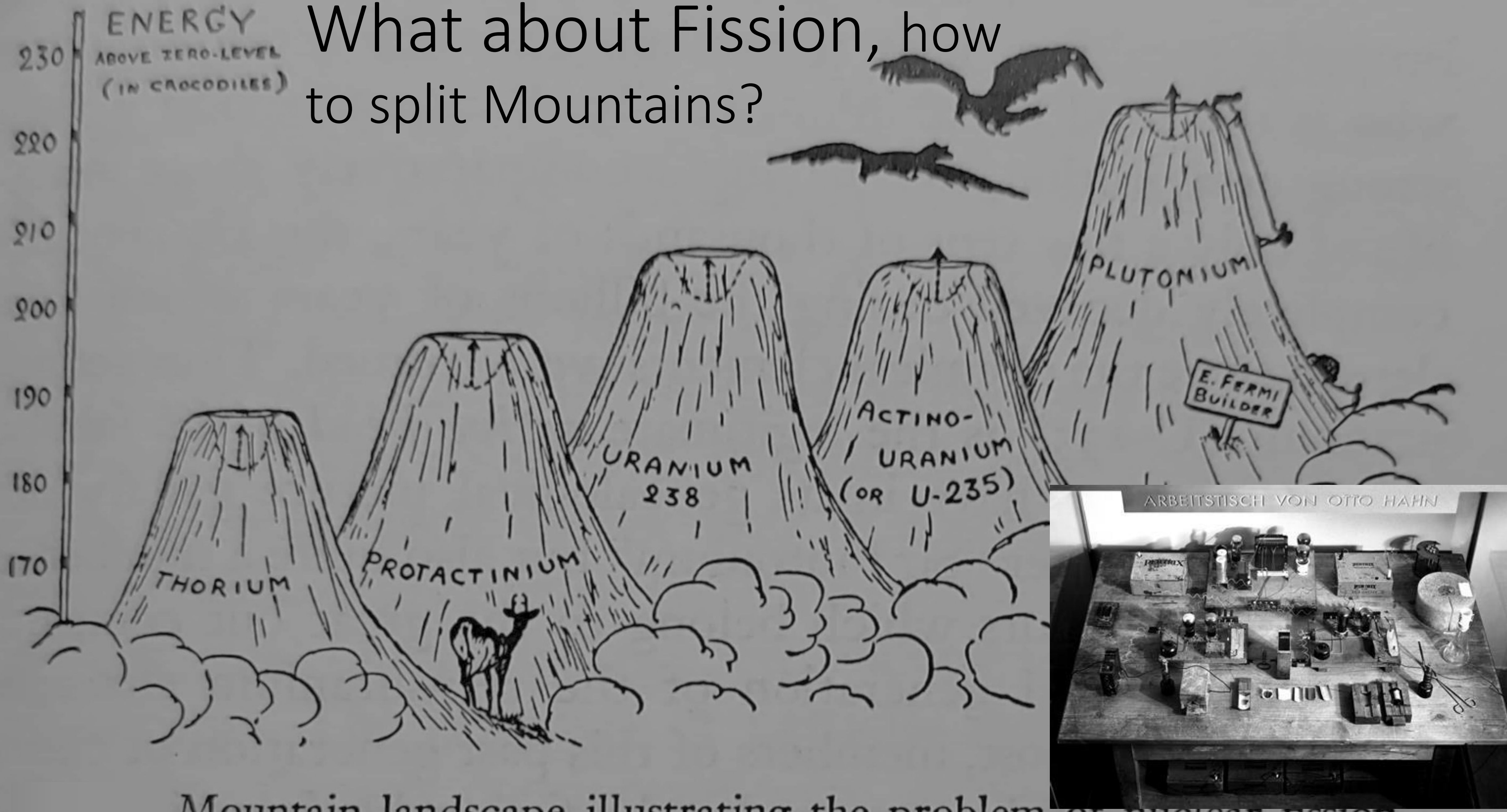


Neutrons for superheavy element production

Fermi claimed that continuous neutron capture would lead to the formation of ever heavier elements, a source of infinite energy through radioactive decay! The nuclear battery! Nobel prize 1938! But Hahn, Straßmann & Meitner demonstrated fission instead!



What about Fission, how to split Mountains?

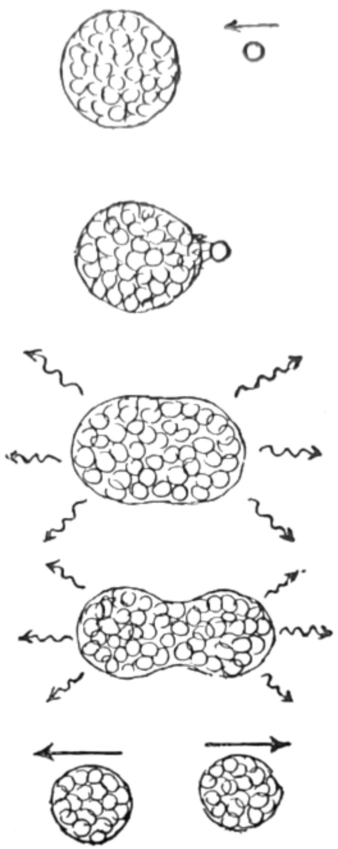


Mountain landscape illustrating the problem of nuclear fission.

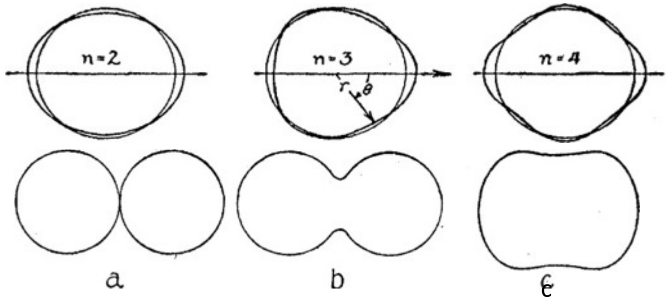
N. Bohr and J. A. Wheeler, first fission model

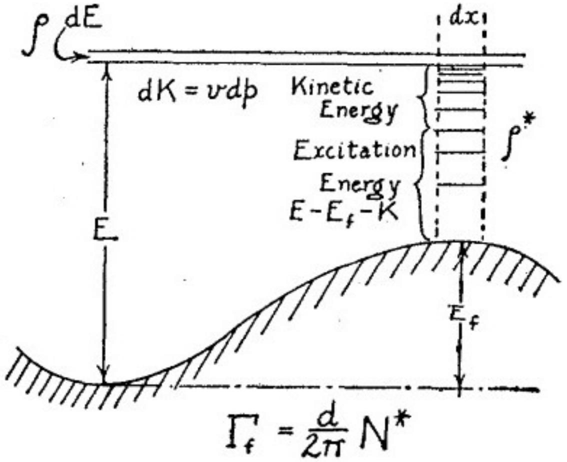
Phys. Rev. 56 (1939) 426-450

On the basis of the liquid drop model of atomic nuclei, the mechanism of nuclear fission was first formulated by describing the sequence of excitation and deformation modes occurring during the fission process. The fission probability increases with excitation energy and level density!



Bohr and Wheeler used reaction models developed by an Hungarian and Austrian Physicists, Eugene Wigner and Viktor Weisskopf to describe the complexity and role of nuclear deformation in terms of vibrational excitations modes in the fission process.

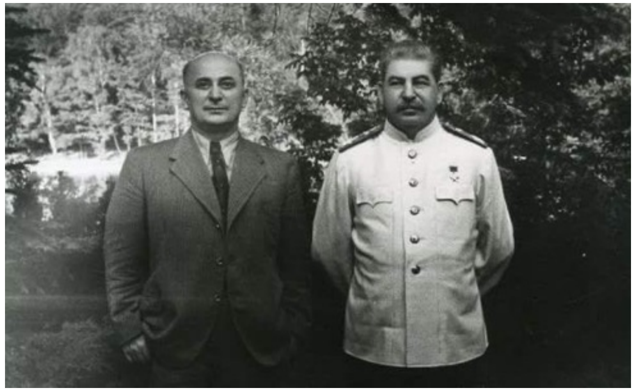




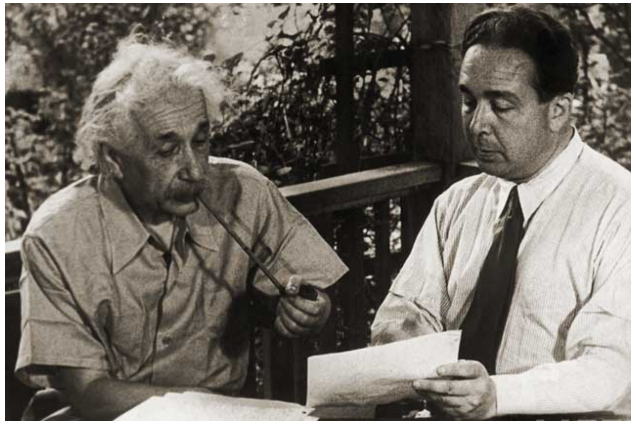
The International Competitors: 1940 to 1945

Germany had the technological and physics advantage: they discovered fission, they had an outstanding team of scientists in the Uranium Club, founded in 1940, and the controlled the Uranium supply. They considered to go for the bomb, but they were betting on a quick victory and did not go for a long-term investment in the Uranium project; later they concentrated on the development of missile-based weapons.

The Soviet Union discovered spontaneous fission, they had world class scientists in the Uranium commission, founded in 1940, they built a reactor for plutonium production in 1942, but had zero Uranium supply. They had to deal with the onslaught of the German armies in 1942, Stalin postponed a bomb development but kept an eye on US-British developments through a ring of well-placed spies.



The United States and the United Kingdom had a big influx of technical and theory expertise through European refugees, who were arguing in favor of the bomb (Einstein-Szilard Letter), convincing Roosevelt to initiate a project towards the development of a bomb. Merging with the British Tube-Alloy project initiated extensive funding for the Manhattan Project, the biggest research project ever started in the United States, $2 Billion (In 2023 dollars, ~ $ 60 Billion). It changed the entire military and research structure in the USA for decades to come!



1942 Recruitment in Berkeley

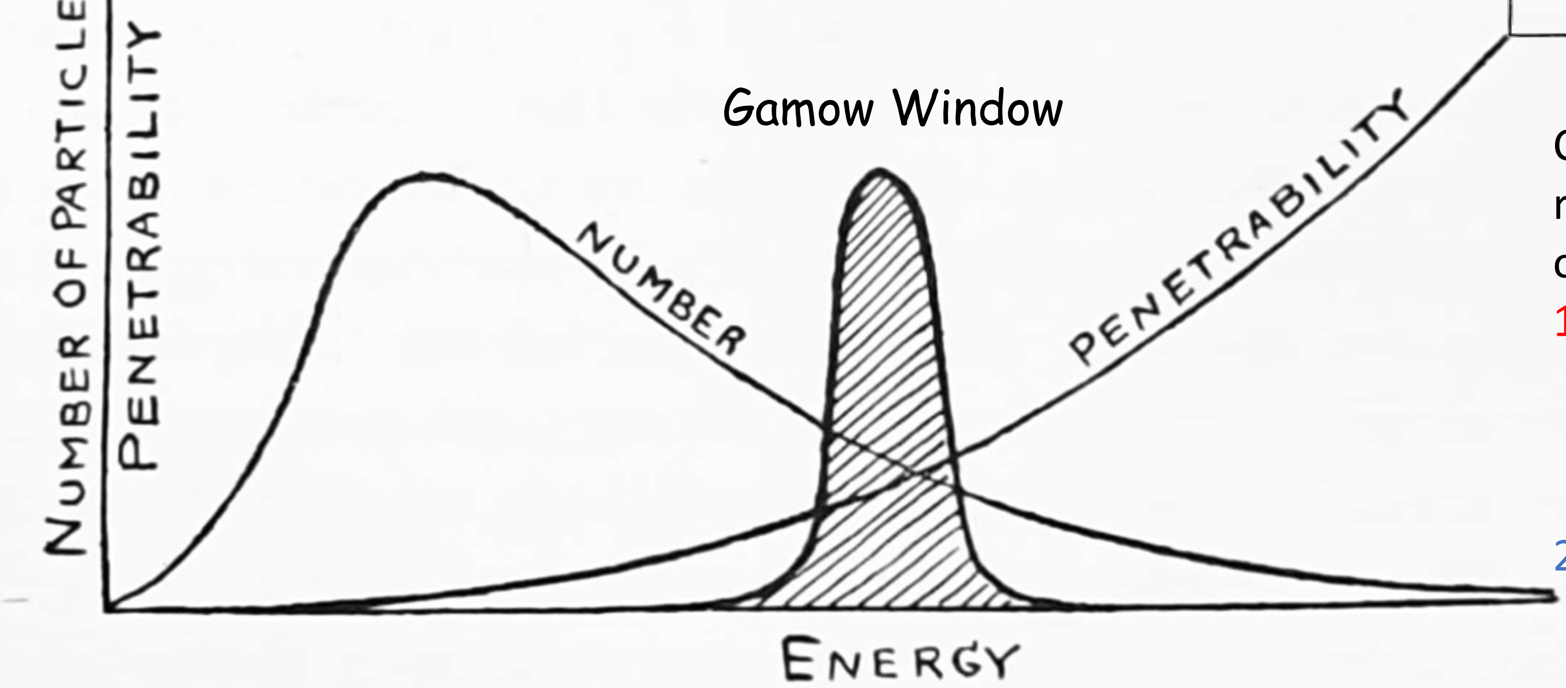
Recruitment of young theorists in Berkeley 1942 for the Manhattan Project.
George Gamow was not eligible as former Red Army officer!

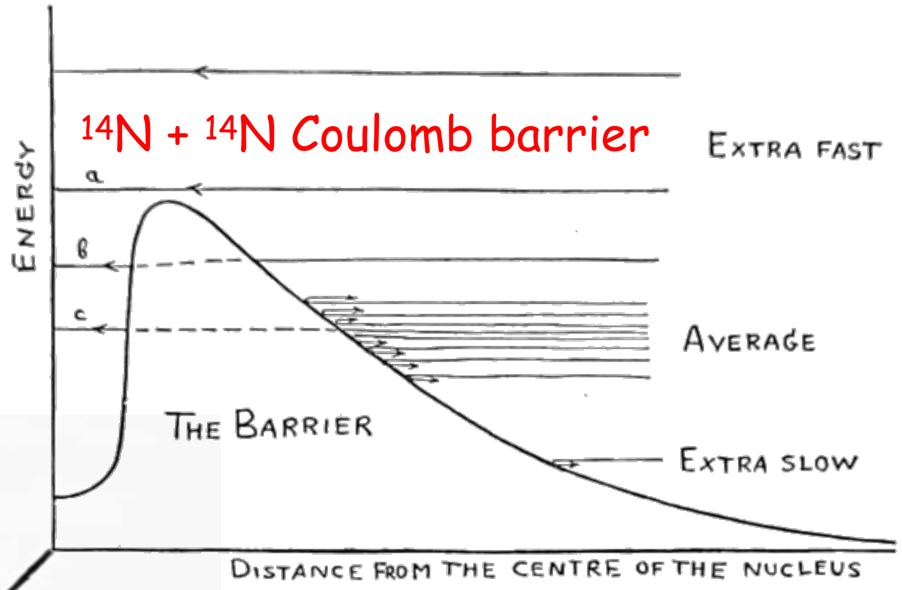
Edward Teller brought up the possibility of fusion reactions in the atmosphere Driven by the energy release of the fission bomb, $^{14}N+^{14}N$ and $^{14}N+^{1}H$, a chain reaction as postulated by Szilard. Oppenheimer was puzzled and concerned!

Oppenheimer became worried about such a possibility, but Hans Bethe as director of the theory division disagreed

What about the Fear?

Maxwell-Boltzmann B distribution expands with Temperature





Coulomb barrier between ^{14}N and ^{14}N is reduced causing an exponential increase of cross section!

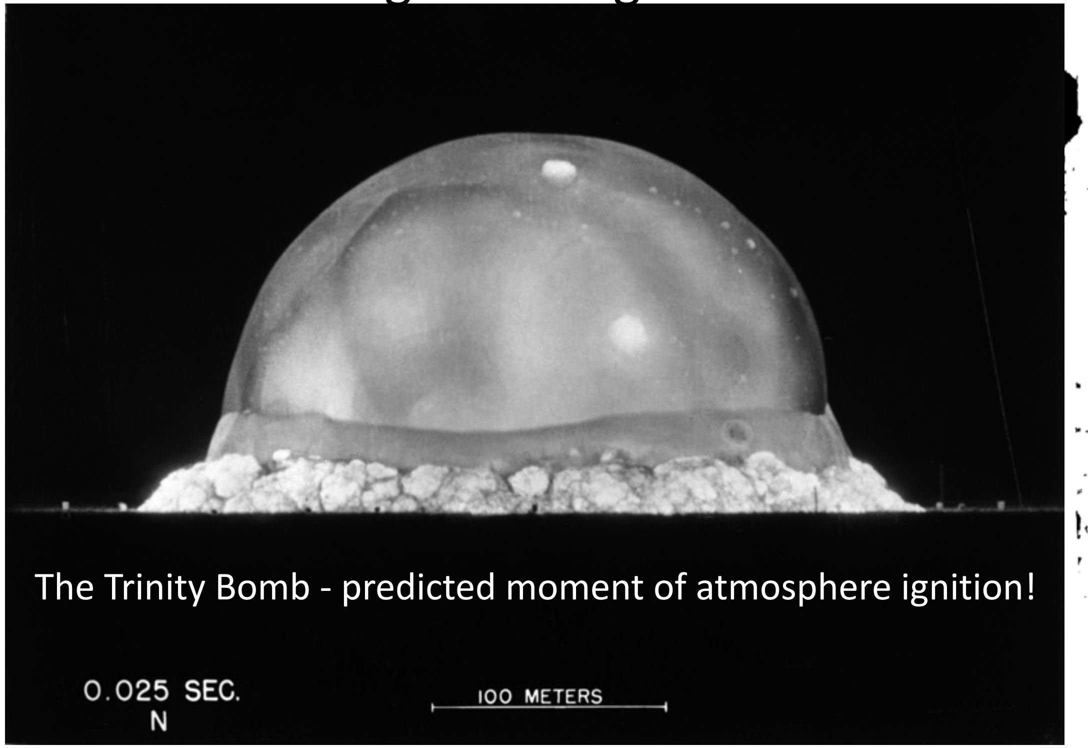
1. Is the temperature generated by a fission bomb sufficient to trigger fusion of nitrogen or oxygen in the atmosphere?
2. Are the radiative cooling effects through gamma, neutrons and electron escape sufficient to prevent that?

The $^{14}N + ^{14}N$ and $^{14}N + ^{1}H$ cross section were only estimated!!!

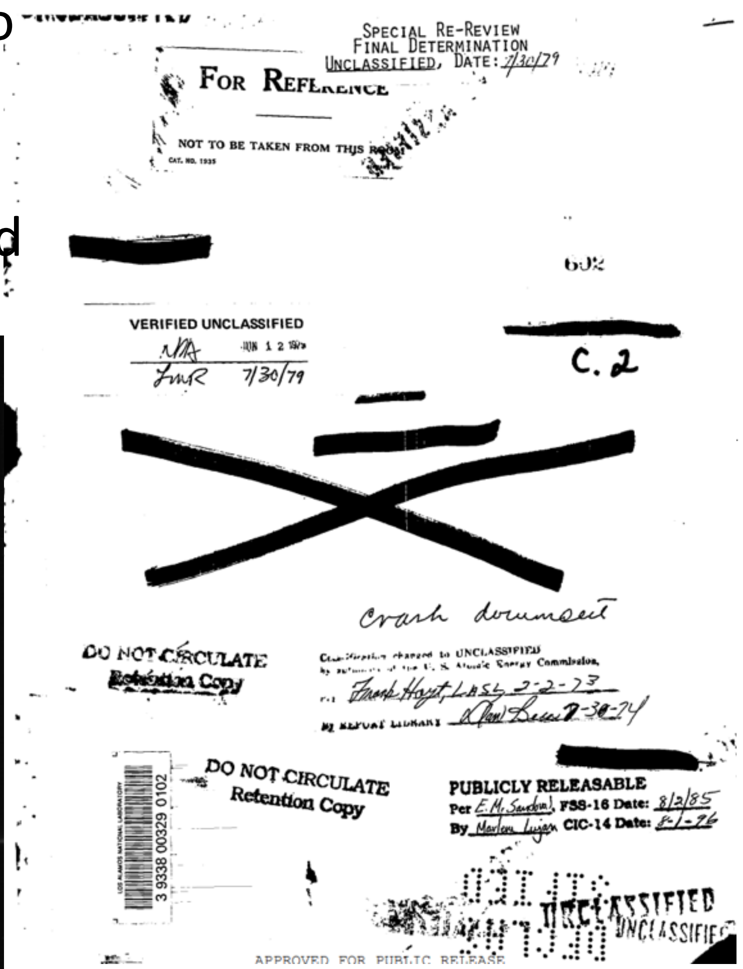
Fusion of Nitrogen and Hydrogen, and Oxygen

$^{14}N+^{14}N$, $^{14}N+^{1}H$. $^{16}O+^{16}O$ in the hotspot of the explosion

Oppenheimer traveled by train to Chicago to discuss the radiation cooling, compensating the released heat from the bomb with Arthur Compton. Classified report by Edward Teller in 1946 signalizes agreement!



The Trinity Bomb - predicted moment of atmosphere ignition!


SPECIAL RE-REVIEW
FINAL DETERMINATION
UNCLASSIFIED, DATE: 7/30/79

FOR REFERENCE

NOT TO BE TAKEN FROM THIS ROOM

[redacted]

VERIFIED UNCLASSIFIED
7/30/79

[redacted]

C. 2

[redacted]

Crash document

DO NOT CIRCULATE
Retention Copy

Classification changed to UNCLASSIFIED
by authority of the U. S. Atomic Energy Commission,

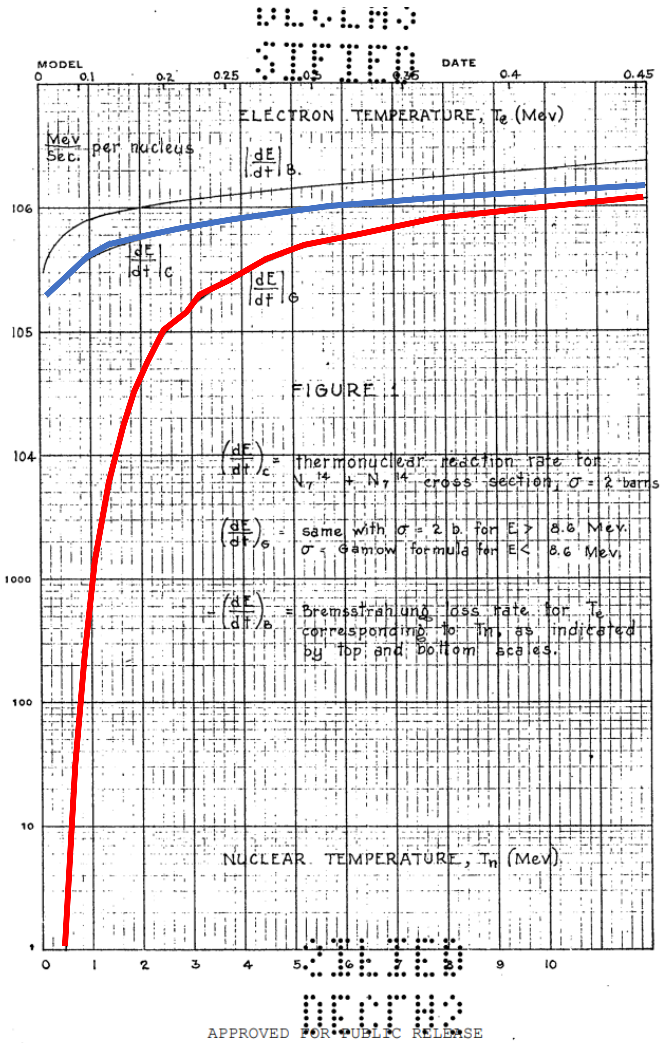
DO NOT CIRCULATE
Retention Copy

[redacted]

PUBLICLY RELEASABLE

UNCLASSIFIED

APPROVED FOR PUBLIC RELEASE

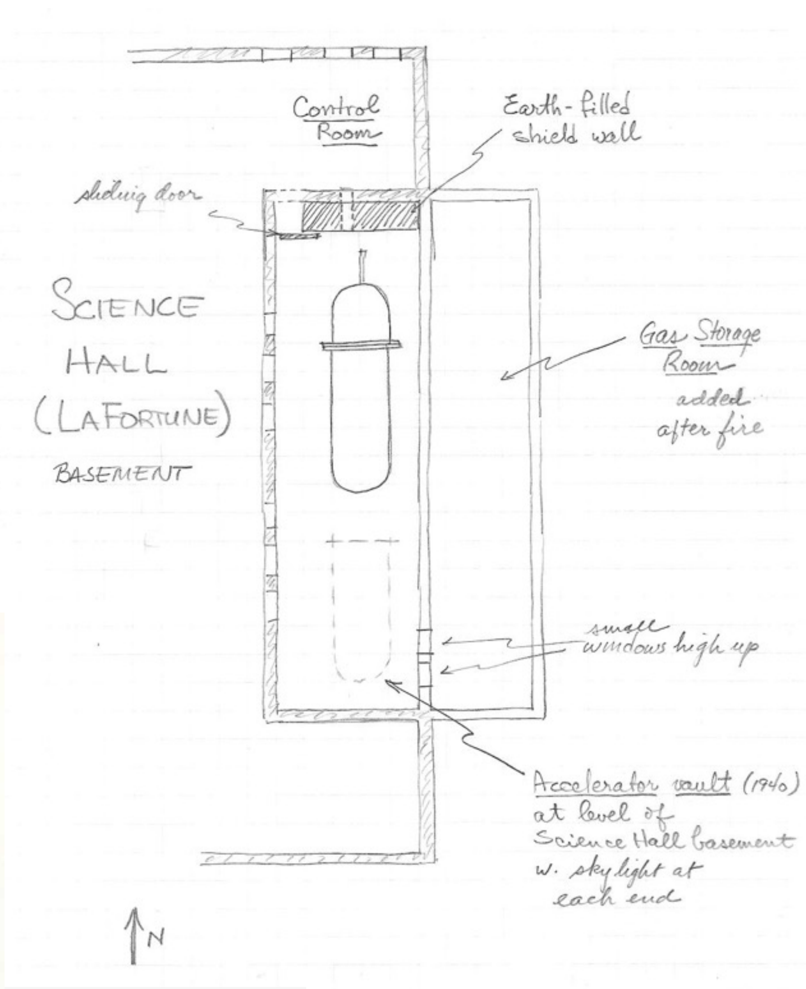


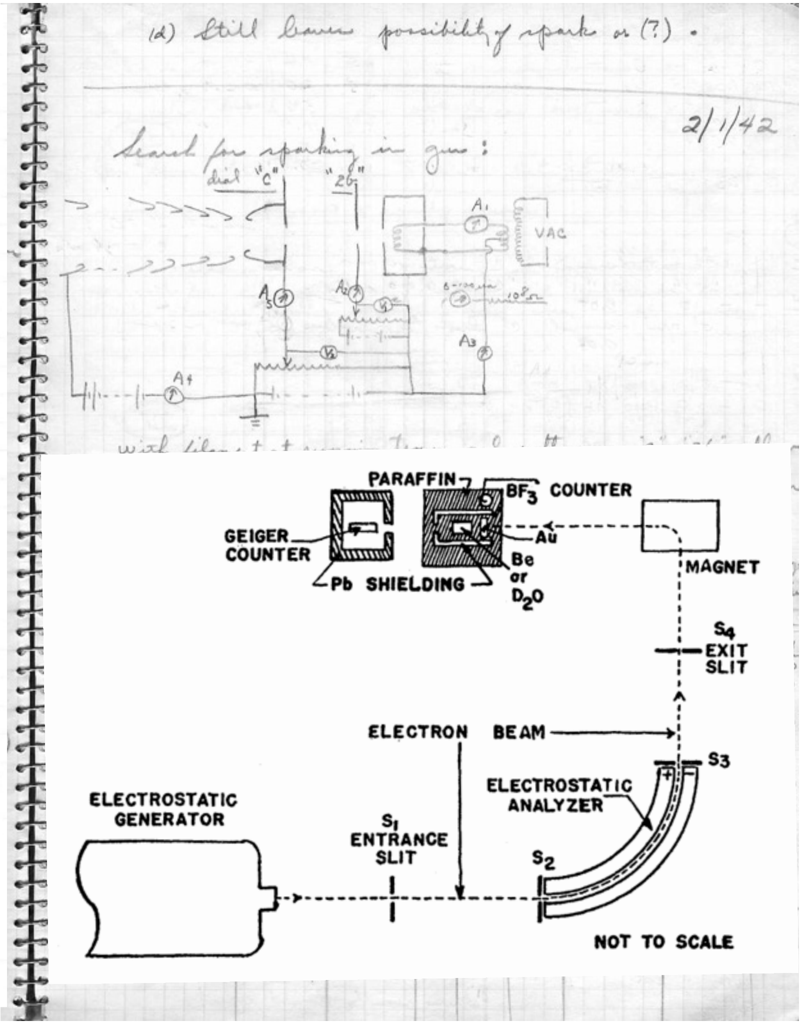
Manhattan Project@nd.edu 1942-1952

A new accelerator, just commissioned at Notre Dame, became part of the Manhattan Project!

Bernie Waldman was in charge!

Daily users from Chicago by South-Shore and Tram

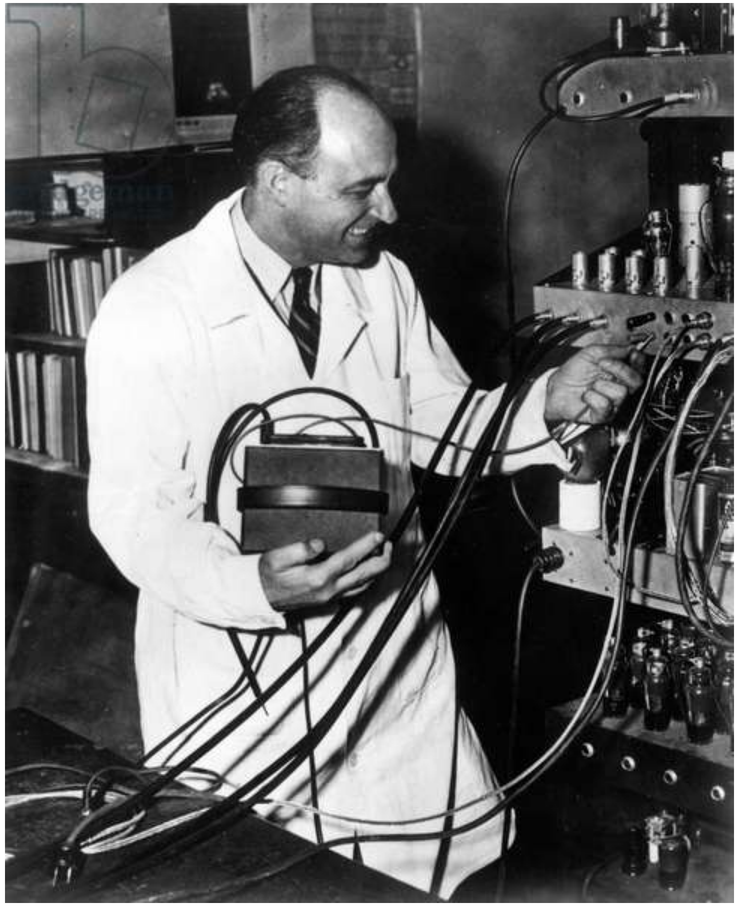


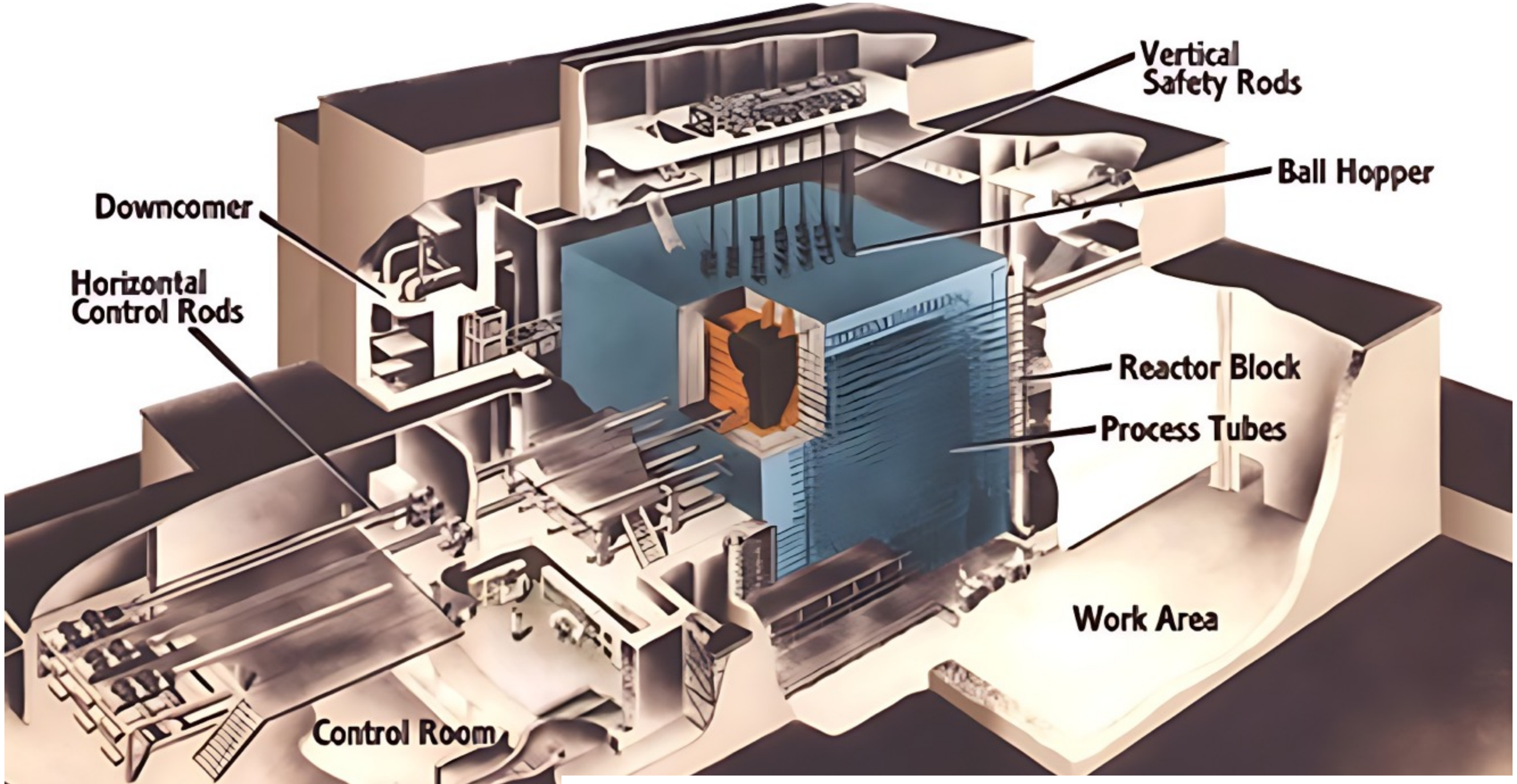


Waldman and Chicago Metallurgical Institute

The new accelerator run by Waldman, Agnew, and Fermi for radiation transmission tests in different materials and radiation effects on materials for the first nuclear reactor in Chicago – the pile - and the reactors in Hanford, WA towards the breeding of plutonium.

The Pile below the Stagg football field in Chicago





The first nuclear reactor alive, soon to be replaced in 1942 by the Hanford reactor facility, operating first three, later nine breeding reactors at the Columbia River!

PHYSICAL REVIEW VOLUME 70, NUMBERS 9 AND 10 NOVEMBER 1 AND 15, 1946

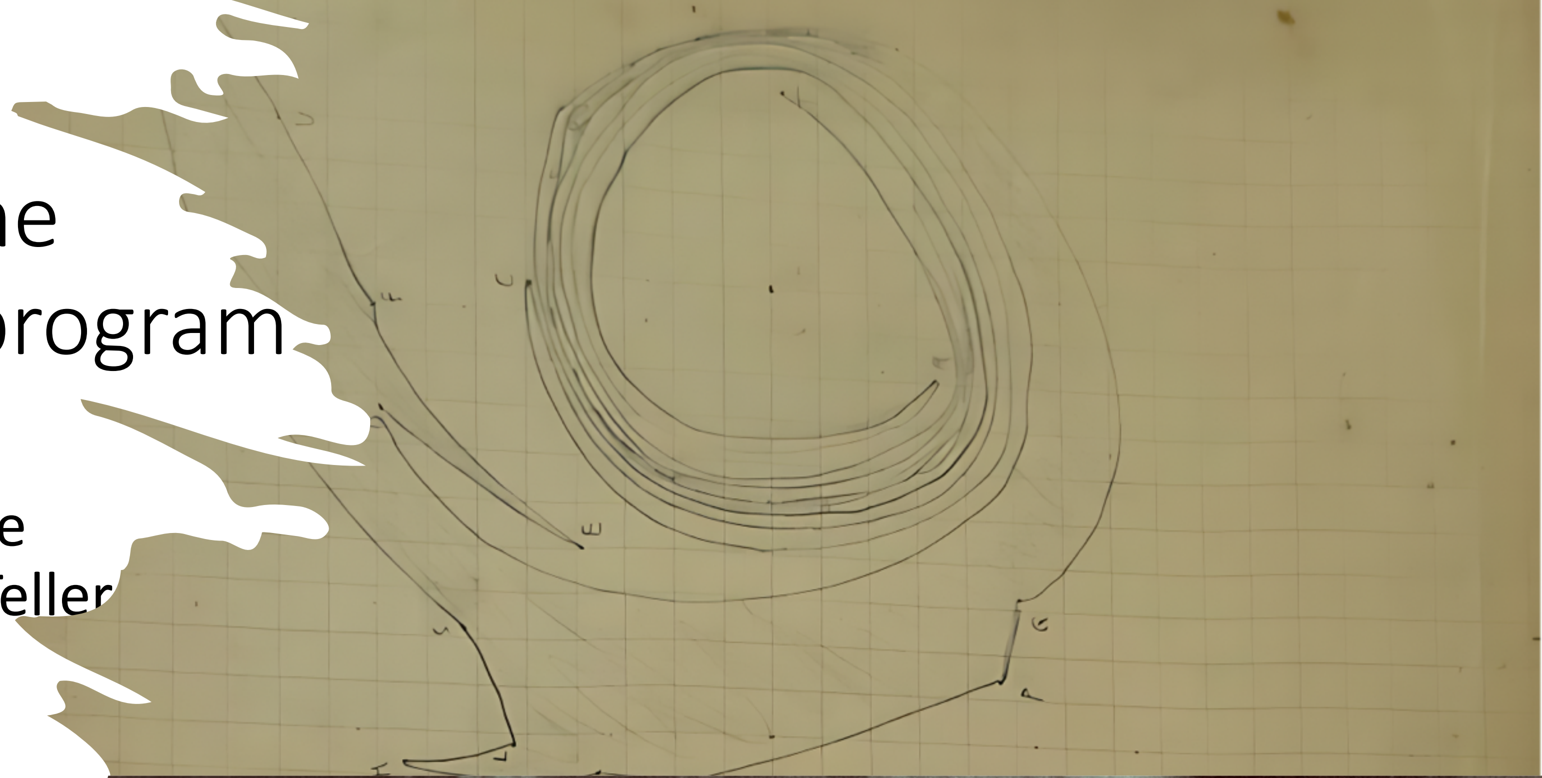
Elastic Backscattering of $d-d$ Neutrons

J. H. Manley,* H. M. Agnew,** H. H. Barschall,*** W. C. Bright, J. H. Coon,*** E. R. Graves, T. Jorgensen,† and B. Waldman††
University of California, Los Alamos Scientific Laboratory, Santa Fe, New Mexico
(Received August 29, 1946)

The backscattering of $d-d$ neutrons was investigated for several materials. A directional thick paraffin detector was used. The detector was sensitive primarily to neutrons which had been scattered elastically or with little energy loss.

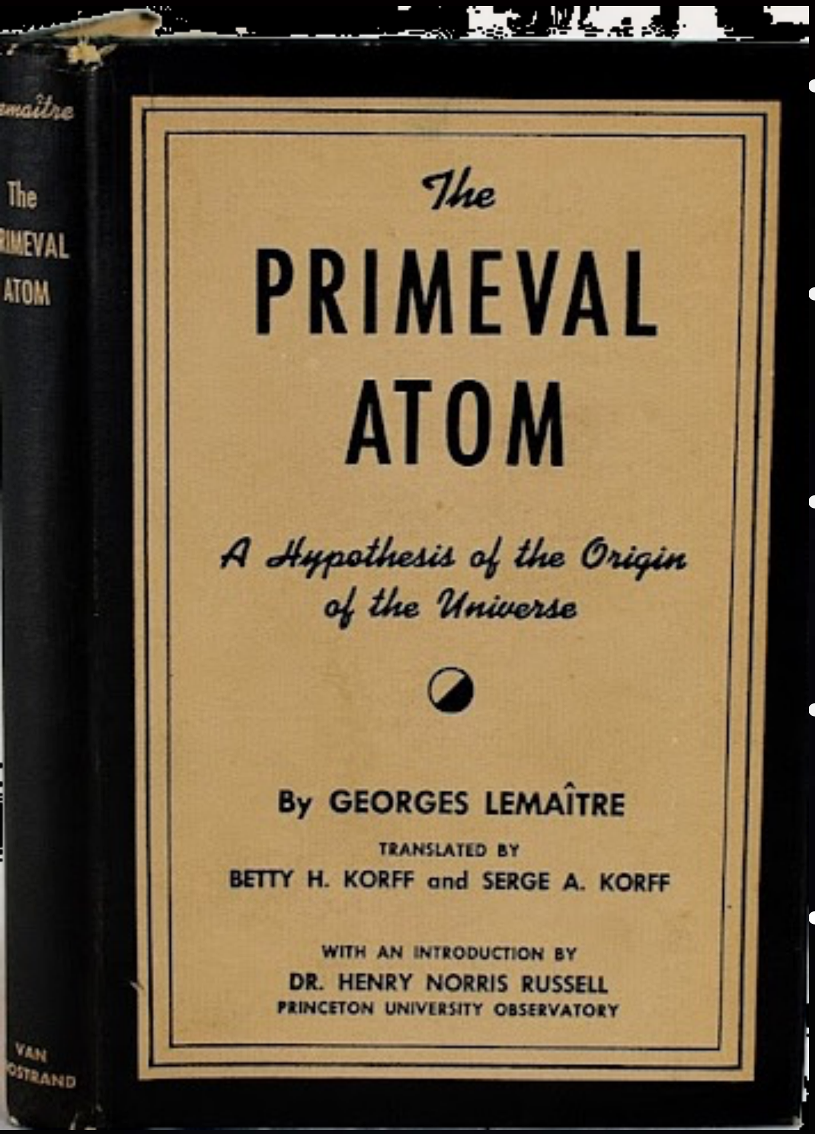

Trinity - Mission Accomplished
New Ideas and Developments in Science
The Big Bang Theory
Heavy Ion Fusion
Super-Heavy Elements
The Physics of Stars

Prewar communications continue …. In view of the rapidly developing test program

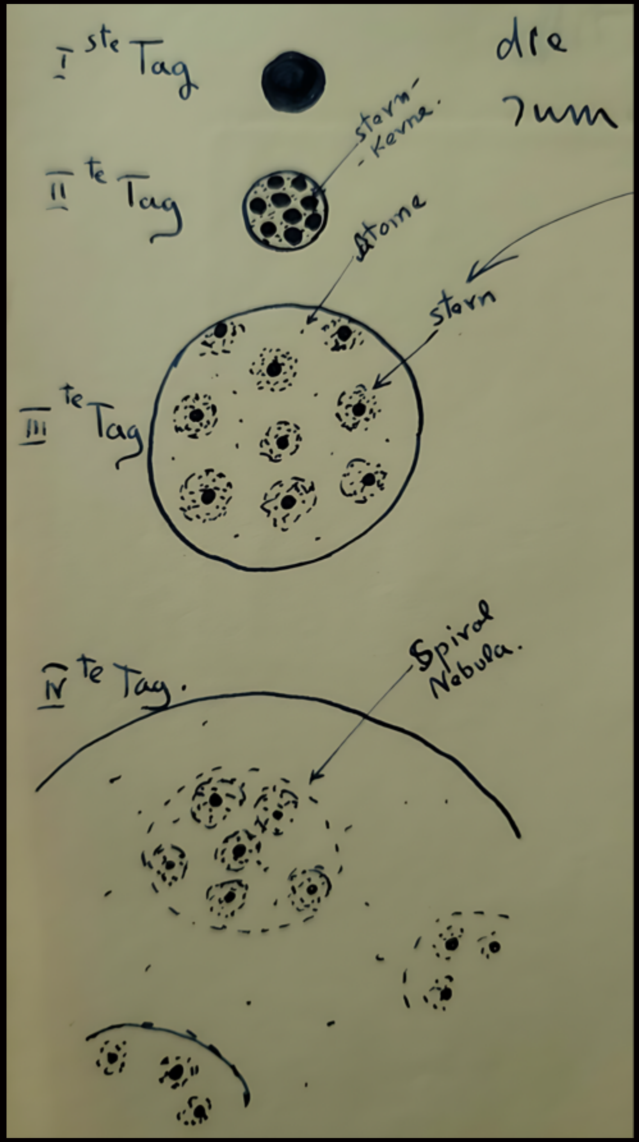


- Close communication and exchange between Weizsäcker, Gamow, and Teller until 1938
- March 1945 Gamow praised the turbulence theory of Weizsäcker explaining galactic shape and rotation
- Teller took German d+d fusion data as first guide for a fusion device
- The question about the source of neutrons for the production of heavy elements triggered new ideas.

The Big Bang Theory



- Failure of Weizsäcker to identify a special neutron source because he did not consider helium burning
- Lev Landau proposed neutron star idea as the natural end of stellar evolution, picked up by Oppenheimer
- Gamow and Weizsäcker considered neutron stars as neutron source, but it represented the end and not the beginning of stellar evolution?
- Gamow picked up on the idea of the primeval atom by George Lemaître and proposed a Big Bang scenario as source of the heavy elements
- With the expansion of the universe, matter clumped, was spinning off, introducing orbital momentum to the universe, while shedding galaxies, stars, and neutrons!



Parents of the Big Bang Nucleosynthesis Idea

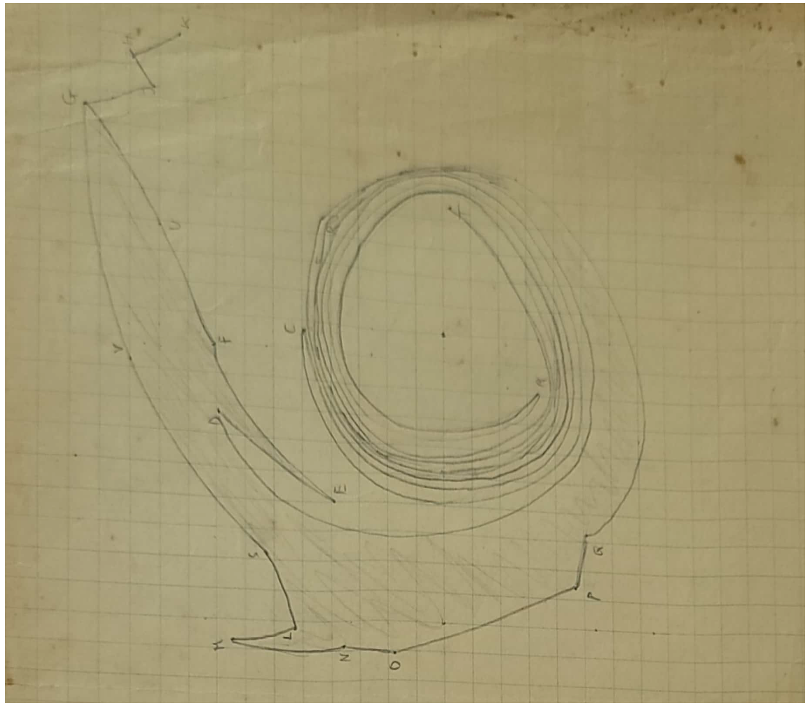
George Gamow and Edward Teller, “The Expanding Universe and the Origin of the Grand Nebulae,” Nature 143 (1939): 116–17.

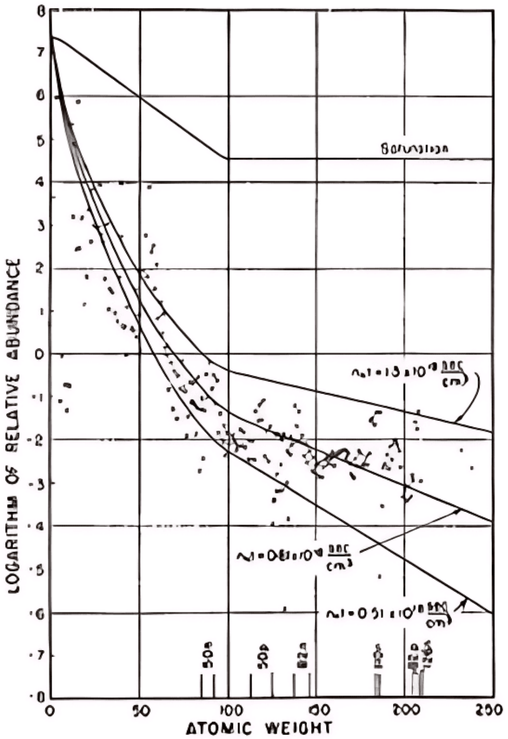
George Gamow, “Expanding Universe and the Origin of Elements,” Phys. Rev. 70, (1946): 572–573.

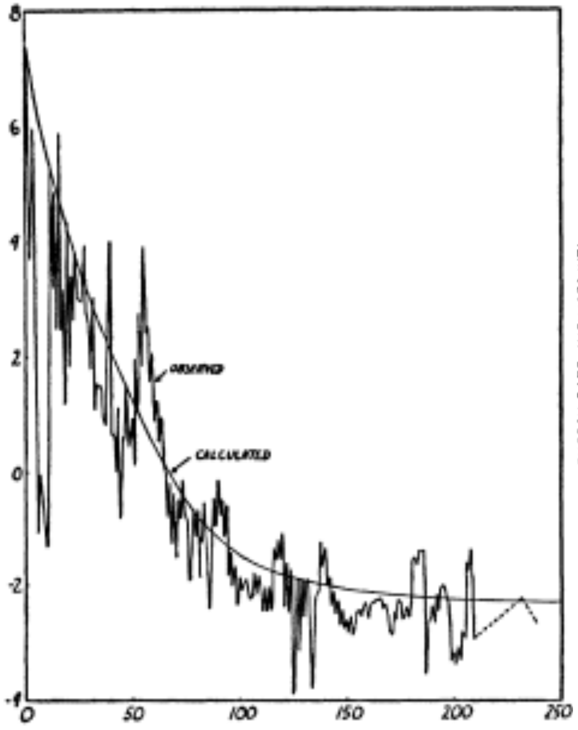
Carl Friedrich v. Weizsäcker, "Das Spektrum der Turbulenz bei großen Reynoldsschen Zahlen." *Zeitschrift für Physik* 124.7 (1948): 614-627.

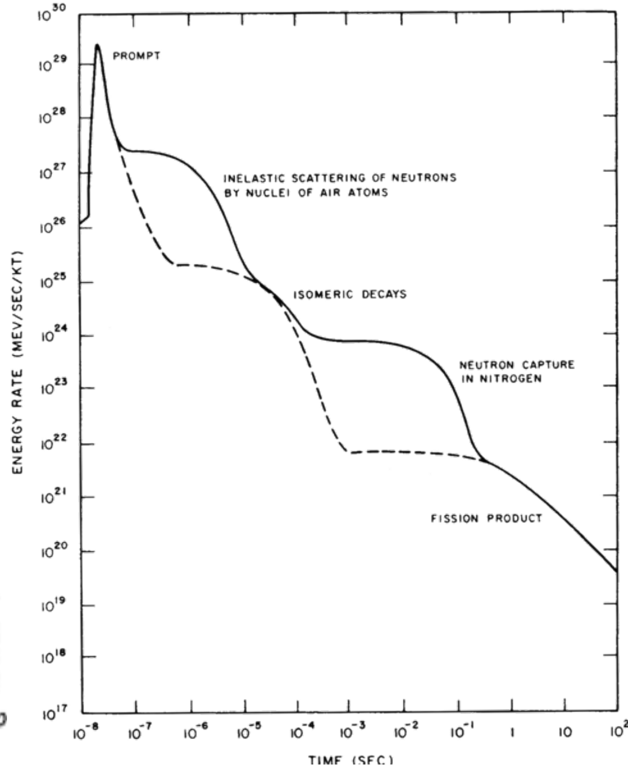
Maria Goeppert-Mayer and Edward Teller, “On the Origin of Elements,” Phys. Rev. 76 (1949): 1226-1231.

Big Bang Nucleosynthesis Predictions









The turbulence theory of Weizsäcker explained the origin of cosmic structures from galaxies, spiral nebulae, planetary systems to the microcosmos to generate neutrons for the build-up of heavy elements in one shot! The Nucleosynthesis predictions came from Georges Gamow, Edward Teller, and Maria Goeppert-Mayer! **It was the time of the nuclear test program 1944 to 1954 and observations of fall-out drove the ideas about neutron release from a single event with subsequent neutron capture.**

From Fission to Fusion

PHYSICAL REVIEW VOLUME 73, NUMBER 8 APRIL 15, 1948

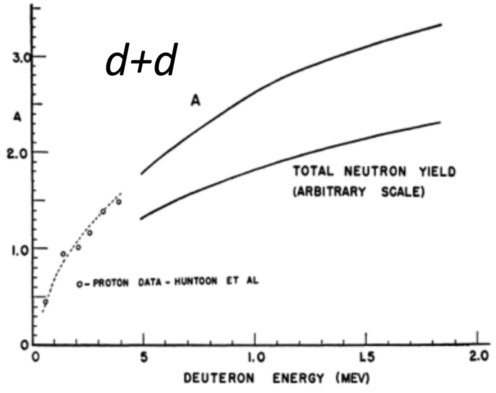
Theoretical Considerations Concerning the $D+D$ Reactions

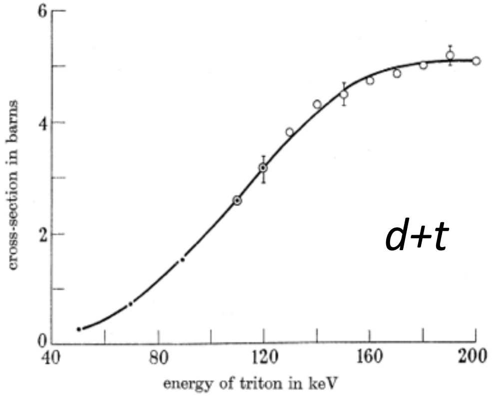
E. J. KONOPINSKI, *Indiana University, Bloomington, Indiana*

AND

E. TELLER, *University of Chicago, Chicago, Illinois*

(Received January 12, 1948)





Konopinski & Teller (1948) considering the D-D reaction, have shown that the cross-section may be made up of terms of the form

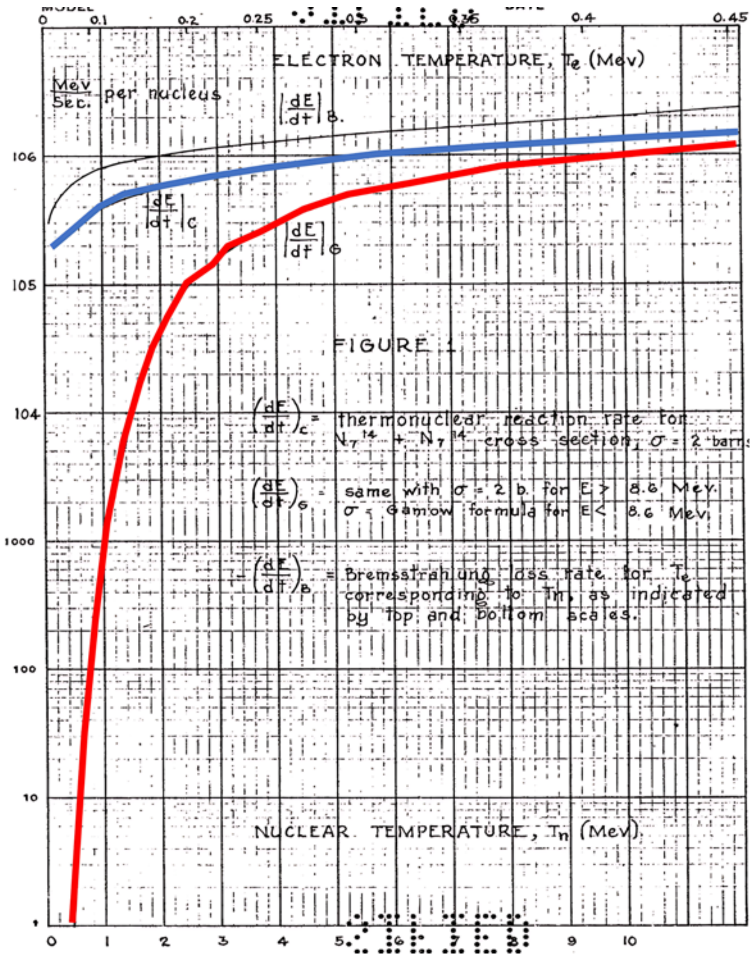
d+d $$\sigma_l = \pi \lambda\!\!\!^{-2}(2l+1)\, g_l\, |\alpha_l|^2 P_l,$$

to the form of a Breit-Wigner resonance given by Bethe (1937). In this way they obtained formulae of the form

d+t $$\sigma(E) = \frac{A}{E} \frac{\exp\left[-\frac{2\pi e^2}{\hbar v}\right]}{(E_r - E)^2 + \frac{1}{4}\Gamma^2}.$$

The Fear of Bigger Bombs – the Super

The Ulam-Teller design was based on the original Teller idea, that the heat would be generated by a fission bomb to create the conditions for fusion. Instead of nitrogen, deuterium and tritium would be the fuel, the latter produced at Hanford via the $^{6}Li(n,t)^{4}He$ reaction.

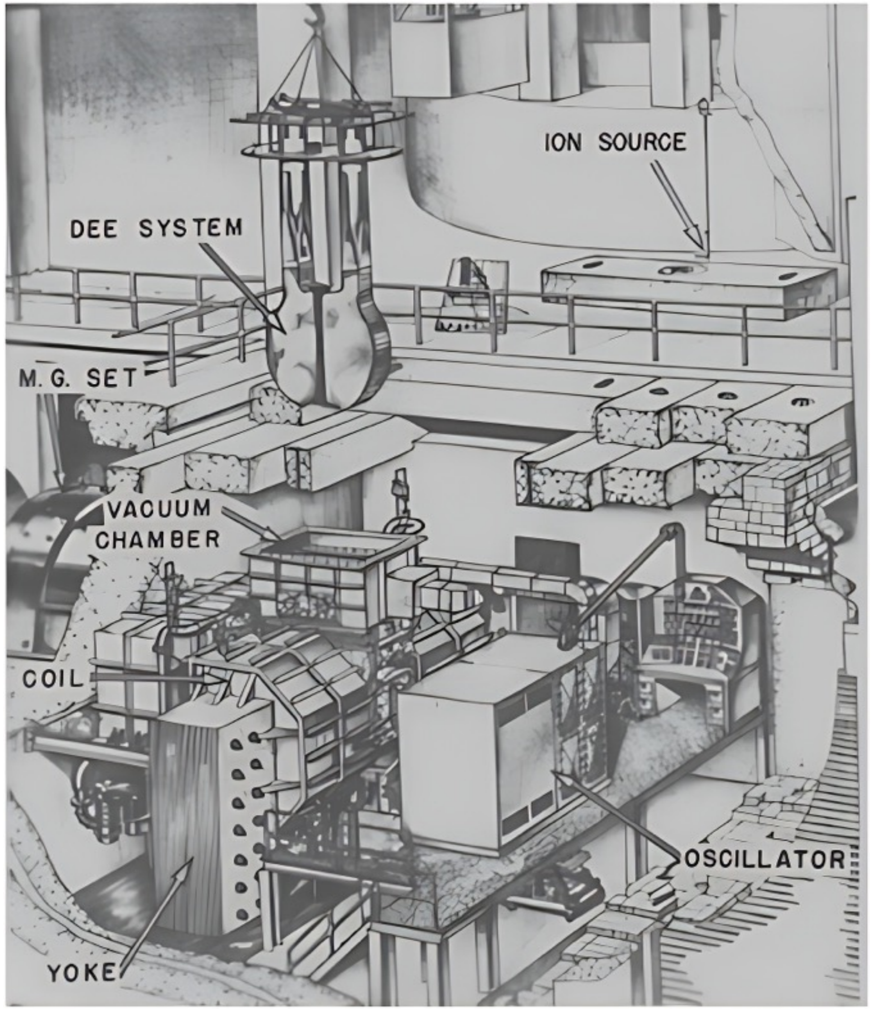


The Ulam-Teller design boosted the yield from the 20 kton to the 20 Mton range, raising again concerns about atmosphere ignition, will radiation cooling be sufficient???

The disquieting feature is that the 'safety factor', i.e. the ratio of losses to gains of energy, decreases rapidly with initial temperature, and descends to a value of only about 1.6 beyond a 10-MeV temperature. It is impossible to reach such temperature unless fission bombs or thermonuclear bombs are used which greatly exceed the bombs now under consideration.

The new 86" Cyclotron

New 86" Cyclotron was installed in 1952 at Oak Ridge to measure heavy ion fusion $^{14}N+^{14}N$, $^{16}O+^{16}O$ etc. This was followed 10 years later by the installation of the 88" cyclotron in Berkeley



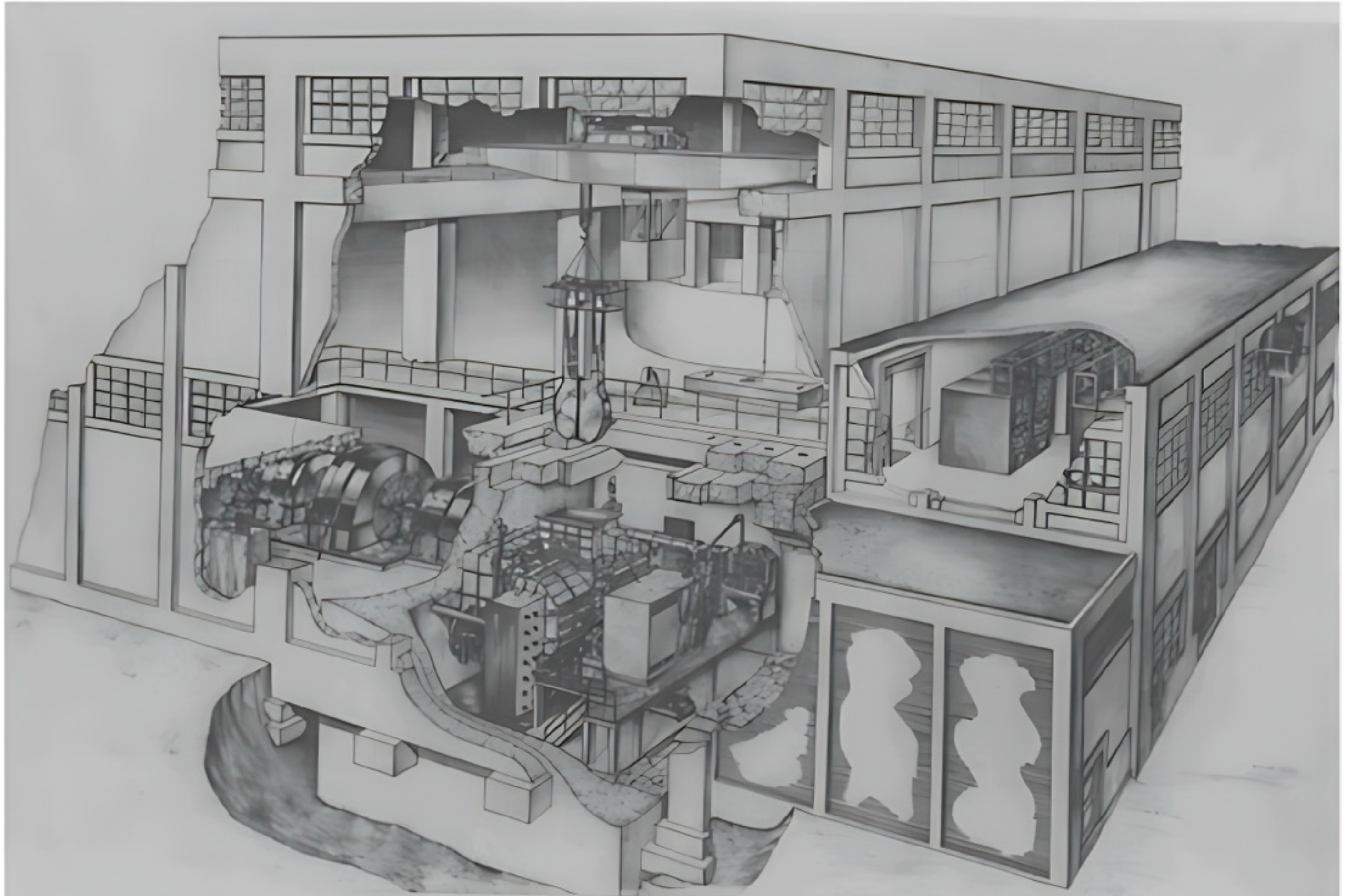
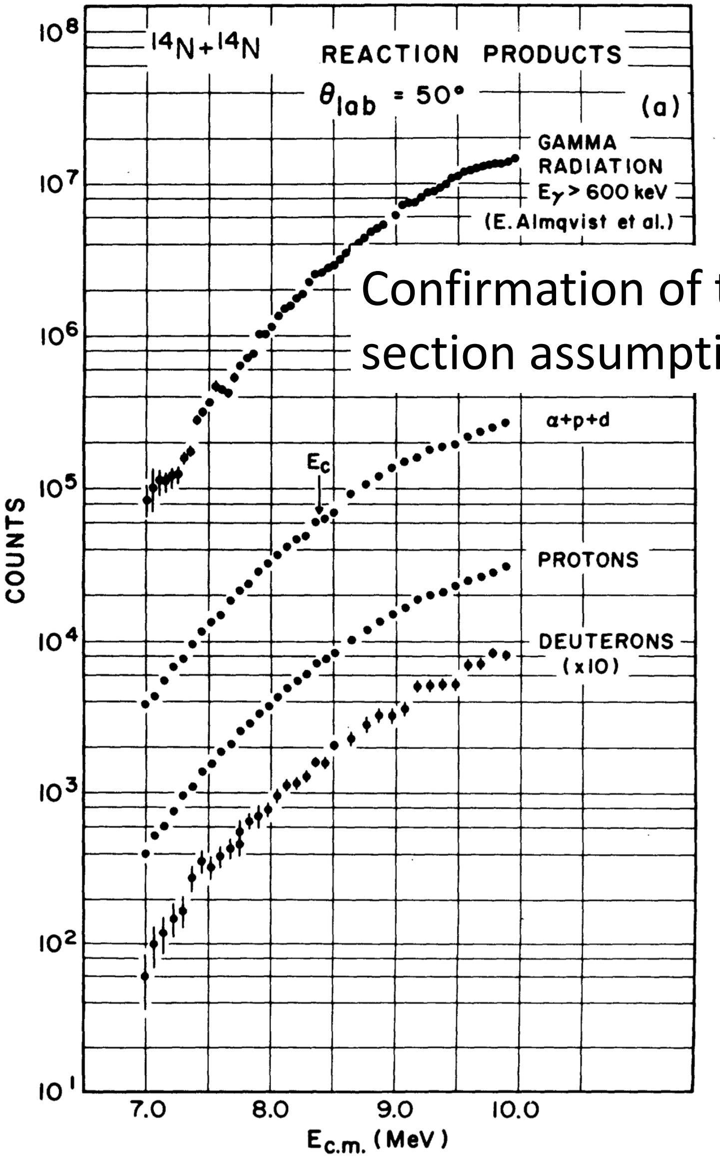
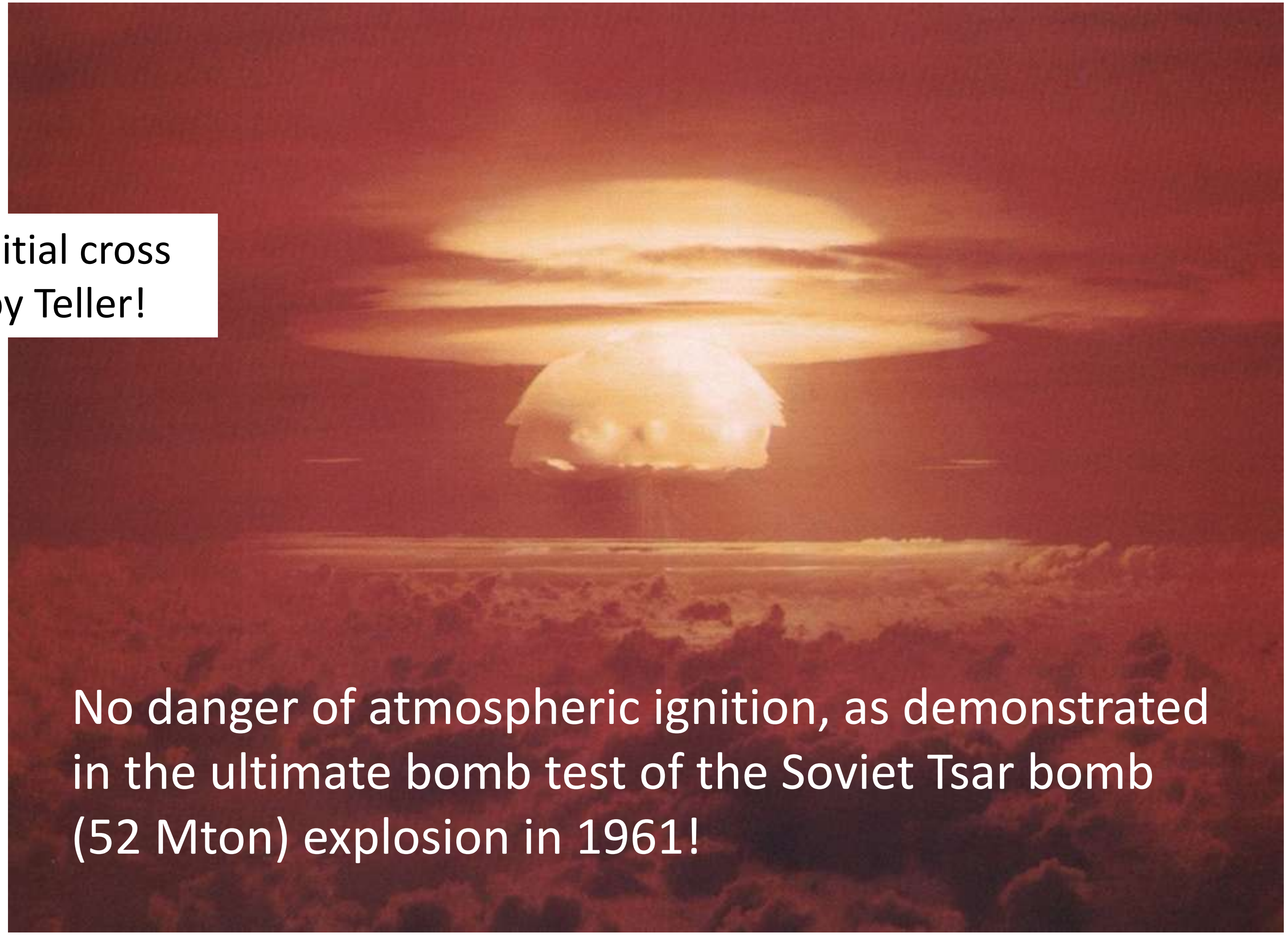


FIGURE I THE 86 INCH CYCLOTRON INSTALLATION

Cross Sections Studies and Confirmation

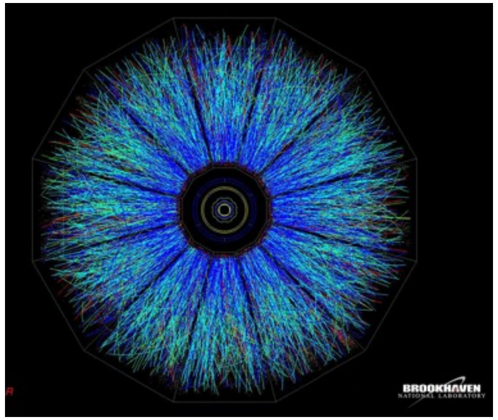


Confirmation of the initial cross section assumptions by Teller!



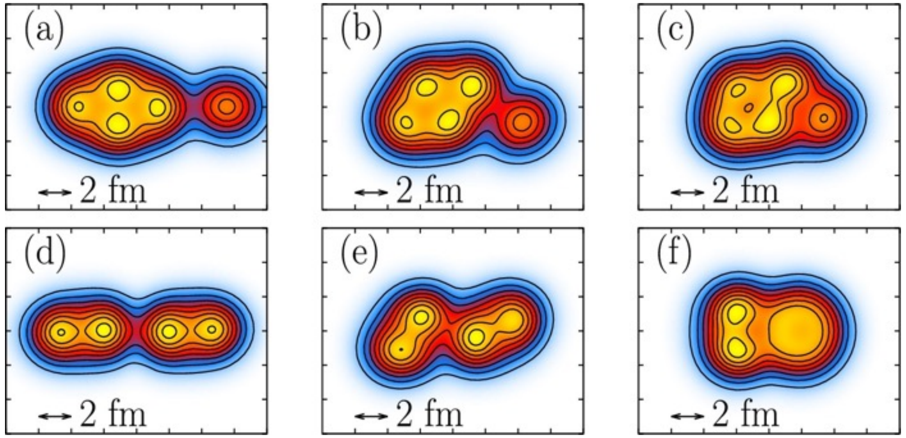
No danger of atmospheric ignition, as demonstrated in the ultimate bomb test of the Soviet Tsar bomb (52 Mton) explosion in 1961!

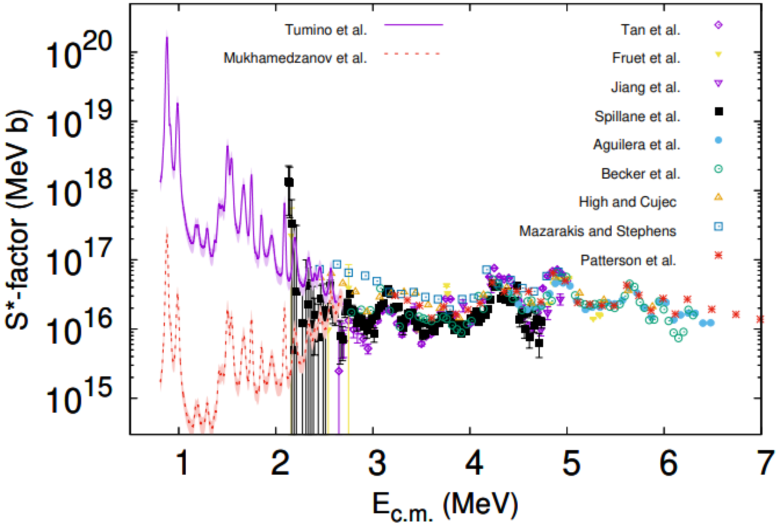
New directions towards high and low energies

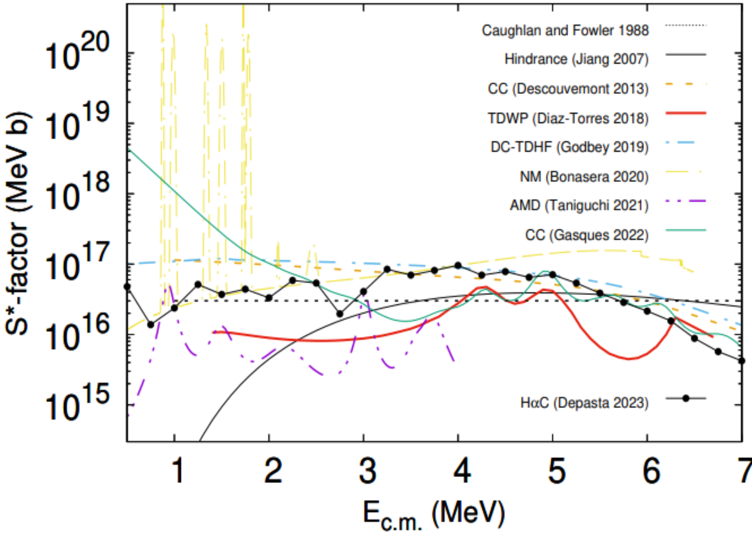


Heavy ion studies opened a new field of heavy ion fusion measurements at Oak Ridge, Berkeley, Brookhaven, leading to the development of the Relativistic Heavy Ion program at BNL and CERN.

In low energy to the search for clustering phenomena in light ion fusion reactions of importance for nuclear burning in late stellar evolution and explosion! These are presently pursued at Notre Dame, Strasbourg, and **LUNA**!

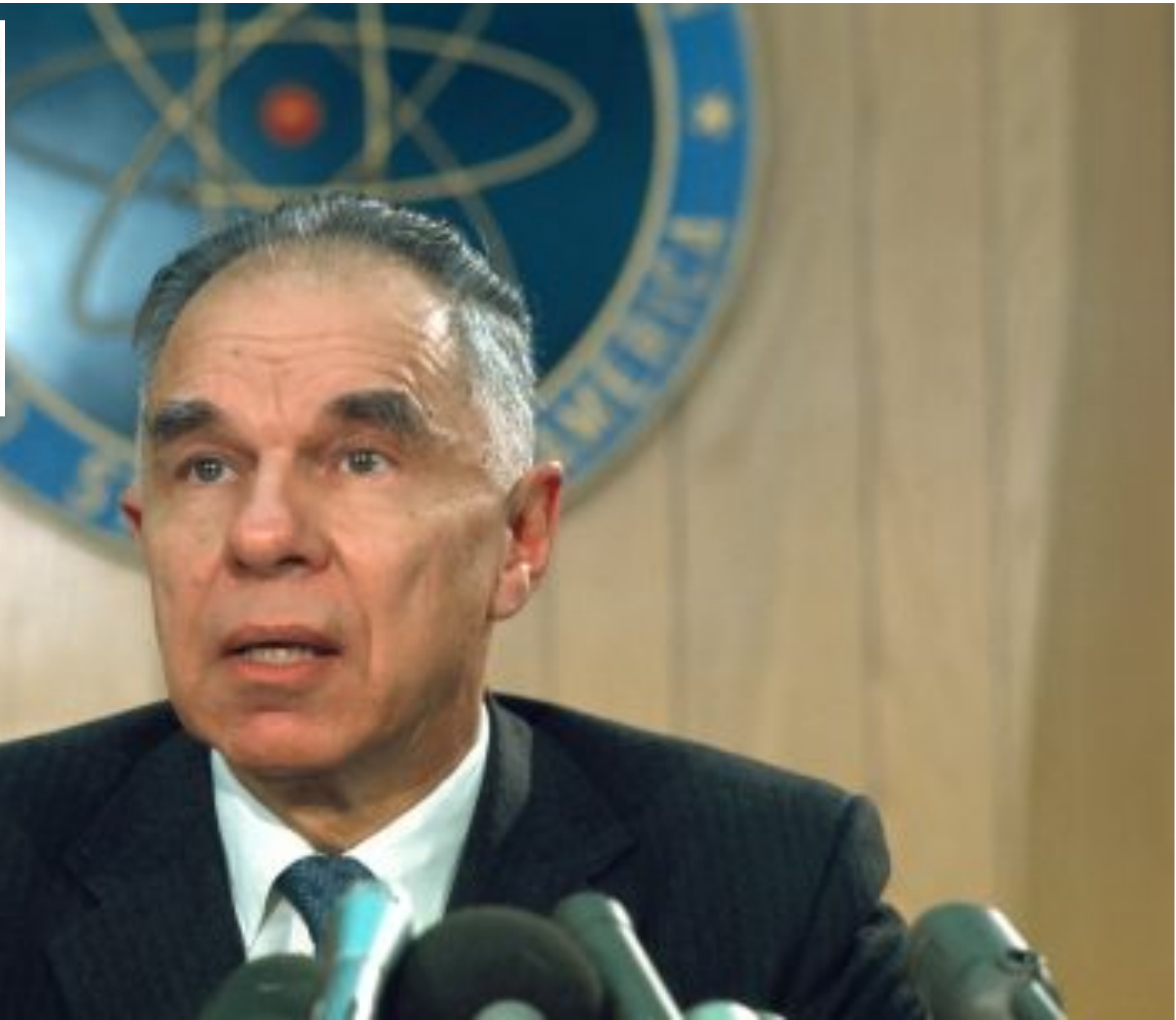


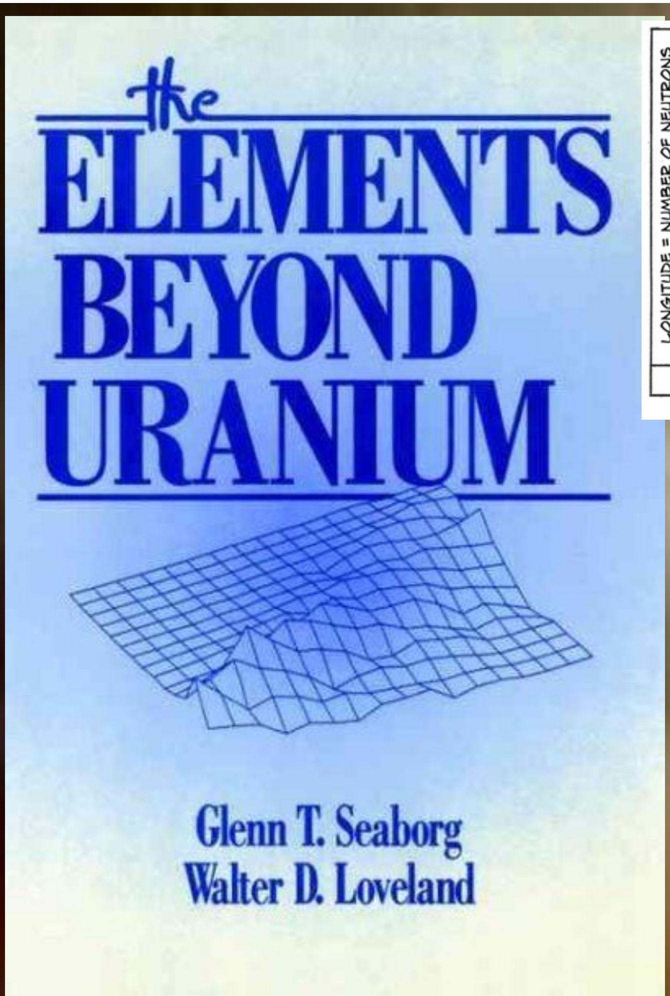


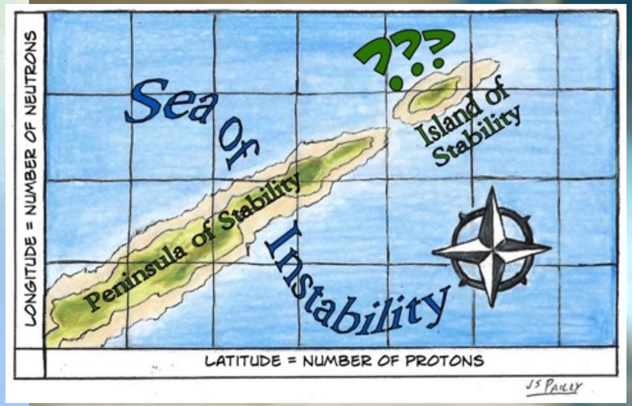


Glenn Seaborg as Head of the AEC

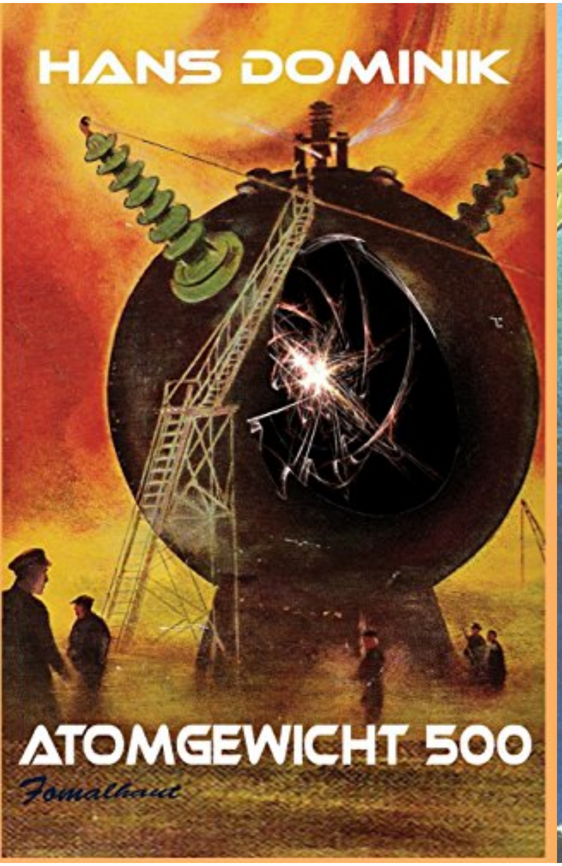
Seaborg received the Nobel price in 1951 for the for the “discoveries in the chemistry of the transuranium elements” (plutonium) and pushed for heavier element searches!

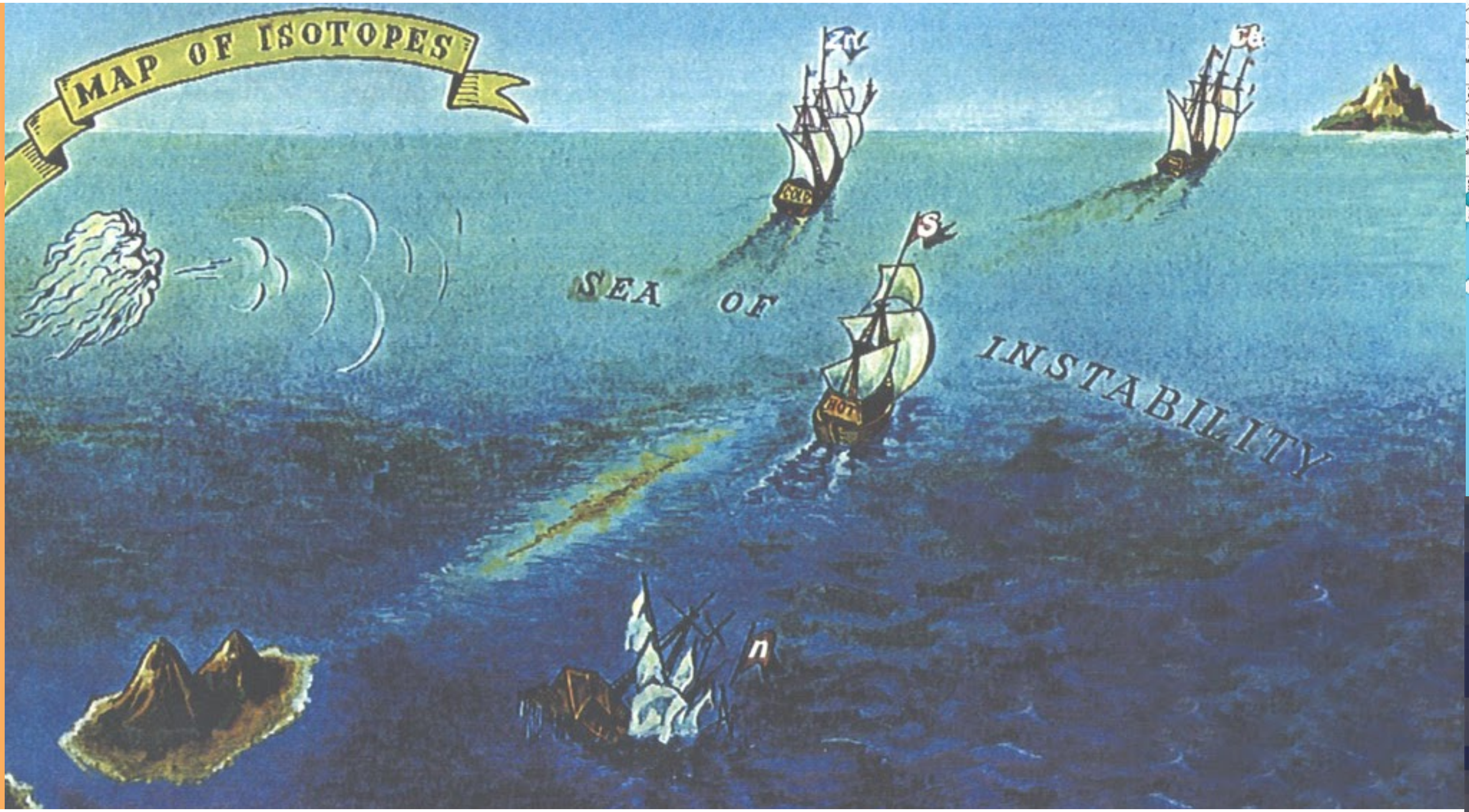


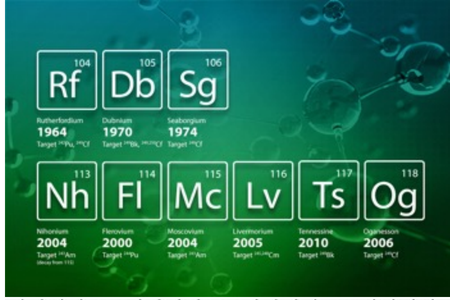


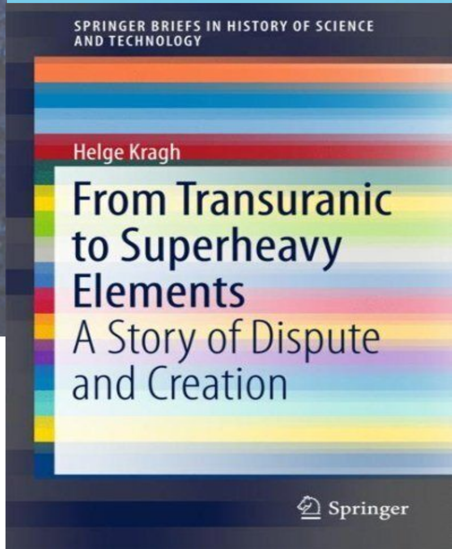


Extending the Nuclide Chart
The Dream of Discovery





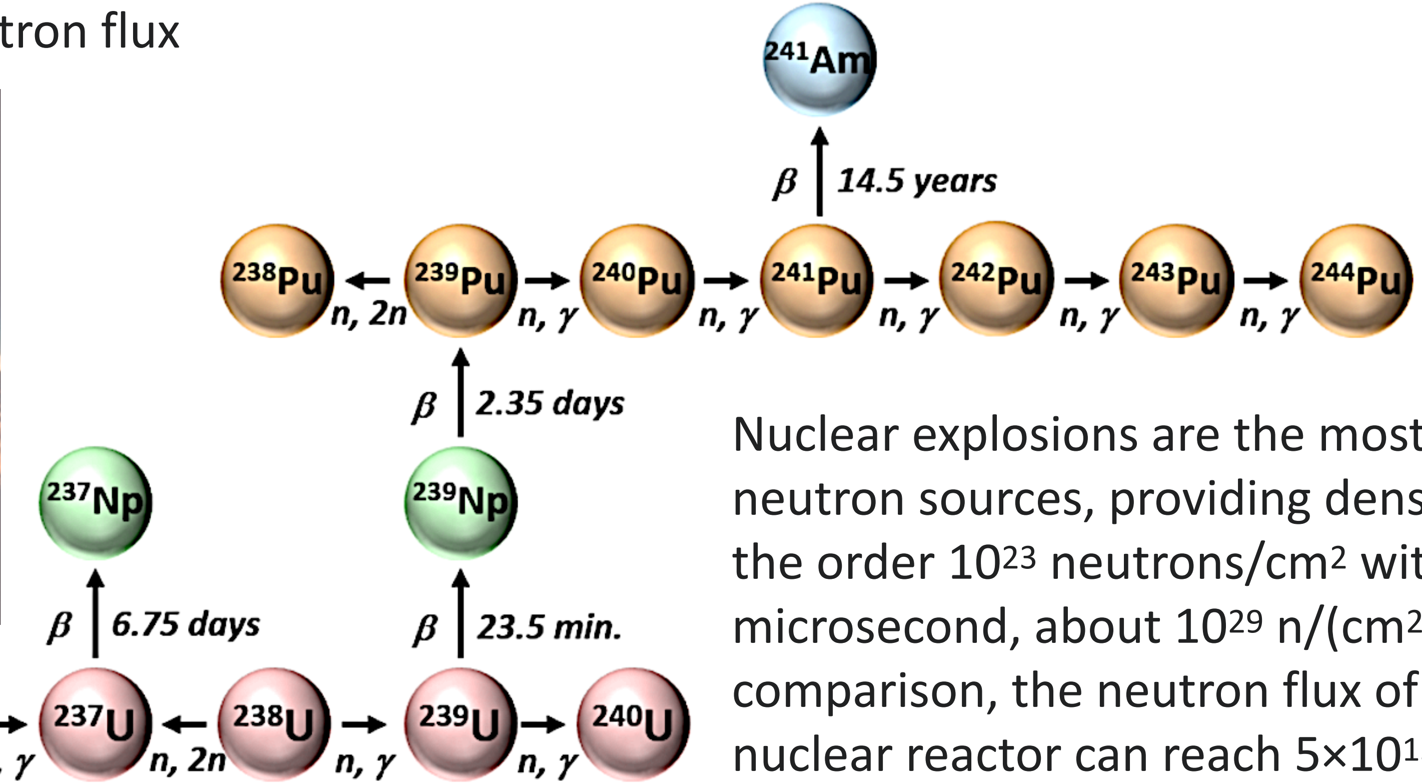
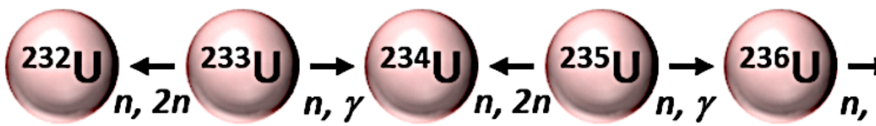




Searching for Superheavy Elements and reaching the Island of Stability at Berkeley (USA), Dubna (USSR/Russia), GSI (Germany) et al.

Neutron Capture in the Bomb

New elements were first discovered in the fallout from the 'Ivy Mike' nuclear test. The examination of the debris from the explosion had shown the production of a new isotope of plutonium, $^{244}_{94}Pu$, which would have formed by the absorption of six neutrons by a uranium-238 nucleus followed by two β^- decays. The probability of such events increases with the neutron flux

Nuclear explosions are the most powerful neutron sources, providing densities of the order 10^{23} neutrons/cm^2 within a microsecond, about 10^{29} n/(cm^2·s). In comparison, the neutron flux of a nuclear reactor can reach 5×10^{15} n/(cm^2·s). NIF reaches about 10^{20} n/cm^2 within a nanosecond’

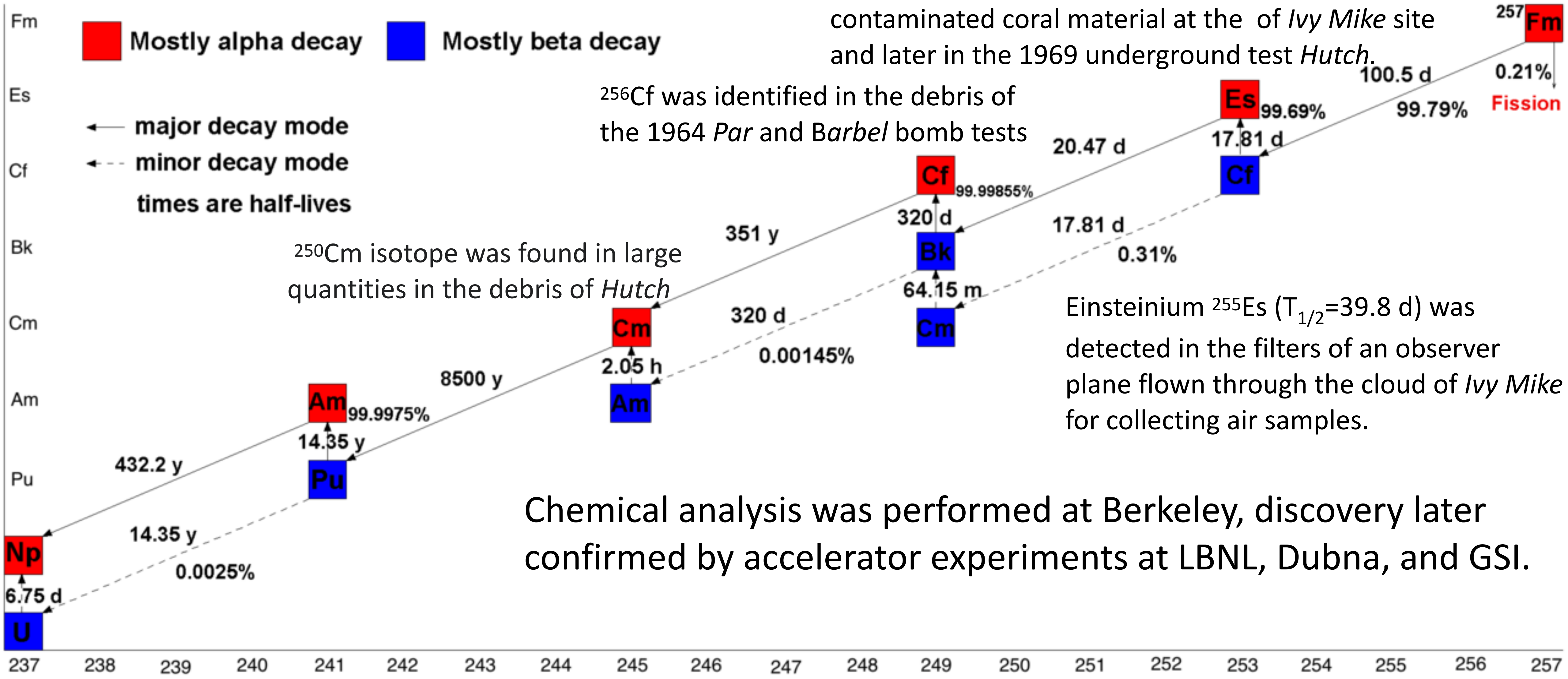
Links to heavier Elements

Fermium ^{257}Fm ($T_{1/2}$=100 d) was discovered in the contaminated coral material at the of *Ivy Mike* site and later in the 1969 underground test *Hutch*.

^{256}Cf was identified in the debris of the 1964 *Par* and B*arbel* bomb tests

^{250}Cm isotope was found in large quantities in the debris of *Hutch*

Einsteinium ^{255}Es ($T_{1/2}$=39.8 d) was detected in the filters of an observer plane flown through the cloud of *Ivy Mike* for collecting air samples.

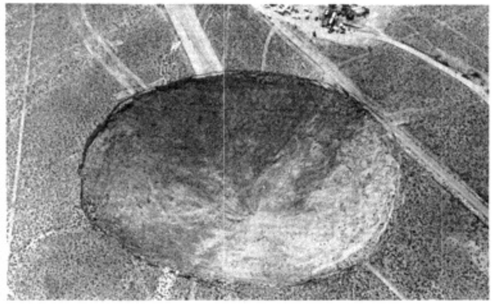


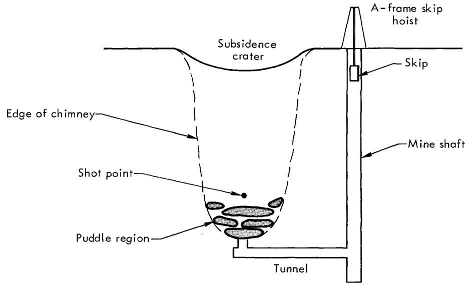
Chemical analysis was performed at Berkeley, discovery later confirmed by accelerator experiments at LBNL, Dubna, and GSI.

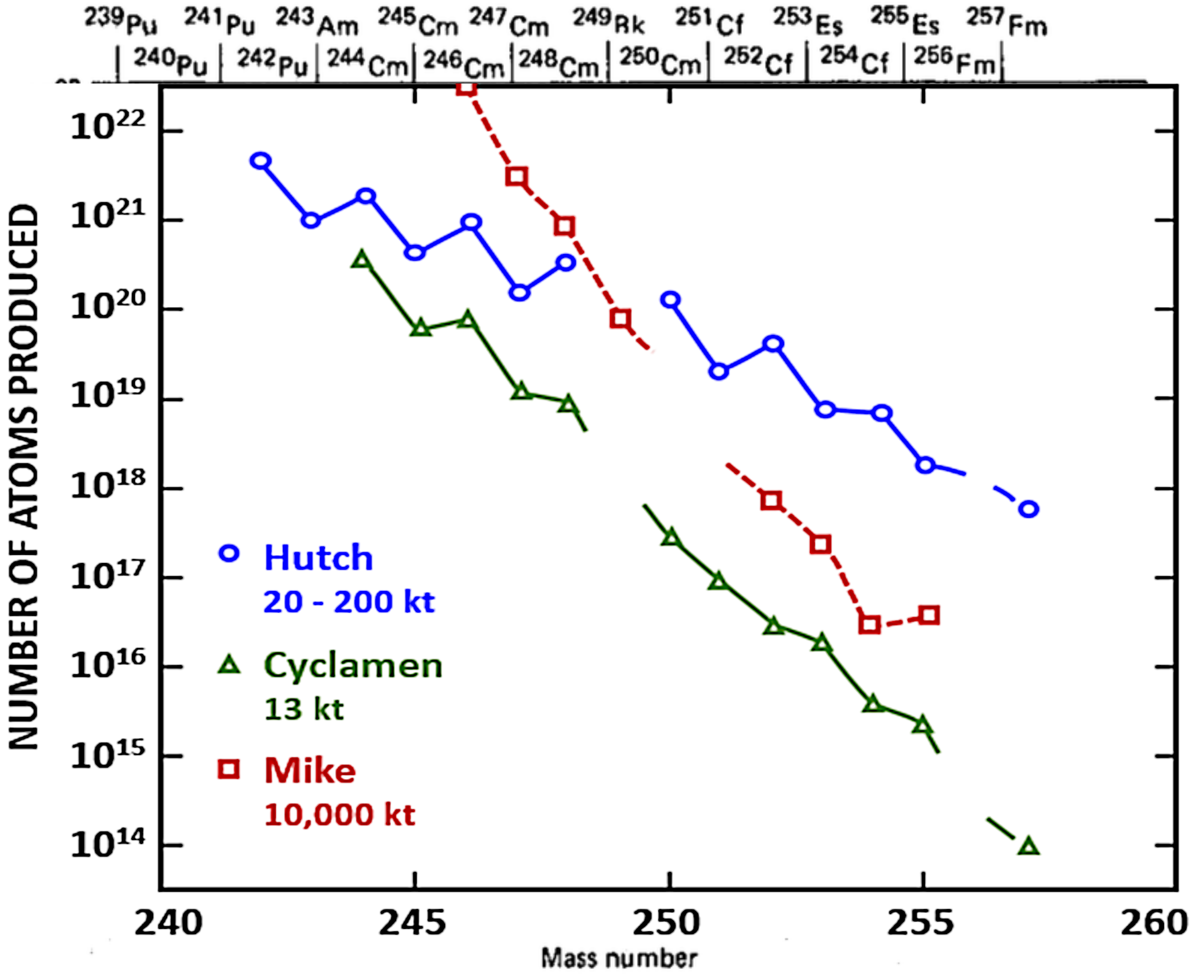
Underground Tests

Between 1962 and 1969 and codenamed Anacostia (5.2 kilotons, 1962), Kennebec (<5 kilotons, 1963), Par (38 kilotons, 1964), Barbel (<20 kilotons, 1964), Tweed (<20 kilotons, 1965), Cyclamen (13 kilotons, 1966), Kankakee (20-200 kilotons, 1966), Vulcan (25 kilotons, 1966), and the biggest one Hutch (~200 kilotons, 1969).

These tests proved more successful with regards to the search of new elements, despite rock melting. Hundreds of kilograms of rock samples were collected and tested.



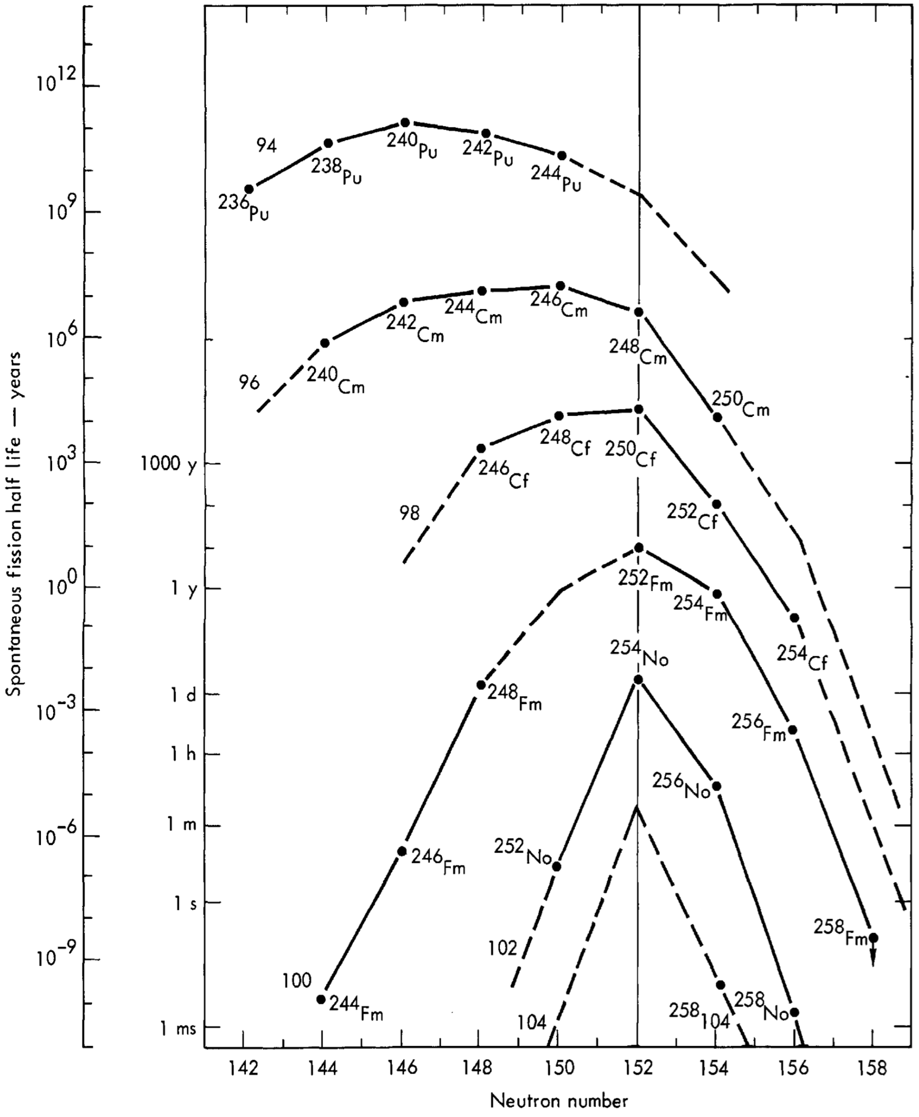




Super-heavies from Hutch

THE RECOVERY AND STUDY OF HEAVY NUCLIDES PRODUCED IN A NUCLEAR EXPLOSION —THE HUTCH EVENT" LLNL Report: **XA04N0908**
R. W. Hoff and E. K. Hulet
Lawrence Radiation Laboratory,

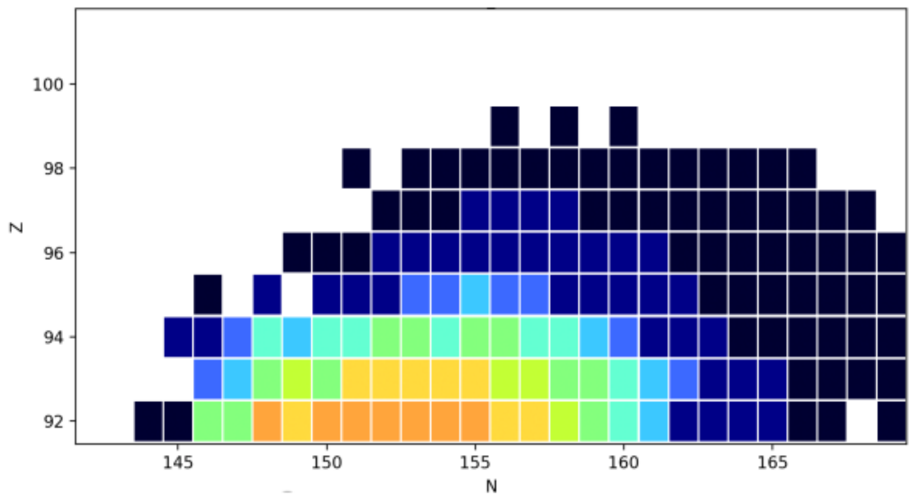
Nuclide	Half-life and decay mode	Total atoms (t_o, 7/16/69)	Total atoms (1/1/70)
^{242}Pu	3.9×10^5 y α	4.22×10^{21}	Same
^{243}Am	8.0×10^3 y α	9.03×10^{20}	Same
^{244}Pu	8.3×10^7 y α	1.71×10^{21}	Same
^{245}Cm	8.3×10^3 y α	3.92×10^{20}	Same
^{246}Cm	4.7×10^3 y α	8.54×10^{20}	Same
^{247}Cm	1.6×10^7 y α	1.60×10^{20}	Same
^{248}Cm	3.8×10^5 y α	3.54×10^{20}	Same
^{249}Bk	314 d β^-	(not measured)	(not measured)
^{249}Cf	352 y α	—	—
^{250}Cm	1.1×10^4 y SF	1.21×10^{20}	Same
^{251}Cf	900 y α	1.82×10^{19}	Same
^{252}Cf	2.7 y α	3.82×10^{19}	3.4×10^{19}
^{253}Cf	18 d β^-	7.20×10^{18}	1.1×10^{16}
^{253}Es	20 d α	—	2.1×10^{16}
^{254}Cf	60 d SF	6.82×10^{18}	9.7×10^{17}
^{255}Es	40 d β^-	1.66×10^{18}	8.9×10^{16}
^{255}Fm	20 h α	—	1.8×10^{15}
^{256}Fm	2.6 h SF	(too short-lived)	—
^{257}Fm	95 d α	5.56×10^{17}	1.6×10^{17}

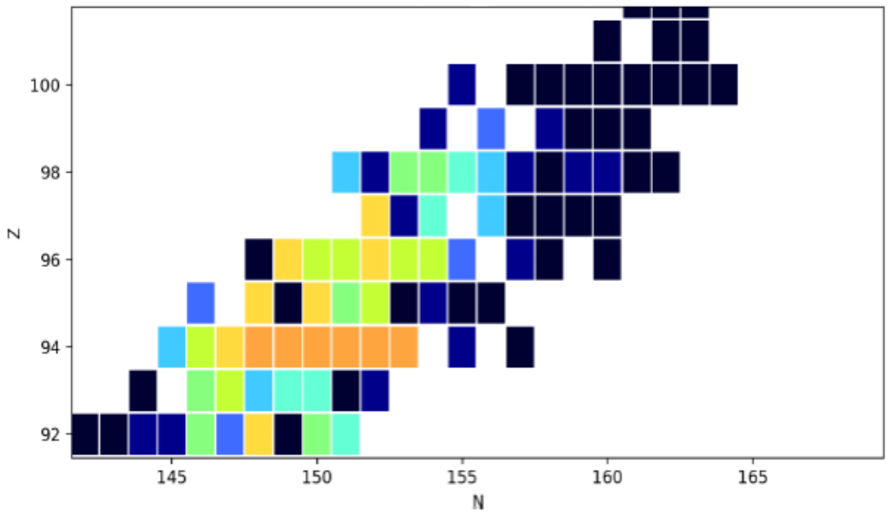


Simulations with modern R-process tools

Matt Mumpower, Prism code 2024

nuclear physics inputs
(Sn, β-rates, n-cap rates, …)





Start with ^{238}U and some neutrons

After a fraction of a second, up to about ~17 neutron captures occur

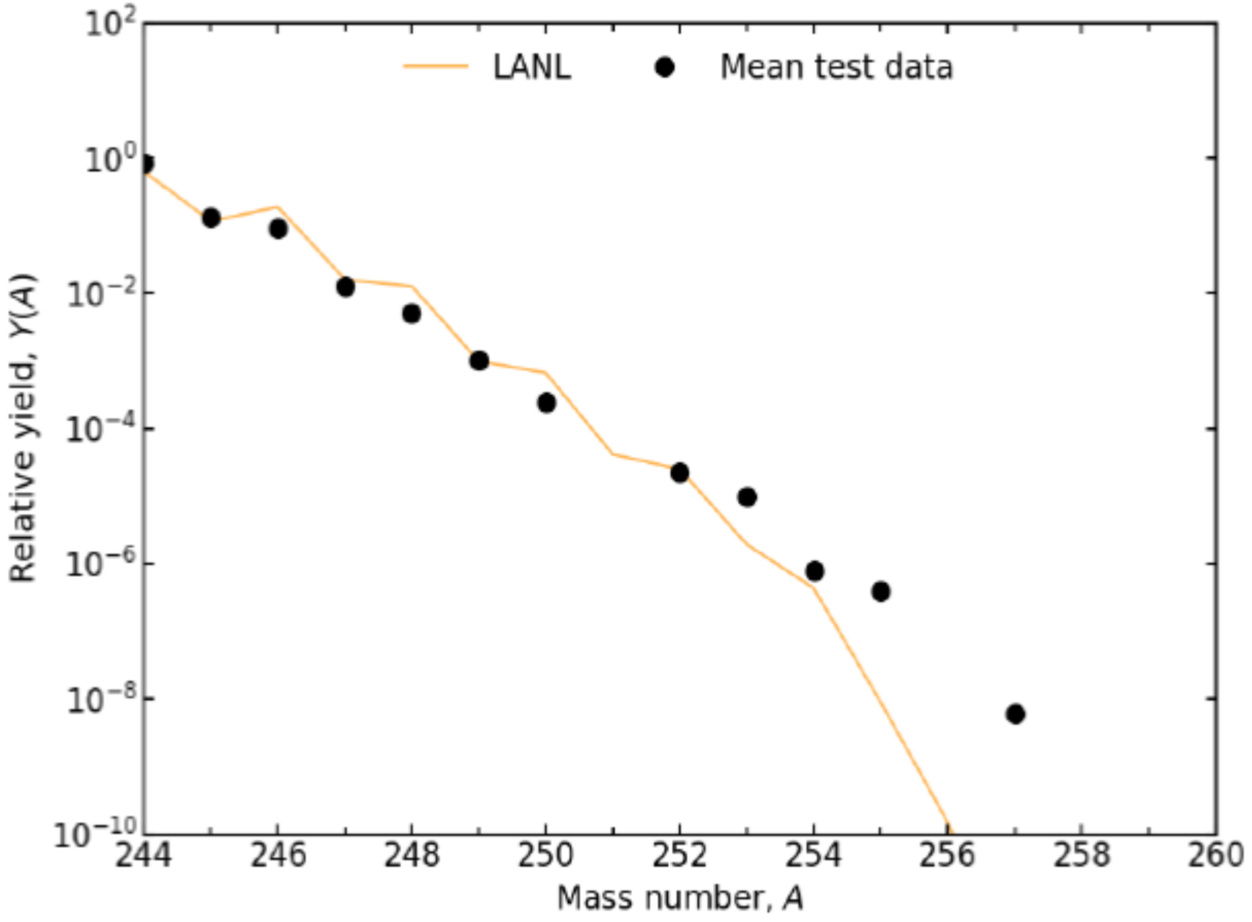
High relative abundance indicated by orange; lower relative abundance by blues and black

Once the neutron flux subsides, material decays back to more stable isotopes

Starting with ^{238}U, we find the Pu ($Z = 94$) chain is primarily populated

Heavier elements follow an exponential drop off in yield

Comparison with observed data

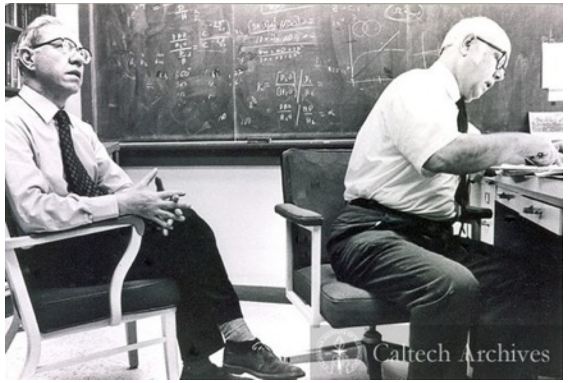


- The calculations seem in good agreement with the data!
- Towards higher masses an exponential decline compared to the observed data can be observed!
- This requires a modification (reduction) in the theoretical fission barriers!
- Fission bombs are not efficient sources for the production of superheavy elements

Other postwar Developments

The observations of the bomb test program influenced the young field of Nuclear Astrophysics, represented by Willy Fowler at Caltech nuclear astrophysics. He was a student like Alvarez at UC Berkeley taking classes with Oppenheimer before the war.

In the framework of the Manhattan Project, Fowler developed ignition systems (^{210}Po-^{9}Be neutron source) for nuclear weapons. As part of the missile program at China Lake, he also considered so-called long-range "delivery systems" for nuclear weapons.
In 1951 Fowler became scientific director of the Vista project, which was established for the study of tactical nuclear weapon systems.



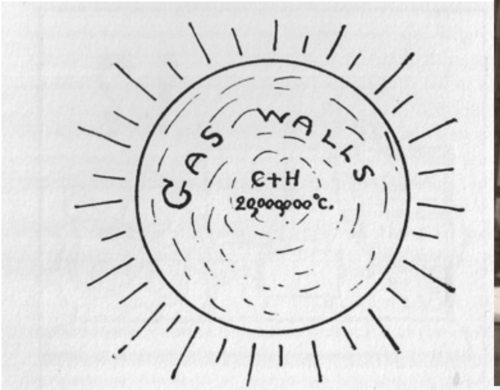
Motivated by Fred Hoyle he returned to Nuclear Astrophysics!

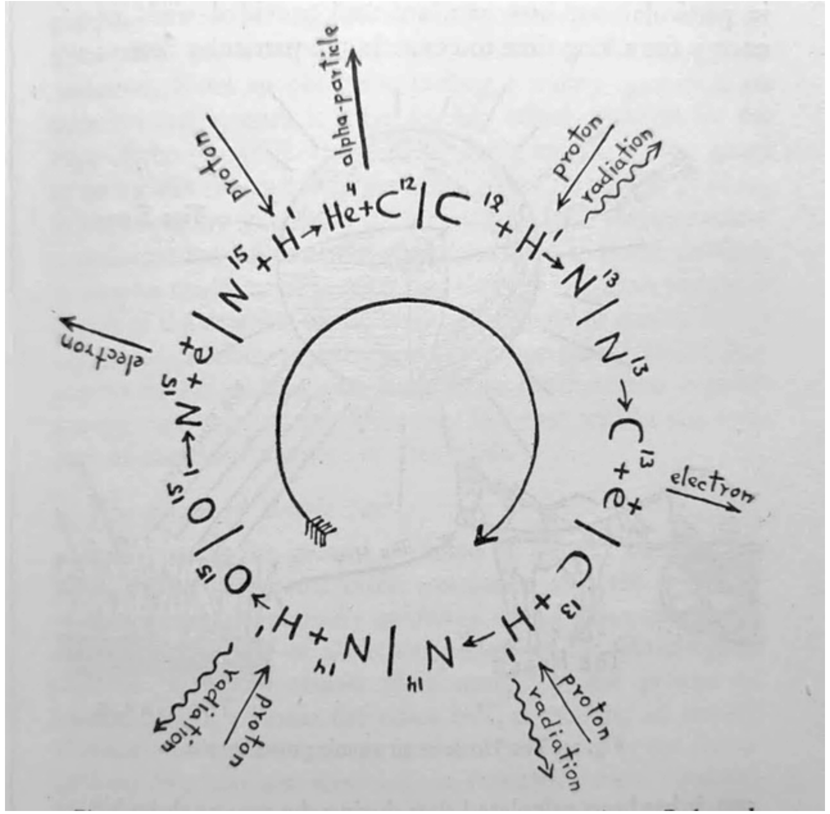
W. Patrick McGray, "Project Vista, Caltech, and the dilemmas of Lee DuBridge," *Historical Studies in the Physical and Biological Sciences* 34 (2), (2004)

J. D. Gerrard-Gough and Albert B. Christman, *The Grand Experiment at Inyokern, History of the Naval Weapons Center, China Lake, California*, vol. 2 (Washington: Naval History Division, 1978).

Bethe Weizsäcker catalytic Cycle

Proposed by Bethe and Weizsäcker in 1938 as energy source of the Sun; with Gamow as communicator and catalyzer!

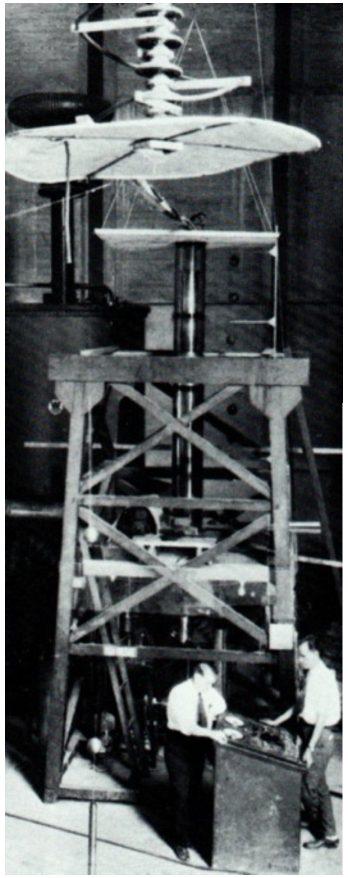




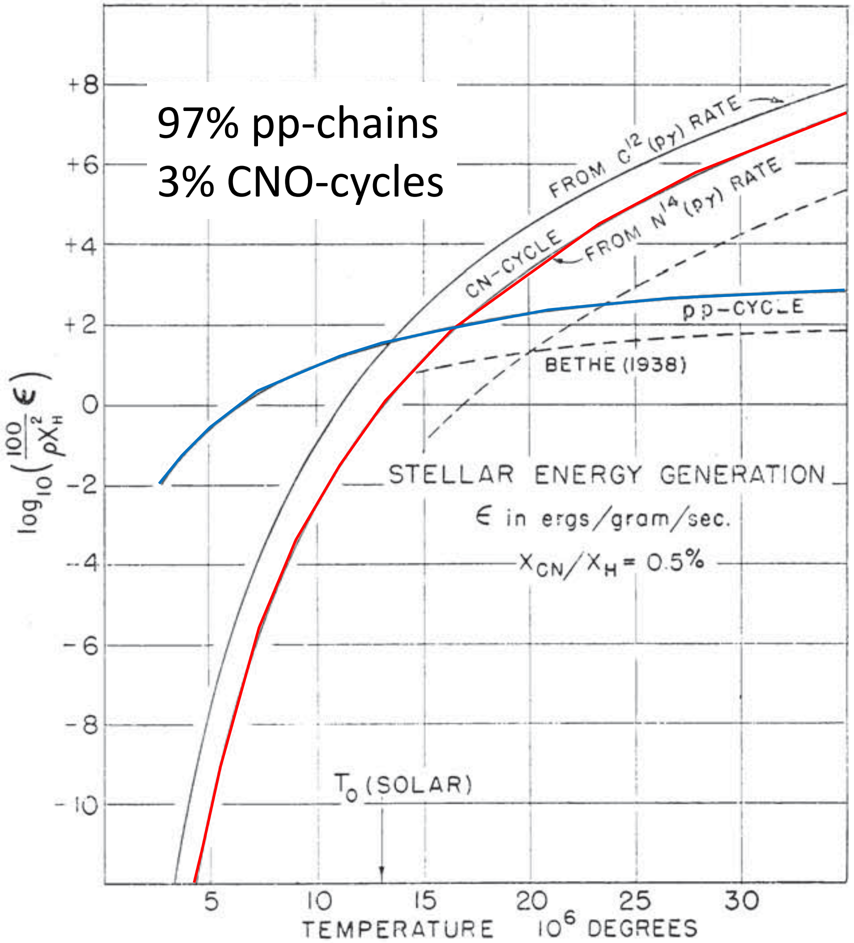
Two seminal papers in 1938/1939 discussed the question of energy generation in the sun and the origin of the elements in our universe! Critchfield and Bethe followed shortly afterwards with the pp-chains!

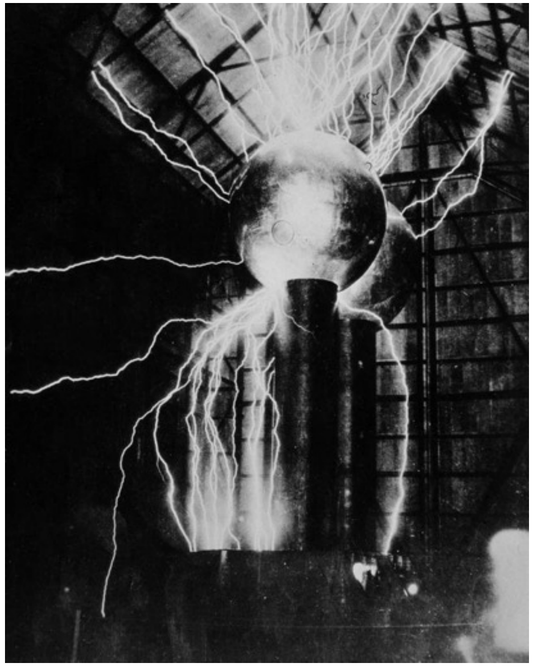
1) Durch Herrn Gamow habe ich erfahren, daß Bethe neuerdings denselben Zyklus quantitativ untersucht hat.

Willy Fowler at Kellogg in Caltech



performed the first experiments of CNO reactions as the solar energy source.

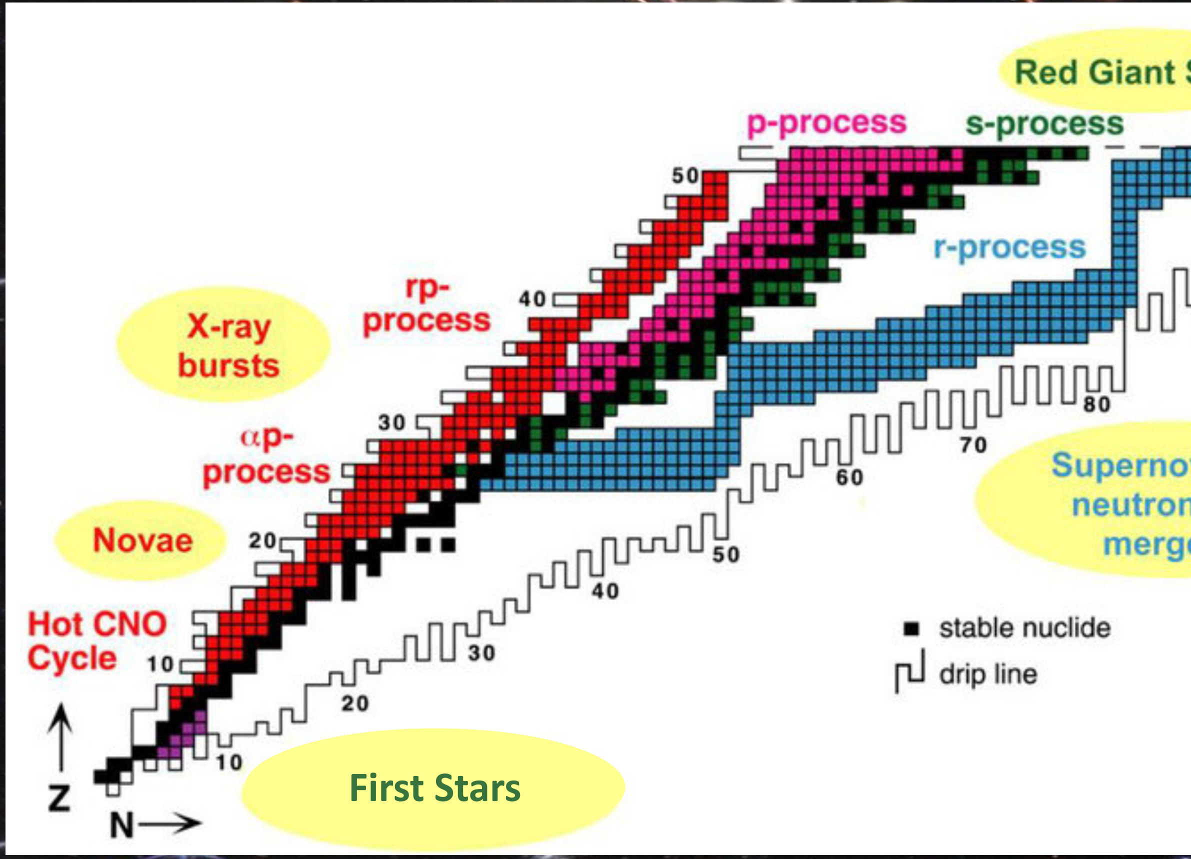




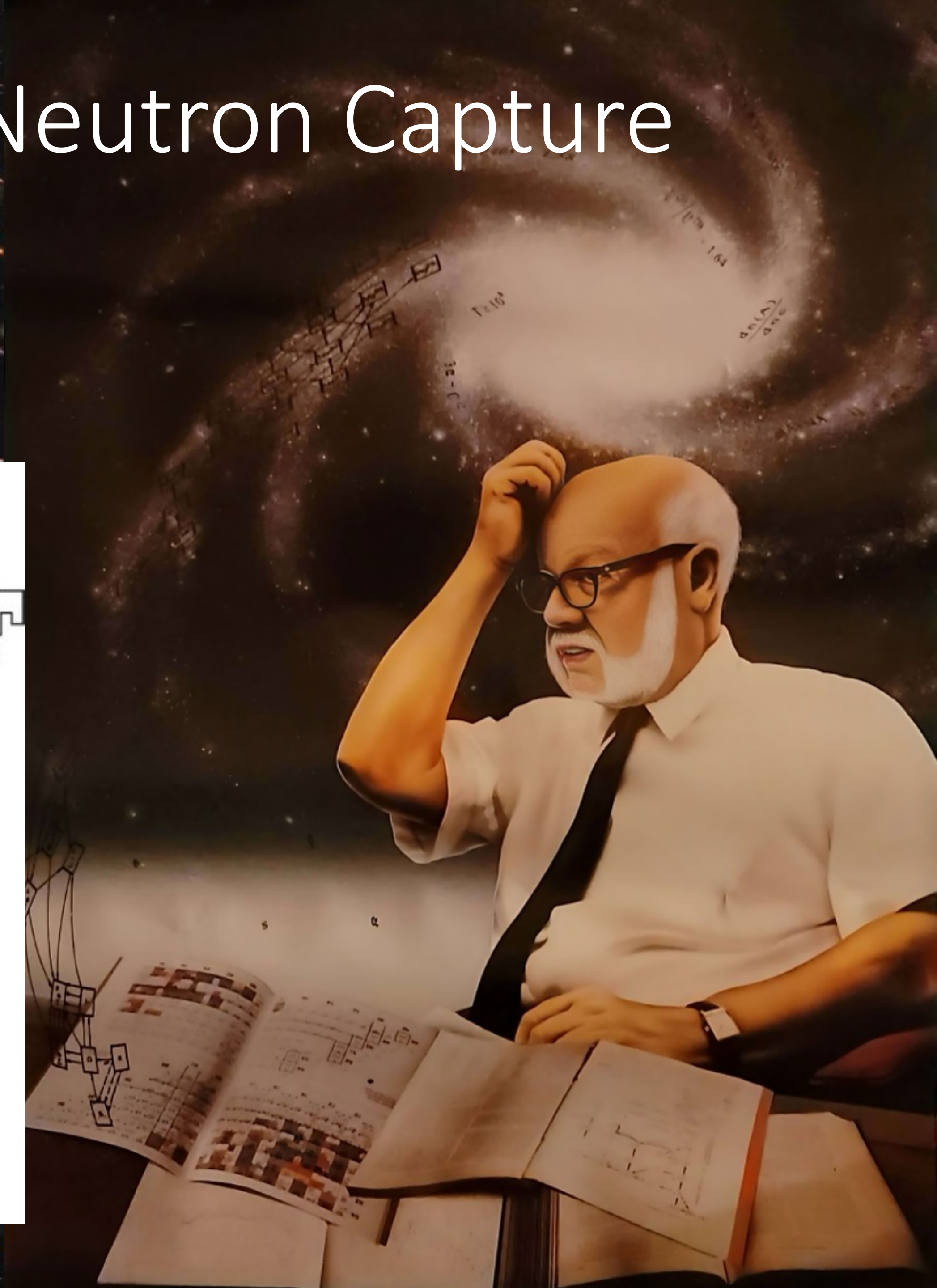
The observation of technetium in stellar spectra and the discoveries of new heavy elements in the debris triggered the idea of the neutron driven processes as the origin of the heavy elements in stars. In the seminal B^2FH paper, Fowler proposed the s- and the r-process – without identifying the site. That was left for later generations!

From Neutron Source to Neutron Capture

Rephrasing from Eddington 1920: “What is possible in the Nevada desert may not be too difficult in stars”

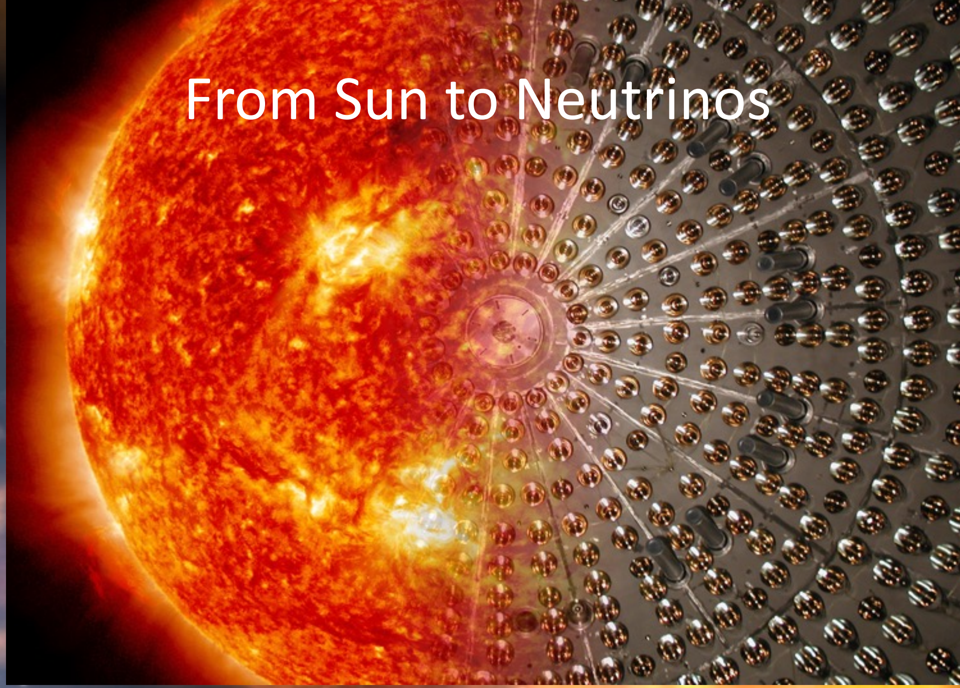


The s-process
The r-process

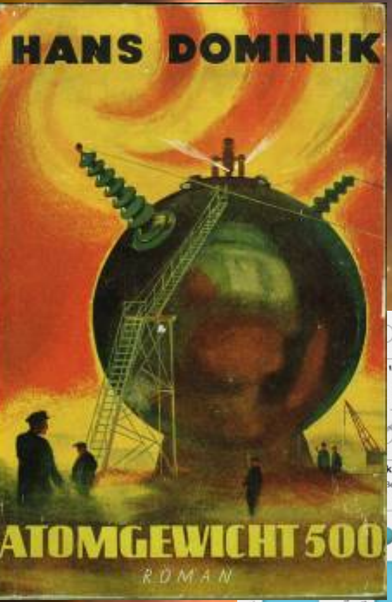


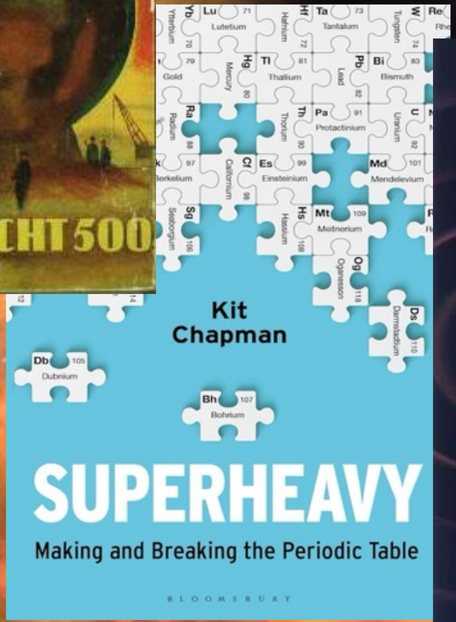
The Science Spin-Off

From Sun to Neutrinos

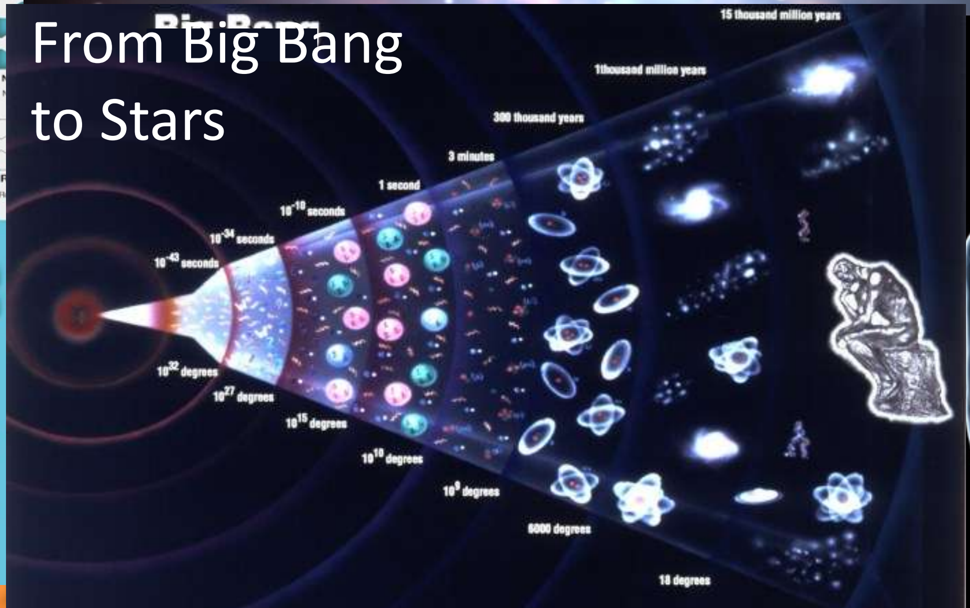


From Superheavies
to Supernovae

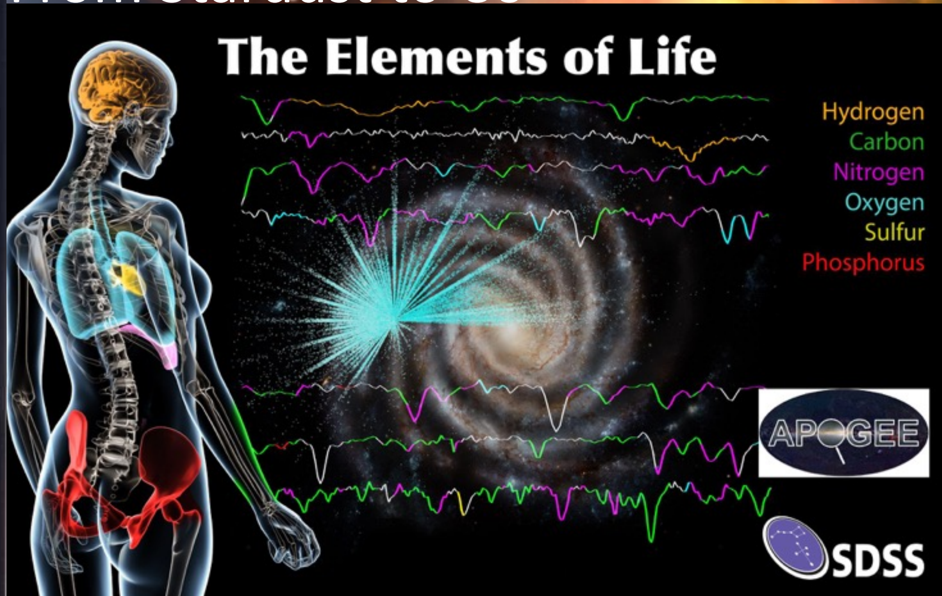




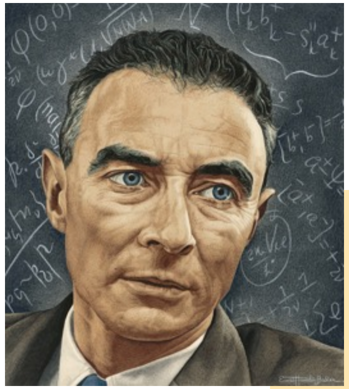
From Big Bang
to Stars



From Stardust to Us



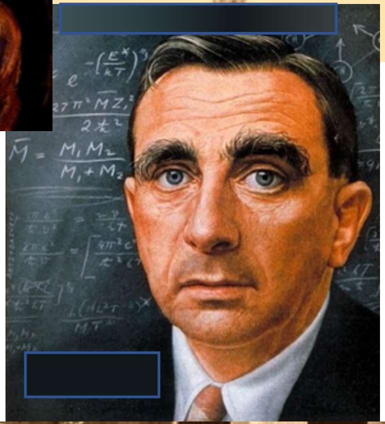
The Participants



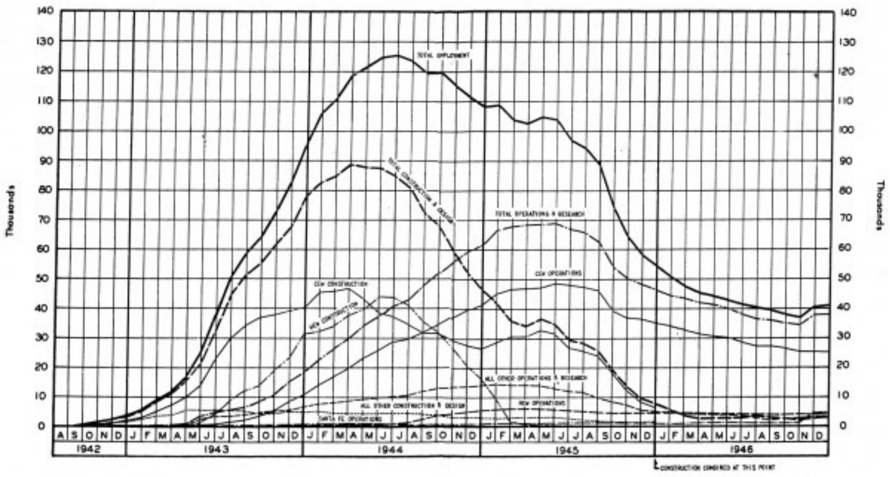
J. Robert Oppenheimer: theoretical physicist in Berkeley and Caltech, focusing on the study of quantum physics and the structure of neutron stars and black holes!

Hans A. Bethe: Trained in Germany by Sommerfeld, he quickly emerged as a rising star in nuclear physics at Cornell, interest in light ion fusion processes in stars!

Enrico Fermi: an Italian physicist, wo used the opportunity of his Nobel prize in 1938 to leave Fascist Italy for the United States. He was essential for the understanding of neutrons and their role in fission.



Edward Teller: Hungarian firebrand, worked with Heisenberg in Germany before emigrating to the United States in 1933. At George Washington University he became an expert in light ion fusion reactions and a vehement spokesperson for the hydrogen bomb.



Plus more than 125,000 scientists, technicians, administrators, military people involved in the project!

The team for Trinity and Hiroshima

Left to right: Norman Ramsey (Brooklyn, NY); Roger S. Warner (Boston, MA); Edward B. Doll (Los Angeles, CA); Harold Agnew (Denver, CO); Luis W. Alvarez (Rochester, MN); Lawrence Johnston (Hollywood, CA); Philip Morrison (Pittsburgh, PA); Robert Serber (Urbana, IL); and Bernard Waldman (South Bend, IN).

Bernard Waldman

Harry Agnew

Bernard Waldman, Luis Alvarez, Robert Serber

The Observer Crew

LA-8819 Report UC-34

The growth of the fireball was to be recorded with a Fastax™ camera mounted on the gyrostabilizer of the Norden™ bomb sight of the photographic aircraft; the camera was to be operated on the first mission by B. Waldman and by R. Serber on the second.

	Hiroshima
Instrument aircraft	V-89, Great Artiste
Position	300 ft behind V-82
Aircraft commander	Maj. C. W. Sweeney
Bombardier	Capt. K. K. Beahan
Scientists, observers	L. W. Alvarez
	H. M. Agnew
	L. Johnston

509th Composite Group

Photo aircraft	V-91, Strange Cargo
Aircraft commander	Capt. Marquardt
Scientists, observers	B. Waldman