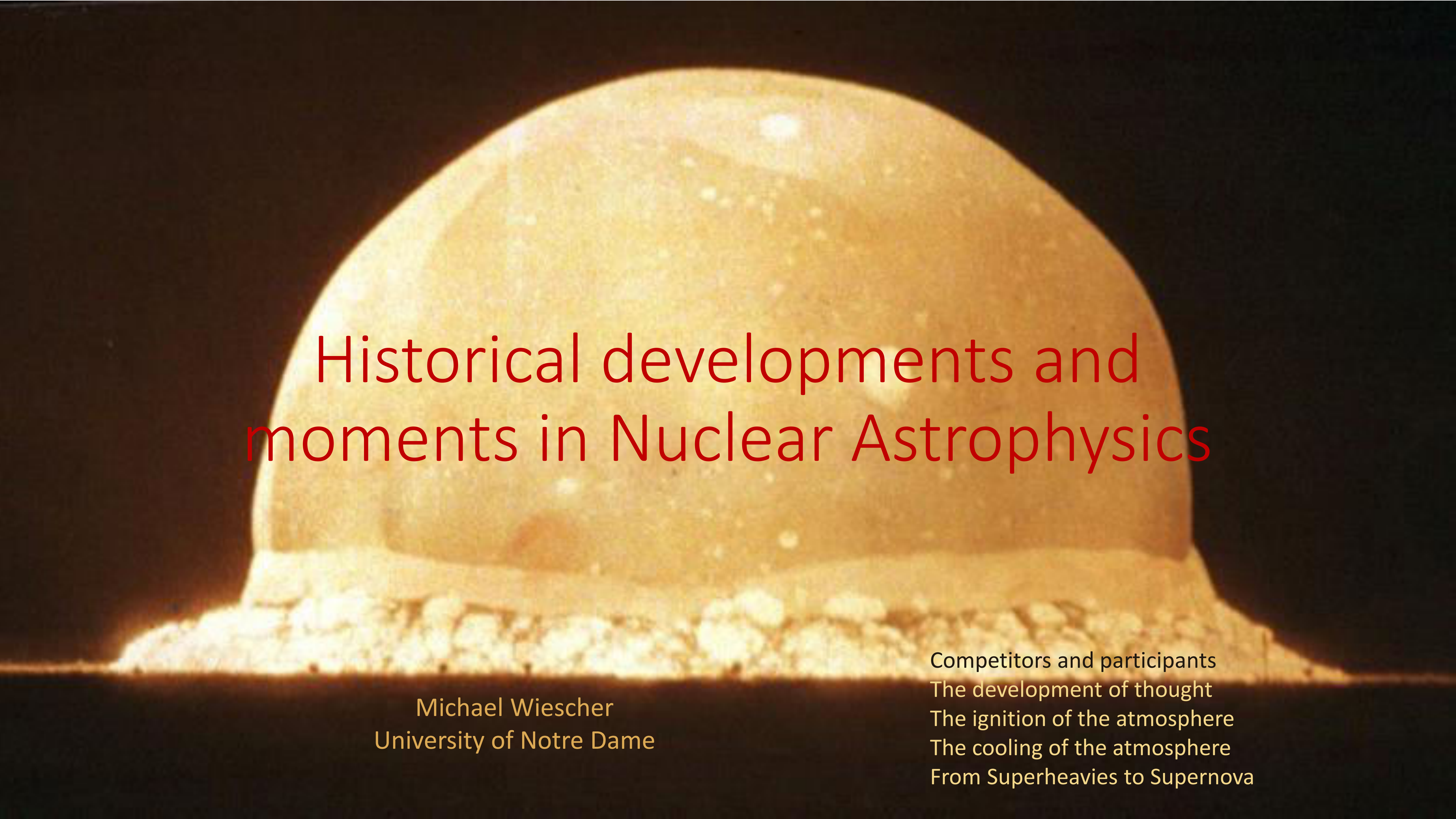


Historical developments and moments in Nuclear Astrophysics

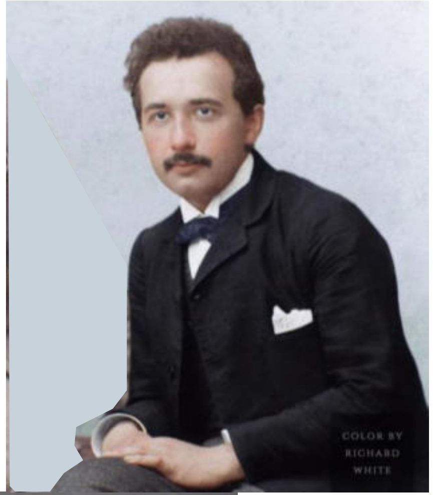
Michael Wiescher
University of Notre Dame

Competitors and participants
The development of thought
The ignition of the atmosphere
The cooling of the atmosphere
From Superheavies to Supernova

The Scientific Basis – Two Formula

for the energy generation in bomb and stars

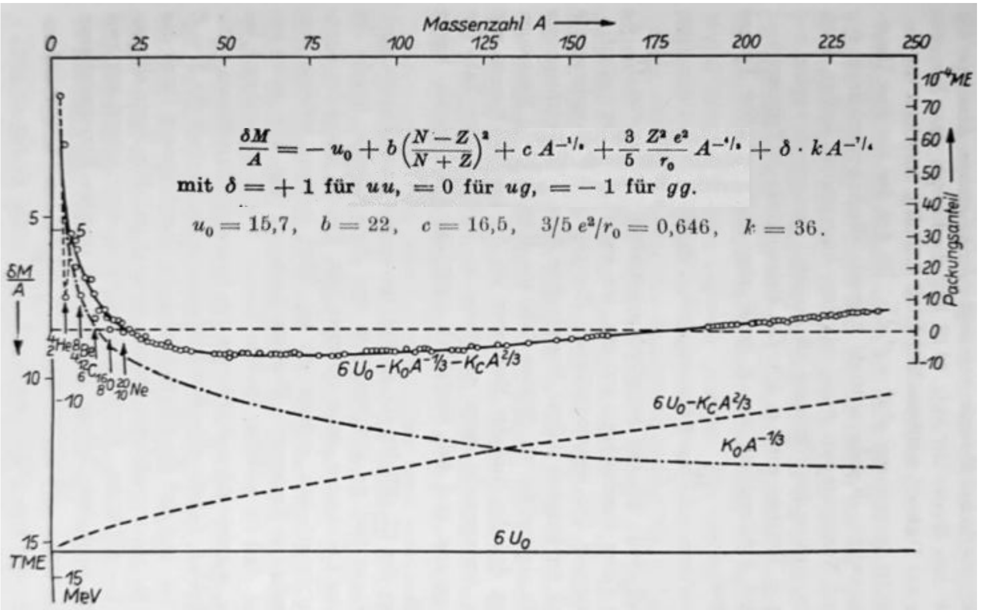
$$E = m \cdot c^2$$



Albert Einstein 1904

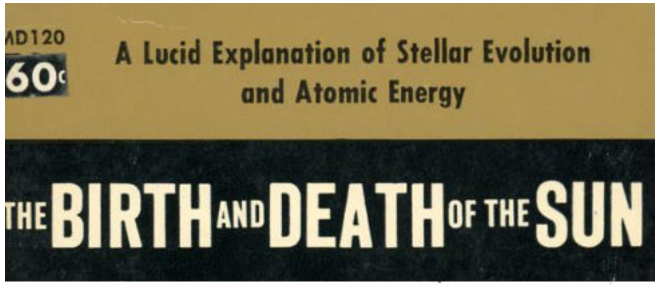
Arthur Eddington 1920: “What is possible in the Cavendish Lab may not be too difficult in the Sun”

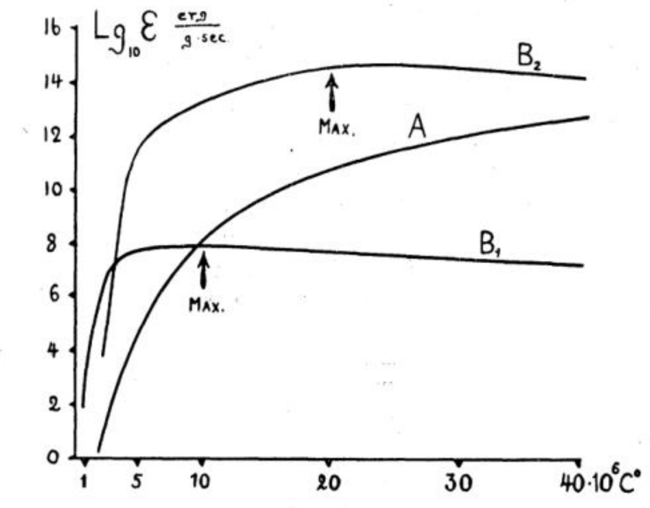
Arthur Eddington 1920



Carl Friedrich von Weizsäcker 1934

A new game with masses and energies

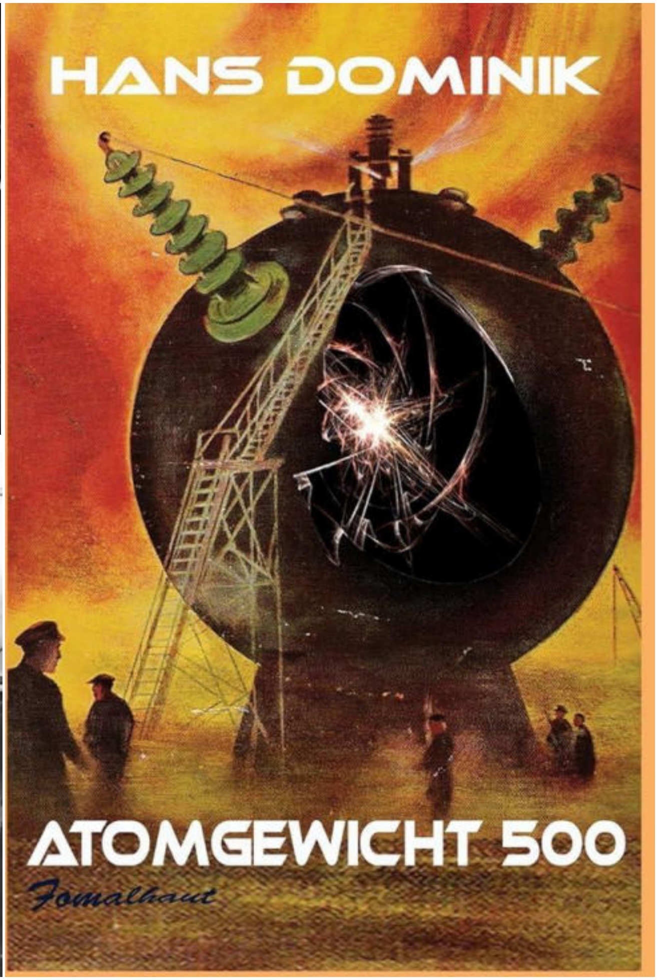




Stars are driven by the release of nuclear energy

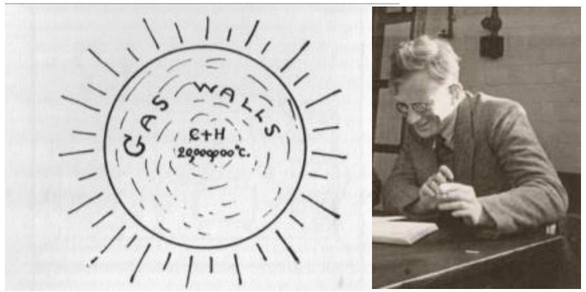
G. Gamow and E. Teller, “The Rate of Selective Thermonuclear Reactions,” *Phys. Rev.* 53 (1938): 608-609.

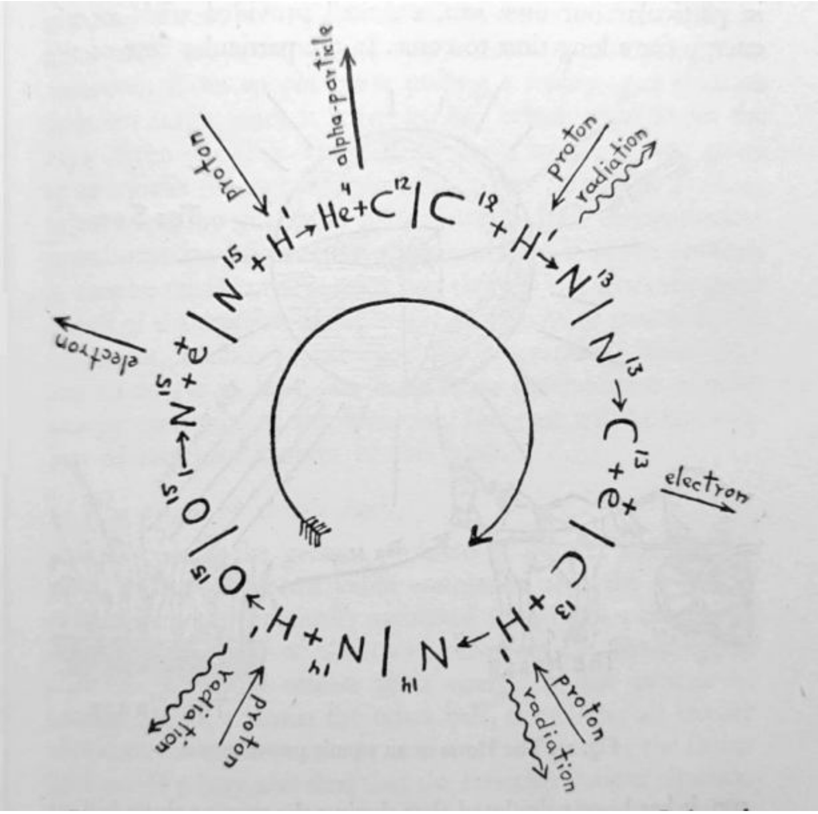
Continuous neutron capture would lead to the formation of ever heavier elements, a source of energy through radioactive decay!



Bethe Weizsäcker Cycle

Proposed as the energy source of the Sun!

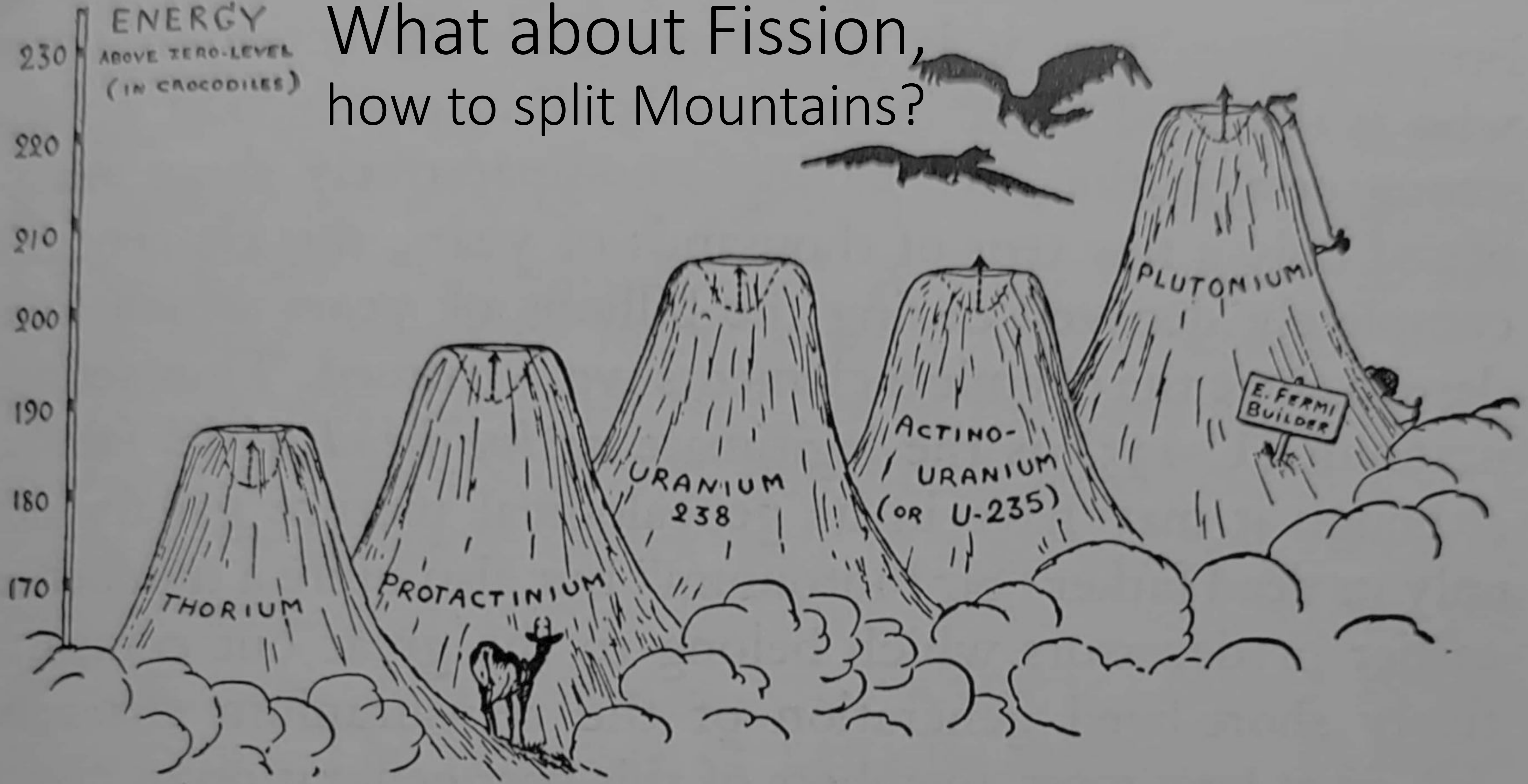




Two seminal papers in 1938 discussed the question of energy generation in the sun and the origin of the elements in our universe!

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

What about Fission,
how to split Mountains?

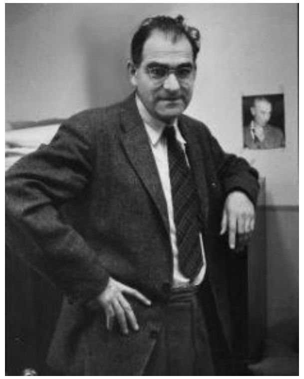


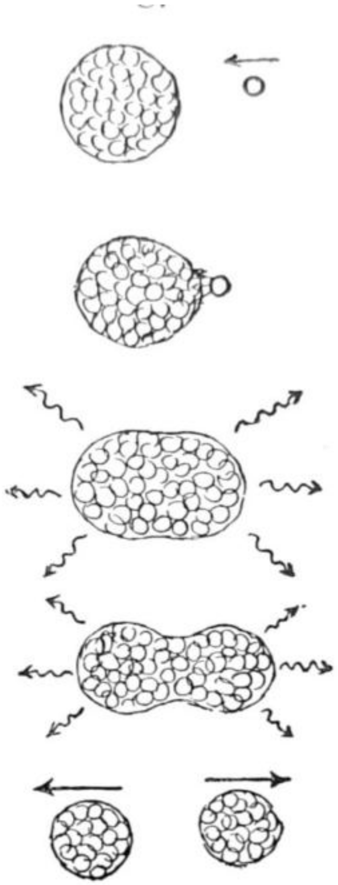
Mountain landscape illustrating the problem of nuclear fission.

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

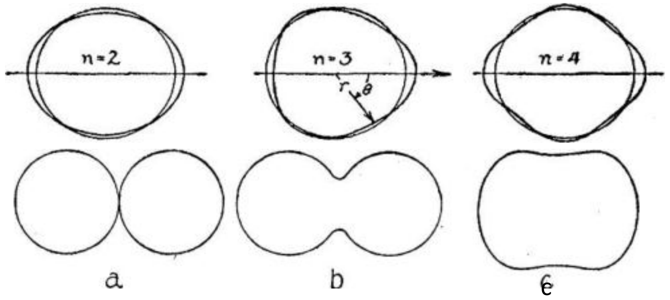
Phys. Rev. 56 (1939) 426-450

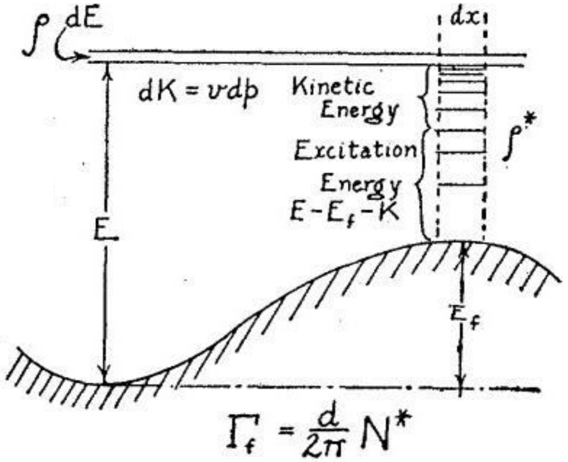
On the basis of the liquid drop model of atomic nuclei, the mechanism of nuclear fission was first formulated by describing the sequence of excitation and deformation modes occurring during the fission process. The fission probability increases with excitation energy and level density!



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 excitations in the fission process.





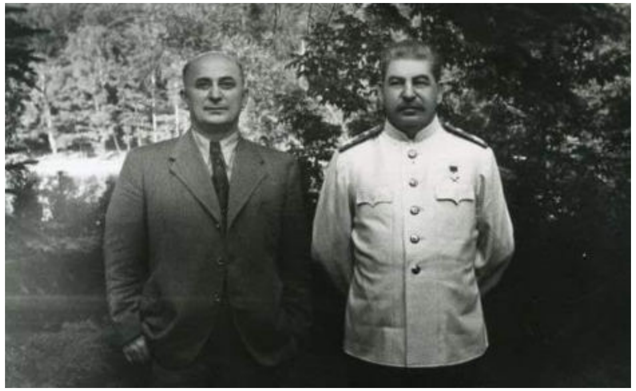
The Race for the Bomb: 1940 to 1945

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.

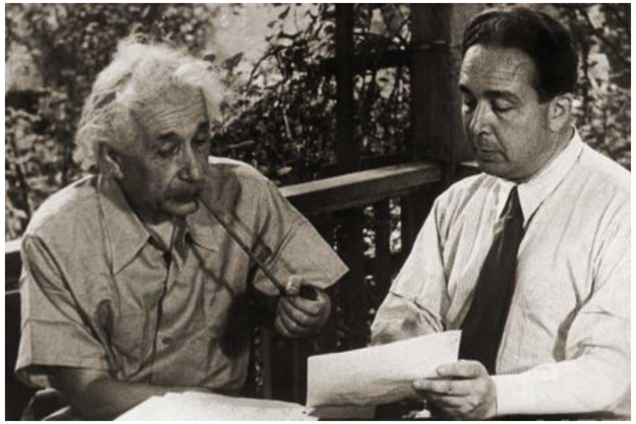
The Soviet Union discovered spontaneous fission, they had world class scientists in the Uranium commission, founded in 1940, they built a reactor for plutonium production in 1942, but had zero Uranium supply.

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.



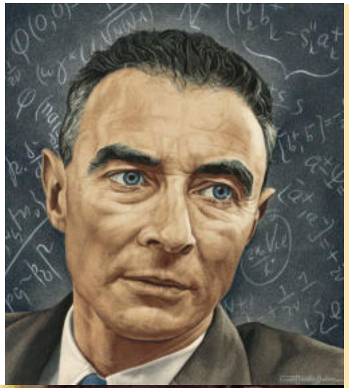
The United States & the United Kingdom had a big influx of technical and theory expertise through European refugees, who were arguing in favor of the bomb (Einstein Szilard Letter), convincing Roosevelt to initiate the Manhattan Project towards the development of a bomb.

The Manhattan Project was 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!



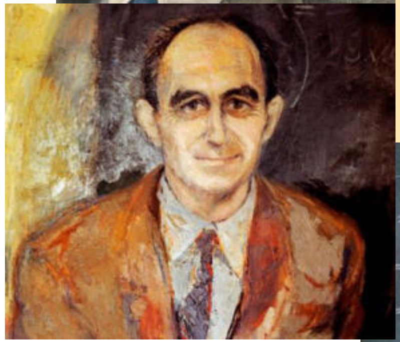
More than one Person

The Participants

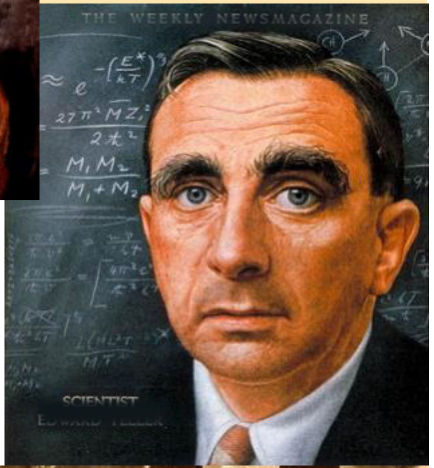



J. Robert Oppenheimer: theoretical physicist in Berkeley and Caltech, focusing on the study of quantum physics and the structure of neutron stars and black holes!

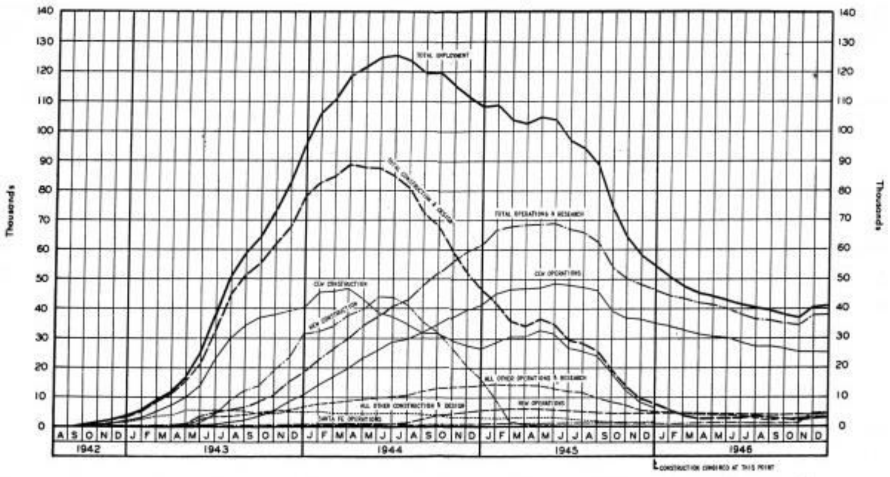
Hans A. Bethe: Trained in Germany by Sommerfeld, he quickly emerged as a rising star in nuclear physics at Cornell, interest in light ion fusion processes in stars!



Enrico Fermi: an Italian physicist, wo used the opportunity of his Nobel prize in 1936 to leave Fascist Italy for the United States. He was essential for the understanding of neutrons and their role in fission.

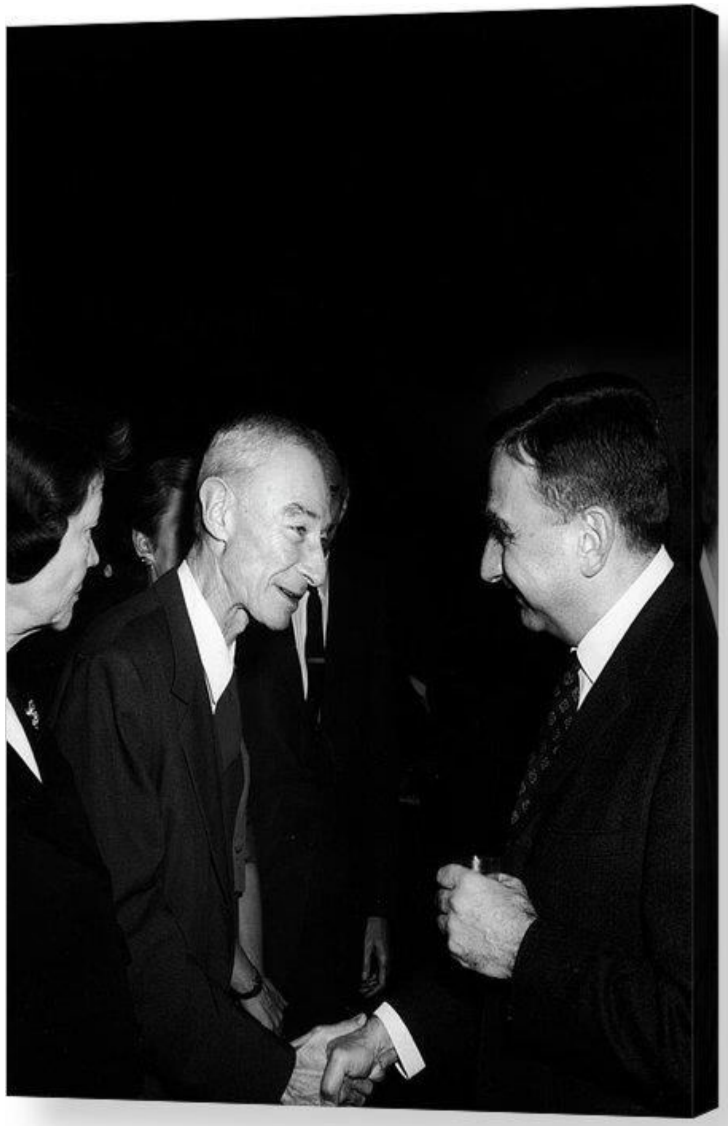


Edward Teller: Hungarian firebrand, worked with Heisenberg in Germany before emigrating to the United States in 1933. At George Washington University he became an expert in light ion fusion reactions and a vehement spokesperson for the hydrogen bomb.



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

1942 Recruitment in Berkeley

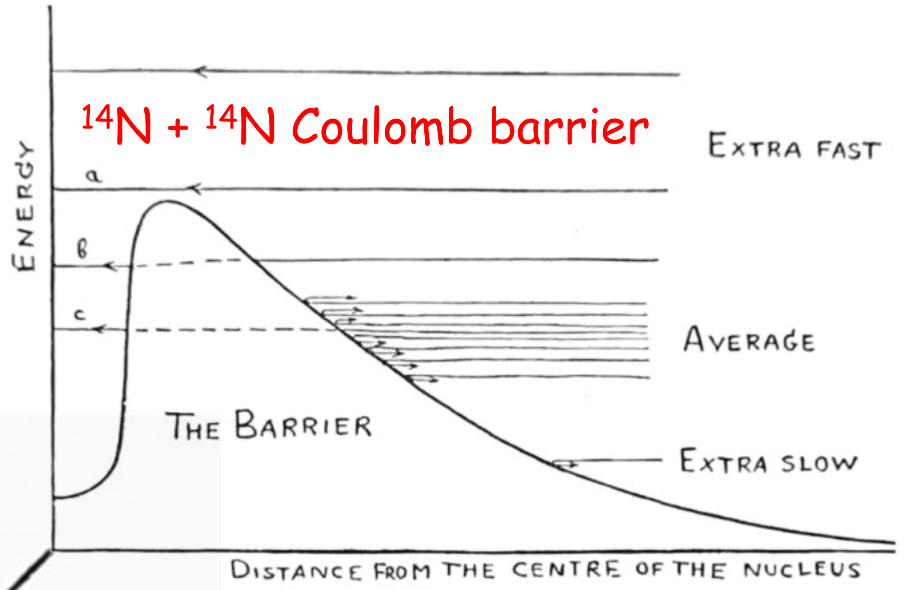


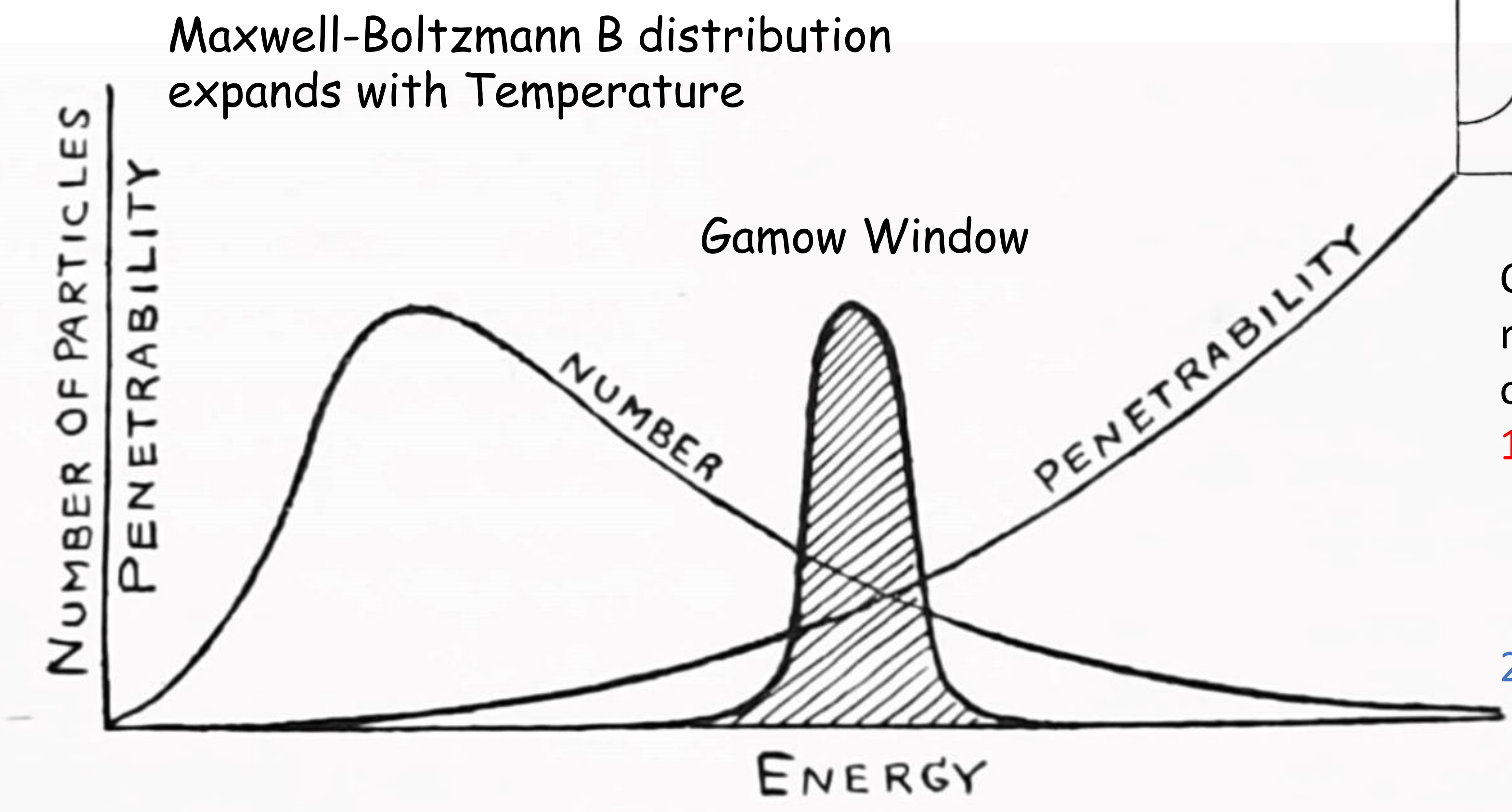
Recruitment of young theorists in Berkeley 1942 for the Manhattan Project.
George Gamow was not eligible as former Red Army officer!

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!

Teller thought in terms of fusion, Oppenheimer in terms of fission!

What about the Fear?





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?

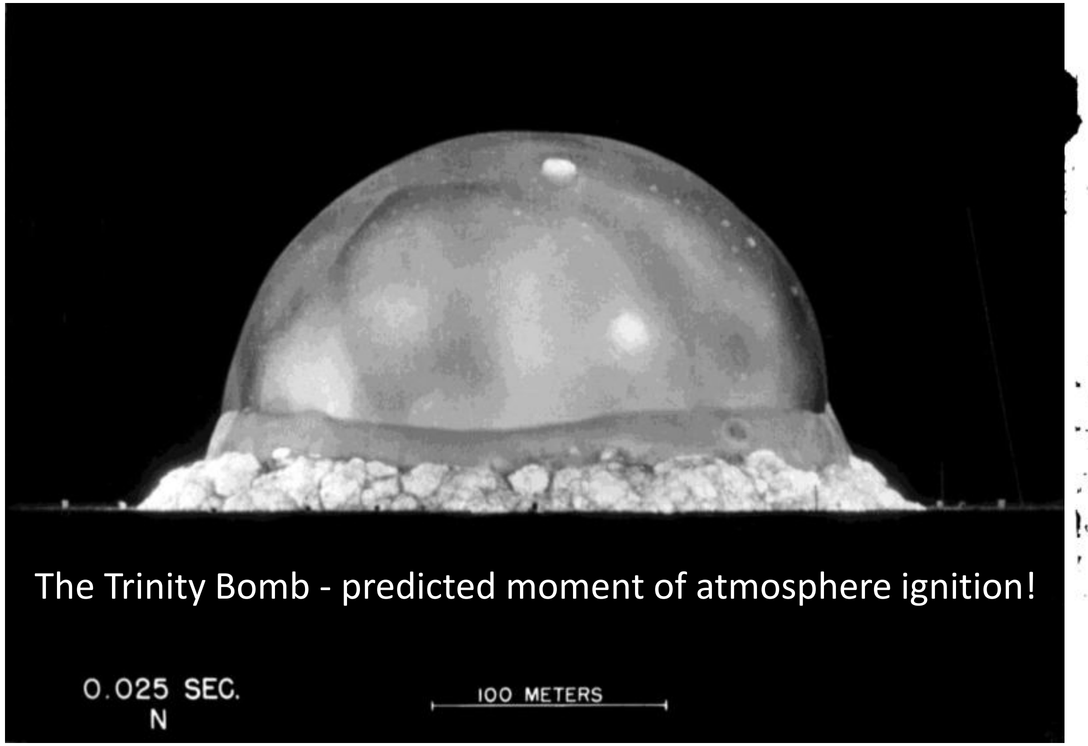
The $^{14}N + {}^{14}N$ and $^{14}N + {}^{1}H$ cross section were only estimated!!!

The Fears of the Trinity Test

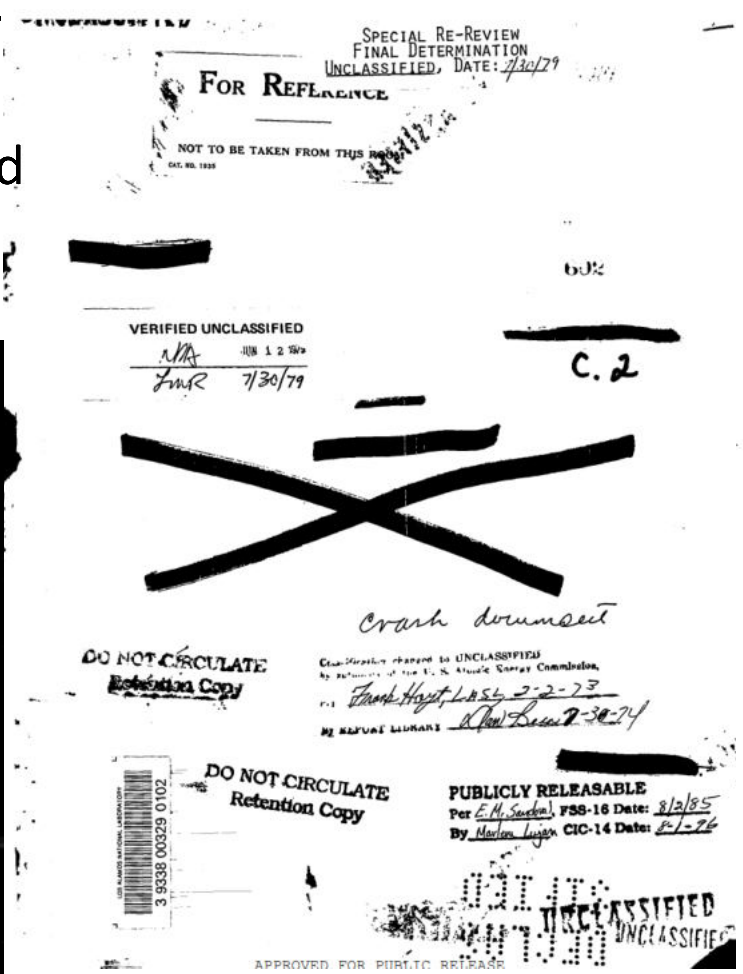
Fusion of Nitrogen and Hydrogen, and Oxygen

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

Bethe dismissed the idea, but 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!



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

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Crash document

DO NOT CIRCULATE
Retention Copy

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

[redacted]

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PUBLICLY RELEASABLE
FSS-16 Date: 8/2/85
CIC-14 Date:

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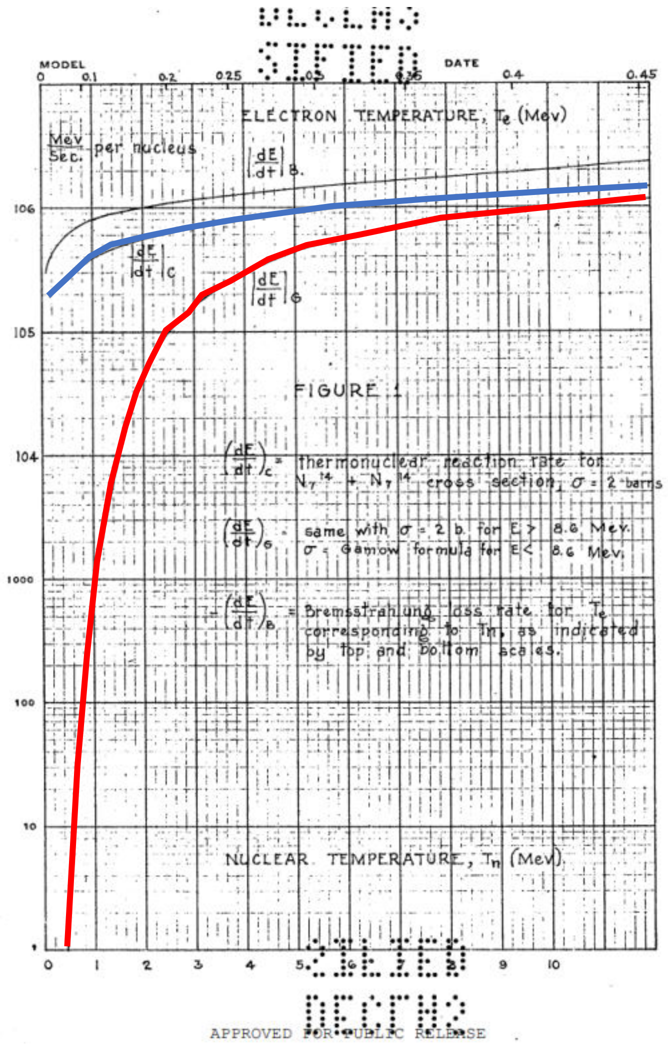
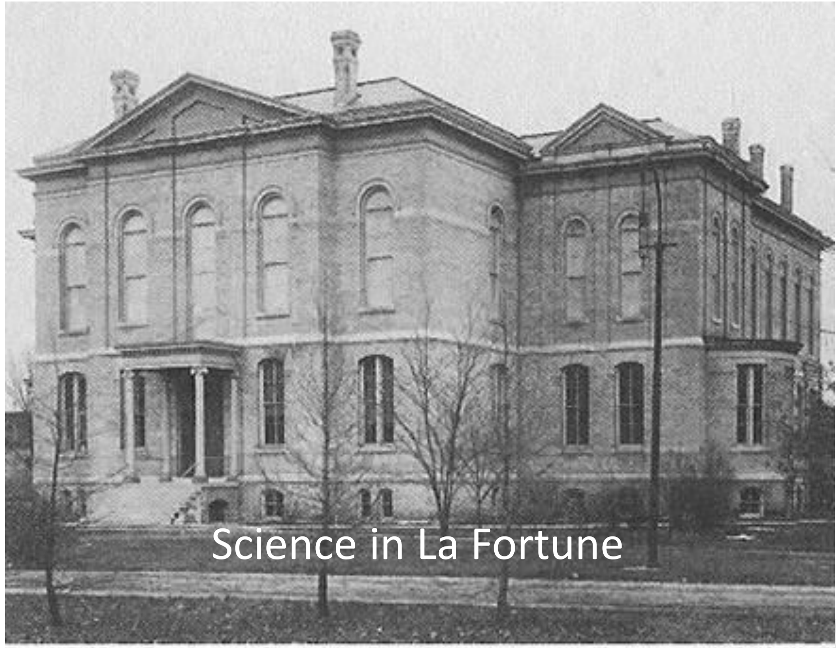
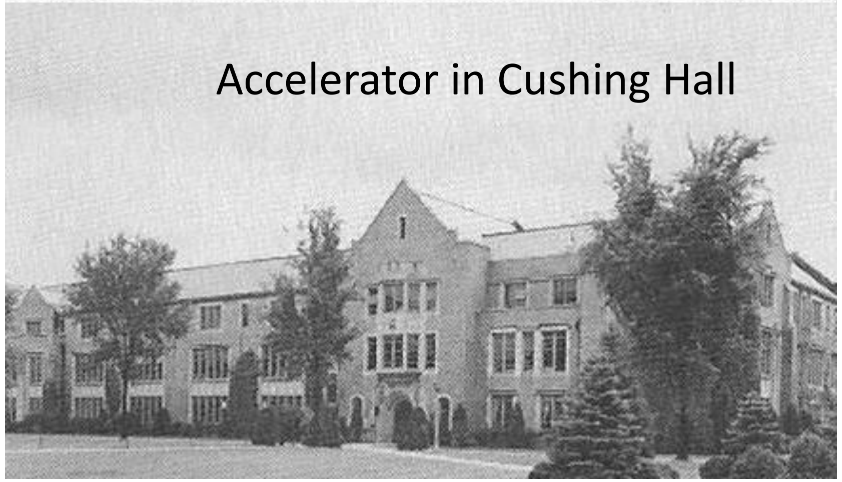
APPROVED FOR PUBLIC RELEASE



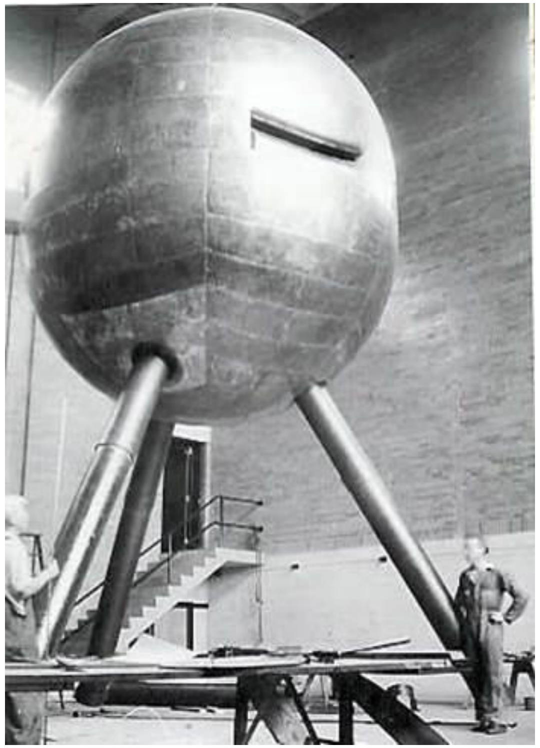
Experience at Notre Dame

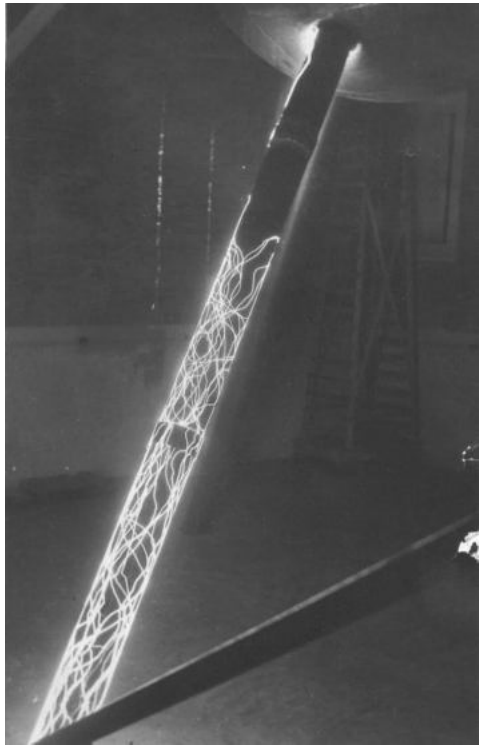


Science in La Fortune



Accelerator in Cushing Hall

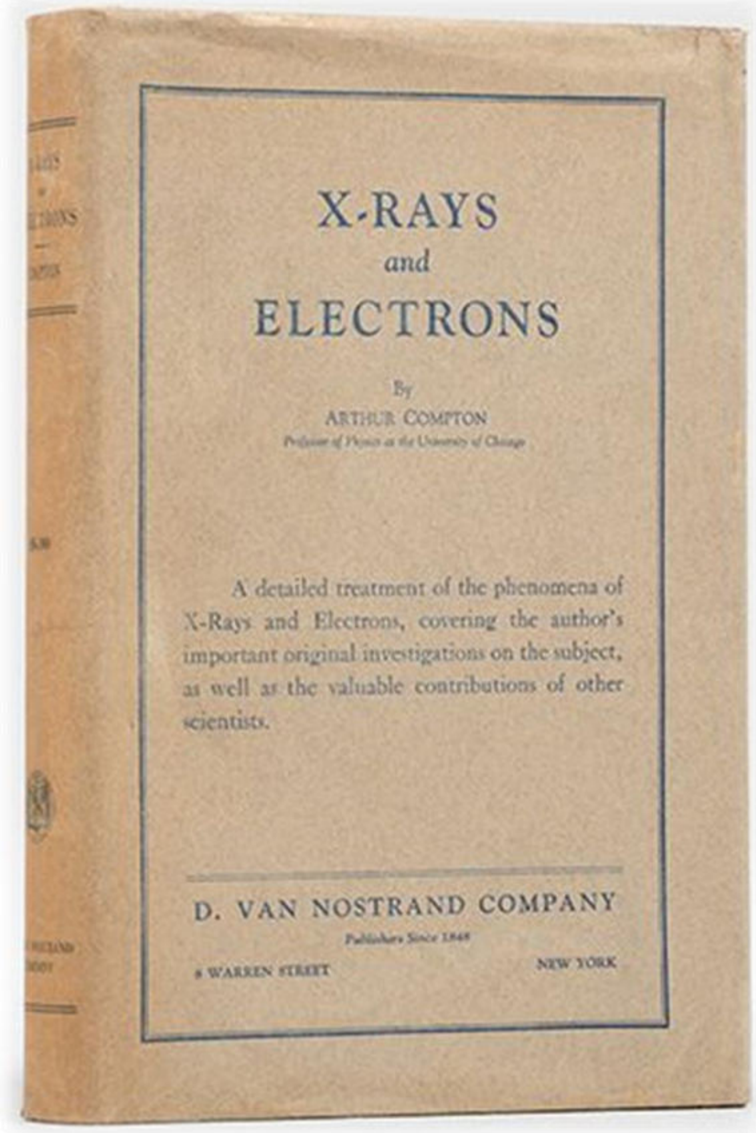




Build in 1936 for $900, commissioned in 1938 as the third electrostatic accelerator in the country! It reached 1 million volt but was not good at humid summer days!

Used for photon excitation and fragmentation studies

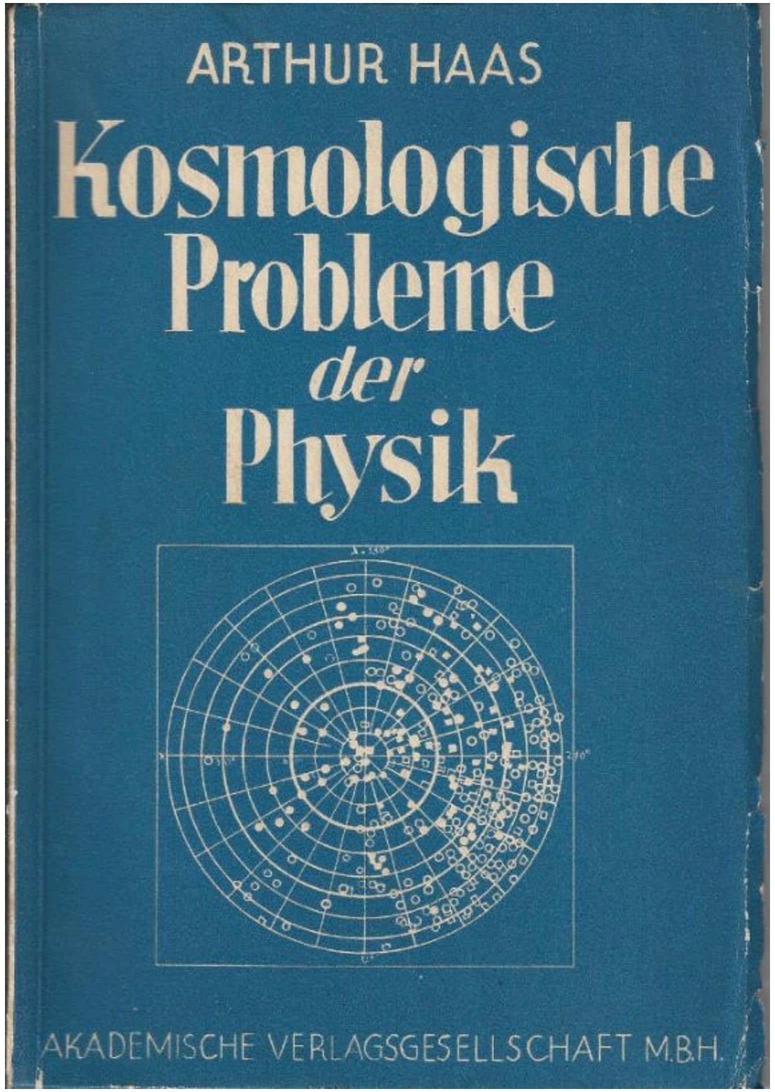
Compton and Haas



Recall Old Times In Vienna

While reminiscing over the old days in Vienna, Dr. Arthur Haas and Dr. Eugen Guth pause a moment from their work in Notre Dame's Science hall. Dr. Guth, a physicist, came to Notre Dame from the University of Vienna. His colleague, Dr. Hass, joined the faculty of Notre Dame last year. (News-Times Photo).

Initial science program at Notre Dame was stimulated and designed by Haas and Guth from Vienna driven by Haas' interest in Cosmology and the idea that the inverse Compton effect and pair production was the origin of mass in the Universe and by Guth's interest in nuclear excitation modes in close interaction with Arthur Compton in Chicago.



PROGRAM

of

SYMPOSIUM

on

THE PHYSICS OF THE UNIVERSE AND THE NATURE OF PRIMORDIAL PARTICLES

TO BE HELD

AT THE UNIVERSITY OF NOTRE DAME

NOTRE DAME, INDIANA

ON THE MONDAY AND TUESDAY OF MAY 2 AND 3, 1938

Everyone interested in the Symposium is cordially invited to attend.

PROGRAM

N. B. — All hours in the program are central standard time. — Any paper not specified as public lecture will be of technical nature.

MONDAY

11:00 A.M. COLLEGE OF ENGINEERING

Carl D. Anderson (California Institute of Technology)
"Some Aspects of the Cosmic-ray Problem."

2:00 P.M. COLLEGE OF ENGINEERING

Manuel S. Vallarta (Massachusetts Institute of Technology)
"The Influence of the Magnetic Field of the Earth on Cosmic-ray Particles."

J. F. Carlson (Purdue University)
"The Theory of Cosmic-ray Particles."

4:30 P.M. PUBLIC LECTURE WASHINGTON HALL

Arthur H. Compton (University of Chicago)
"Whence Cosmic Rays?"

8:30 P.M. PUBLIC LECTURE WASHINGTON HALL

Harlow Shapley (Harvard University)
"The Distribution of Matter in the Metagalaxy."

TUESDAY

9:00 A.M. COLLEGE OF ENGINEERING

Gregory Breit (University of Wisconsin)
"The Nature of the Forces between Primordial Particles."

10:30 A.M. COLLEGE OF ENGINEERING

Canon Georges Lemaître (University of Louvain, Visiting Professor at the University of Notre Dame)
"The Significance of the Clusters of Nebulæ."

Arthur H. Compton (University of Chicago)
"Recent Research on Cosmic Rays."

2:00 P.M. COLLEGE OF ENGINEERING

William D. Harkins (University of Chicago)
"The Heat of the Stars and the Building of the Atoms in the Universe."

Eugene Guth (University of Notre Dame)
"The Relativistic Theory of Primordial Particles."

Arthur E. Haas (University of Notre Dame)
"Cosmic Constants."

4:30 P.M. PUBLIC LECTURE WASHINGTON HALL

Carl D. Anderson (California Institute of Technology)
"The Basic Constituents of Matter."

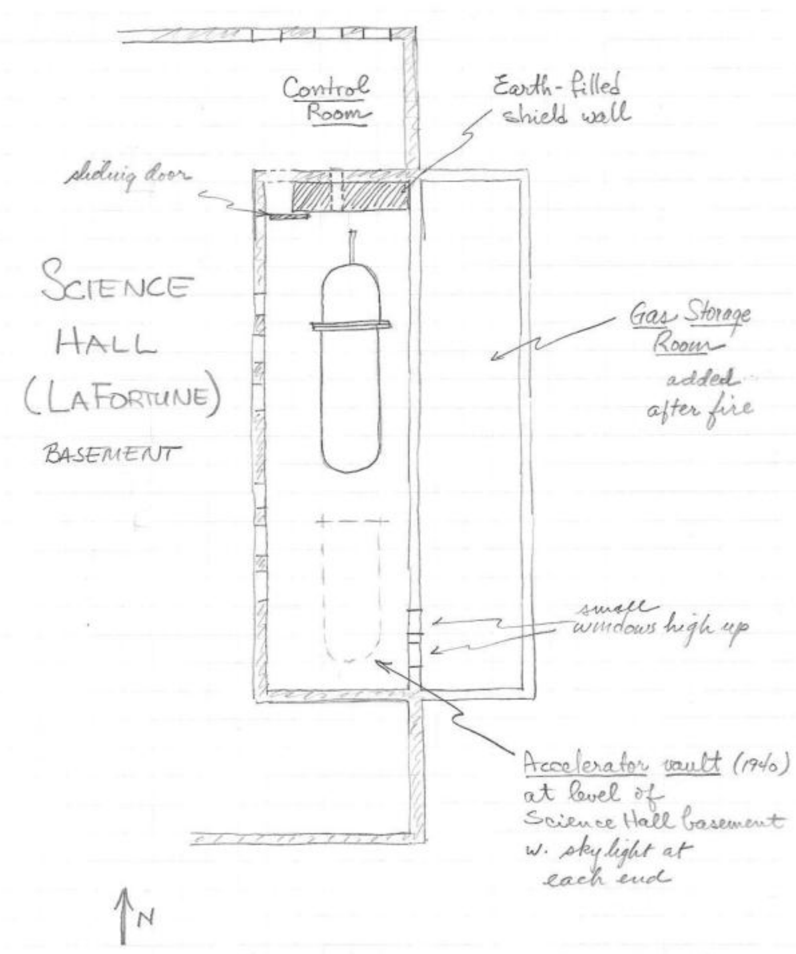
Concerning Accommodations : The LaSalle, the Oliver, and the Hoffman Hotel in the City of South Bend offer first-class accommodations. The prices of rooms at these hotels are about the same — single rooms with bath ranging from $2.25 to $4.00, and double rooms with bath from $3.50 to $5.50. Early reservation of rooms is advised, as there is to be in South Bend a convention on the same days as the symposium. The University of Notre Dame, two miles from the business center of the city, may be reached by street-car in ten minutes.

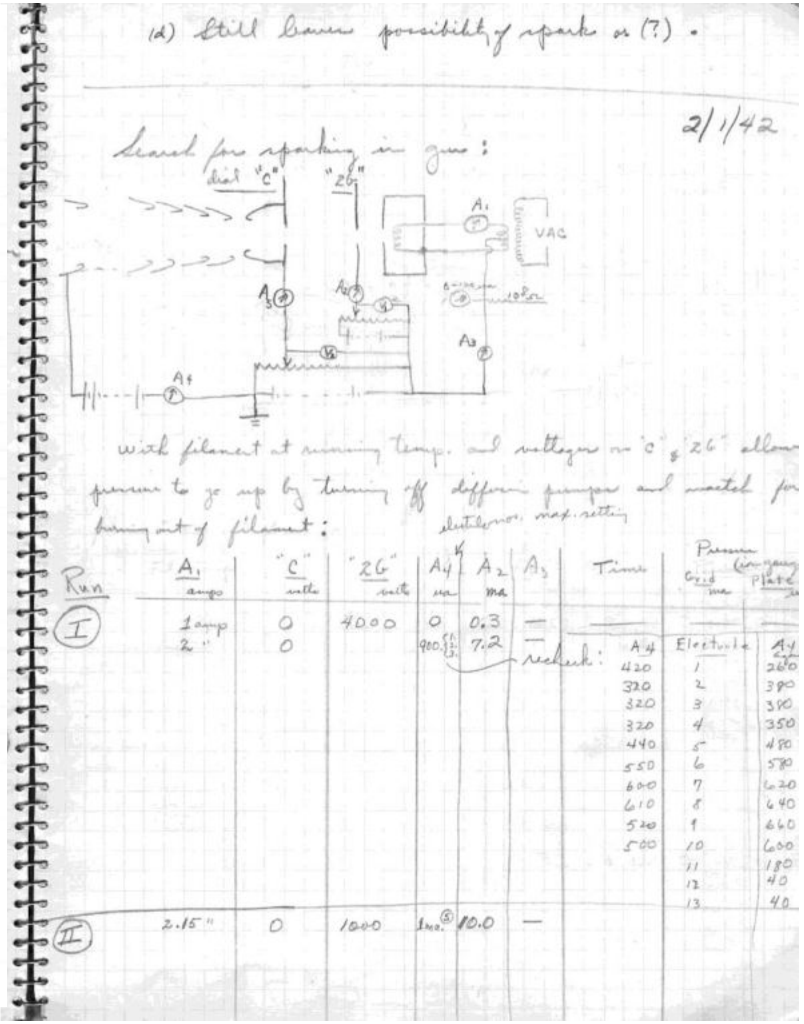
— The Department of Physics.

Manhattan Project@nd.edu 1942-1952

New accelerator commissioned for war effort through the University of Chicago Metallurgical Center, became part of the Manhattan Project! Bernie Waldman was in charge!

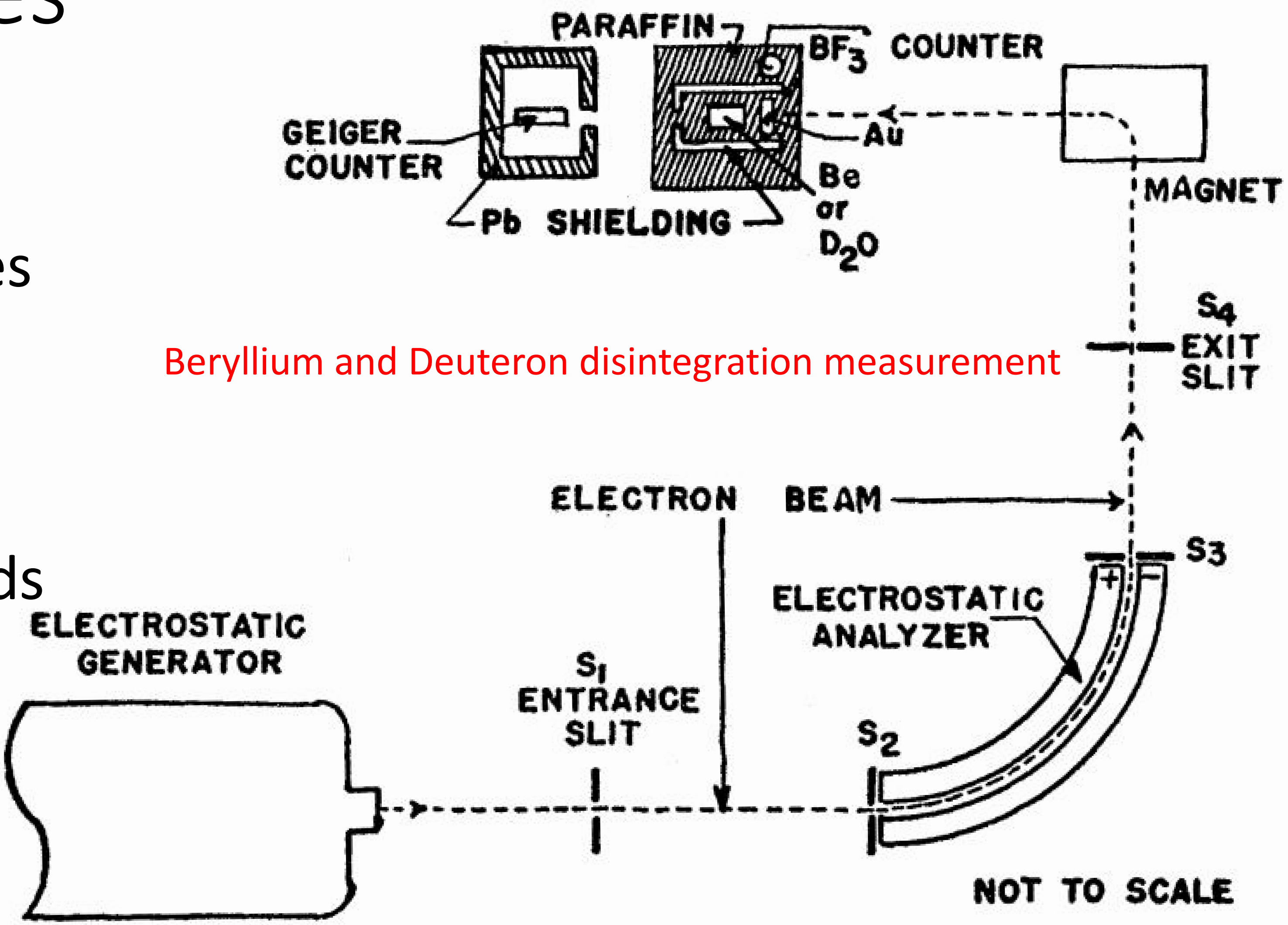
Daily users from Chicago by South-Shore and Tram





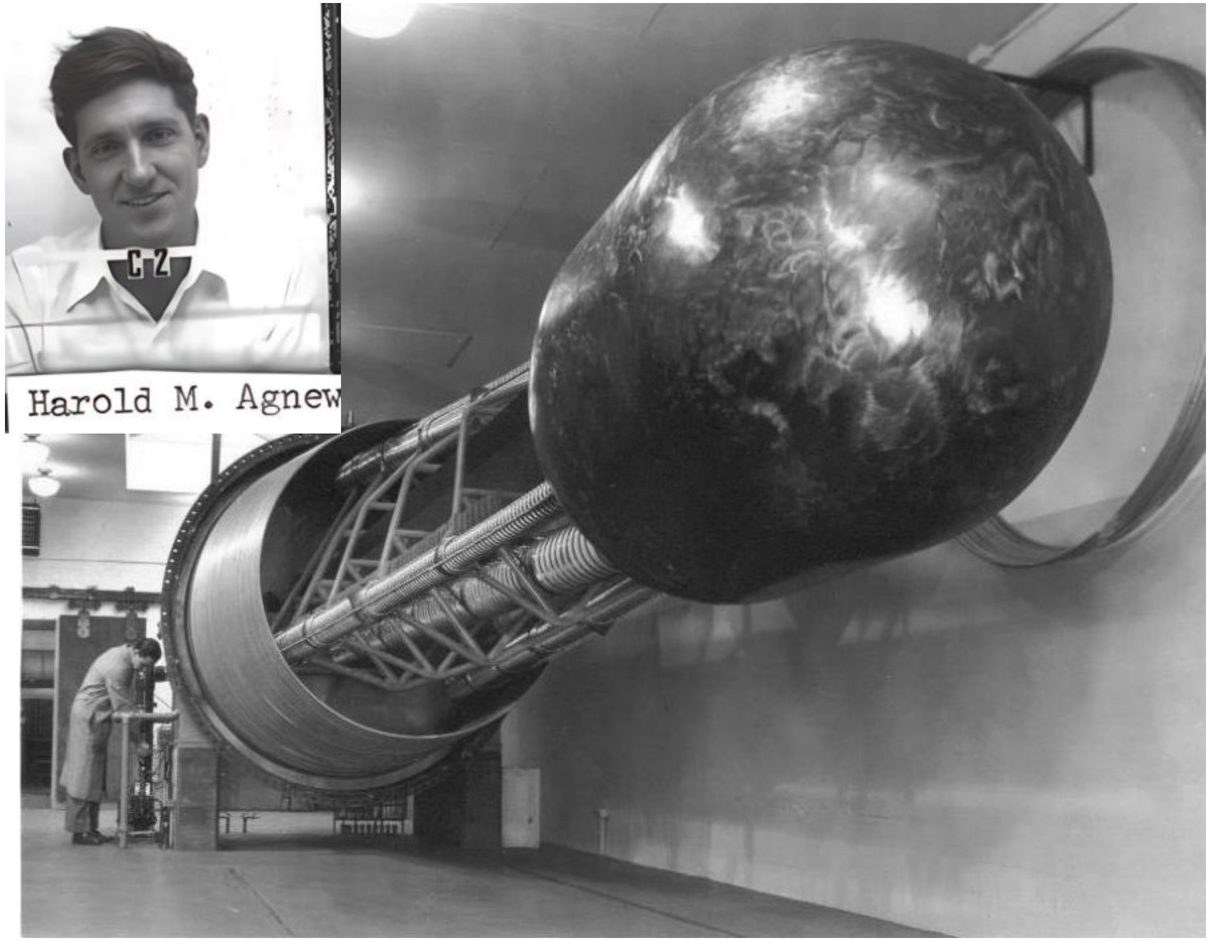
Electron beam induced radiation and absorption studies

Bremsstrahlung studies
Photodisintegration studies
Photoexcitation studies
Electron induced isomers
Neutron backscattering
Neutron detection methods
Based on publications between 1945-1955



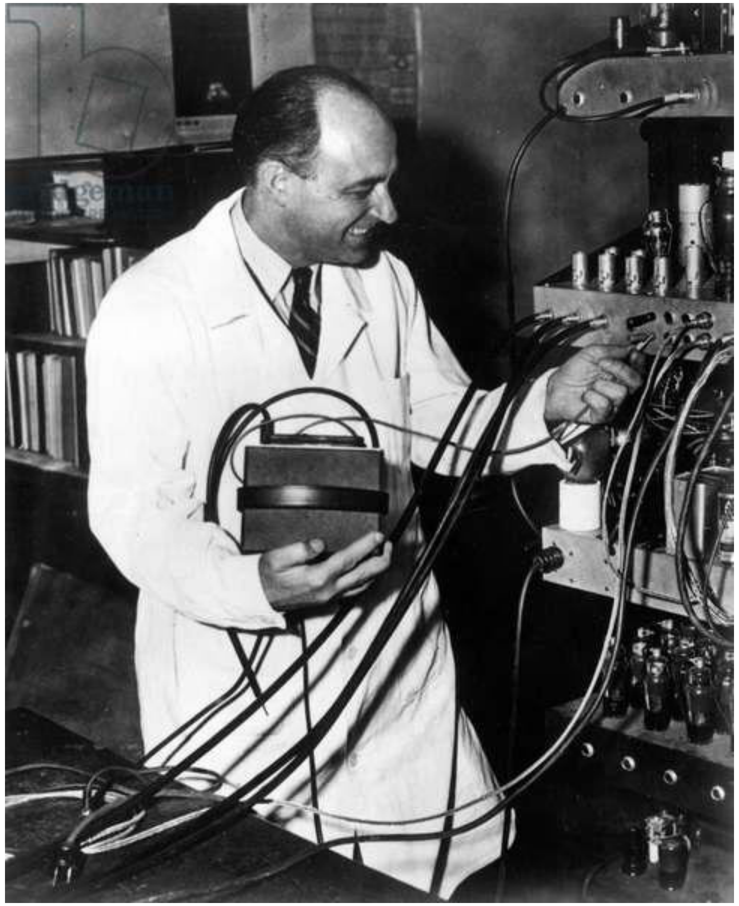
Beryllium and Deuteron disintegration measurement

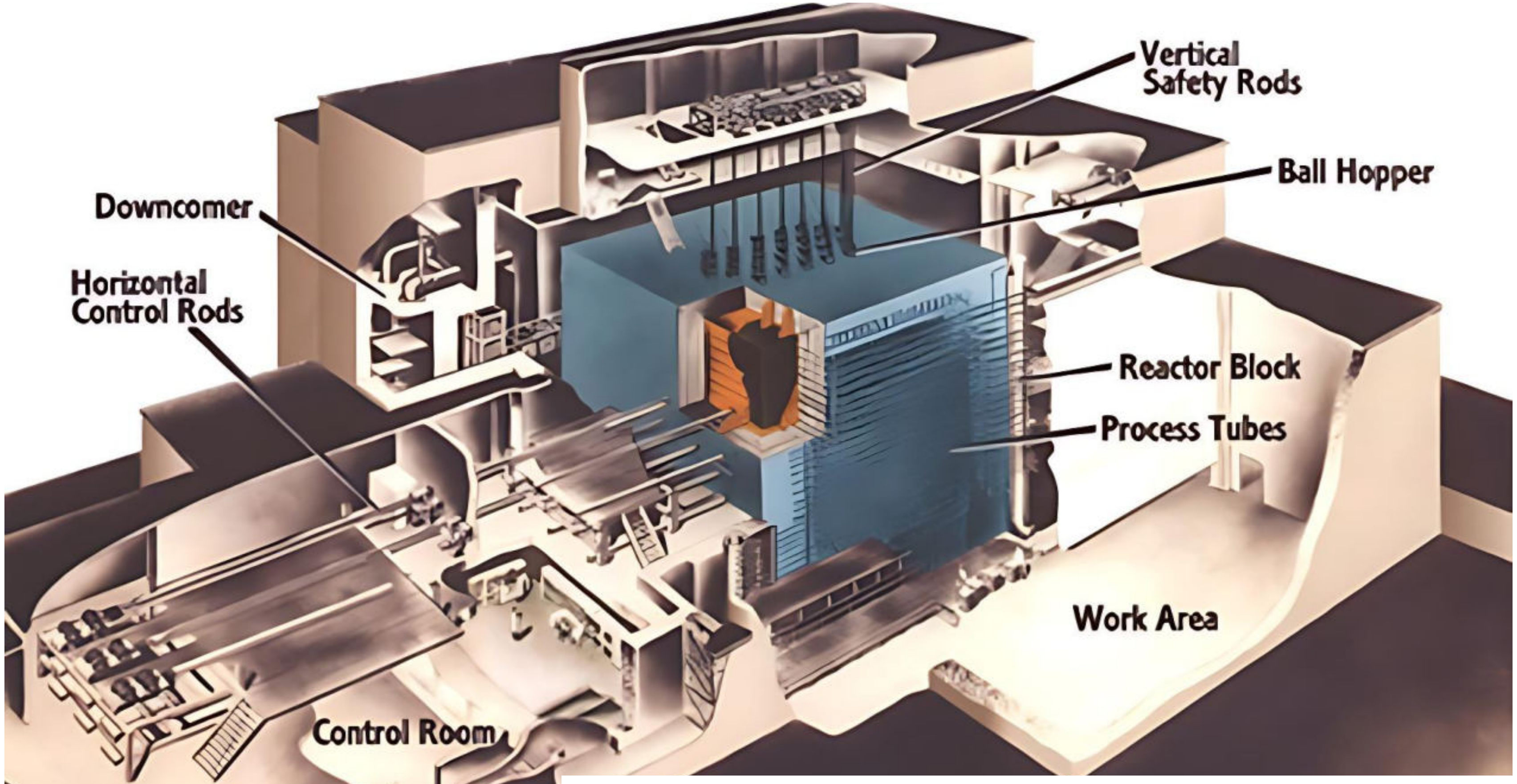
Waldman and Chicago Metallurgical Institute



The new accelerator run by Waldman, Agnew, and Fermi for radiation tests absorption 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

The team for Trinity and Hiroshima

Bernard Waldman

Harry Agnew

Bernard Waldman, Luis Alvarez, Robert Serber

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).

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

Bernie Waldman, letter to his wife, Aug. 8, 1945

I worked hard the next day and got my stuff ready and at about 2:00 AM off we went. It certainly was an experience. After about 5 hours we sighted Japan and in we went. The bomb was dropped and it was another Trinity except that I was in the best possible observation position. The sight was magnificent but the destruction horrible. We had an uneventful trip home. We never saw flak or an enemy plane the entire trip.

Then we awaited the press release with great anxiety. At last it came. I hope you heard it. I feel rather fortunate to have been there as an official observer when the first one was used but somehow the destruction and horror of it is terrifying. It is a most fiendish device. I hope we do not have to use again.

New Ideas and Developments in Science

Ignition of the Atmosphere
Heavy Ion Fusion Reactions
Super-Heavy Elements
The Physics of Stars

From Fission to Fusion

PHYSICAL REVIEW VOLUME 73, NUMBER 8 APRIL 15, 1948

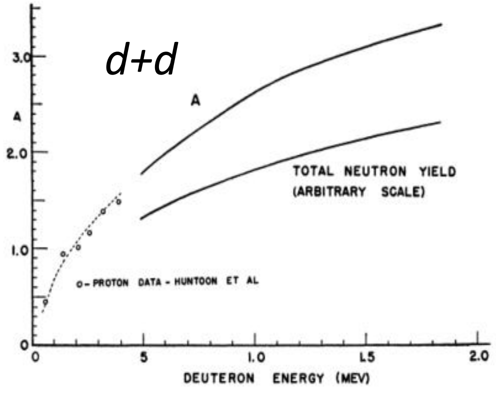
Theoretical Considerations Concerning the $D+D$ Reactions

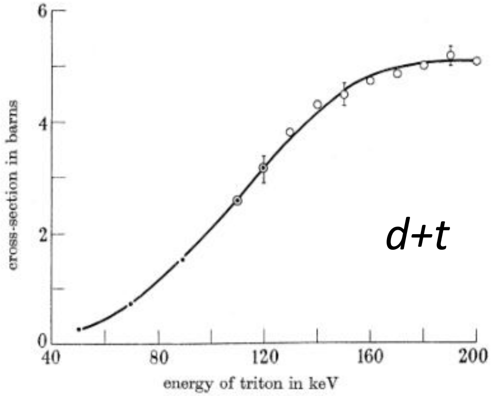
E. J. Konopinski, *Indiana University, Bloomington, Indiana*

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

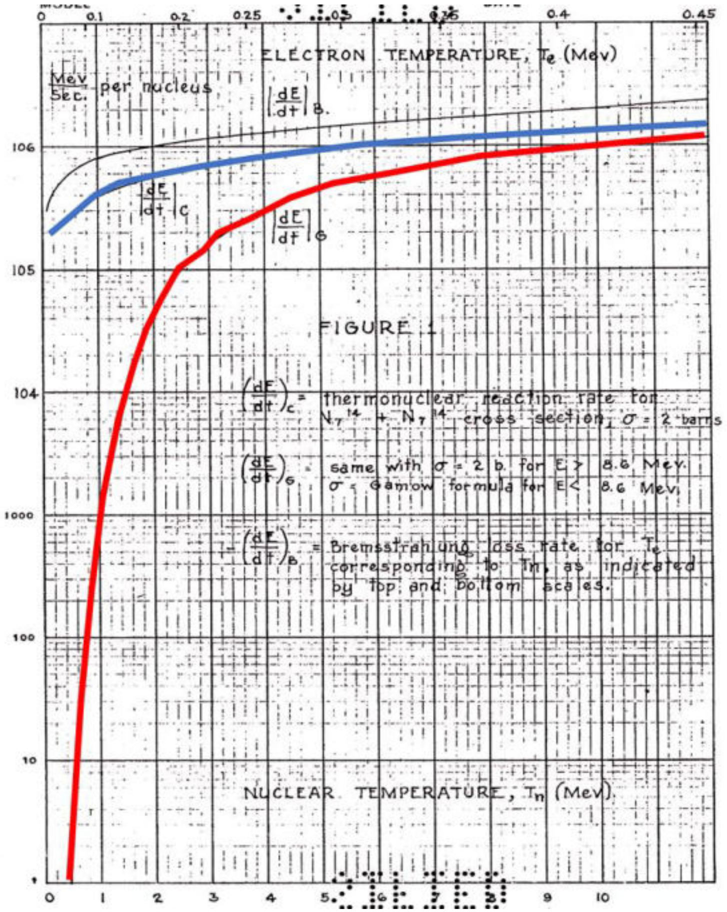
d+d $$\sigma_l = \pi \lambda\!\!\!^{-2}(2l+1)\, g_l\, |\alpha_l|^2 P_l,$$

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

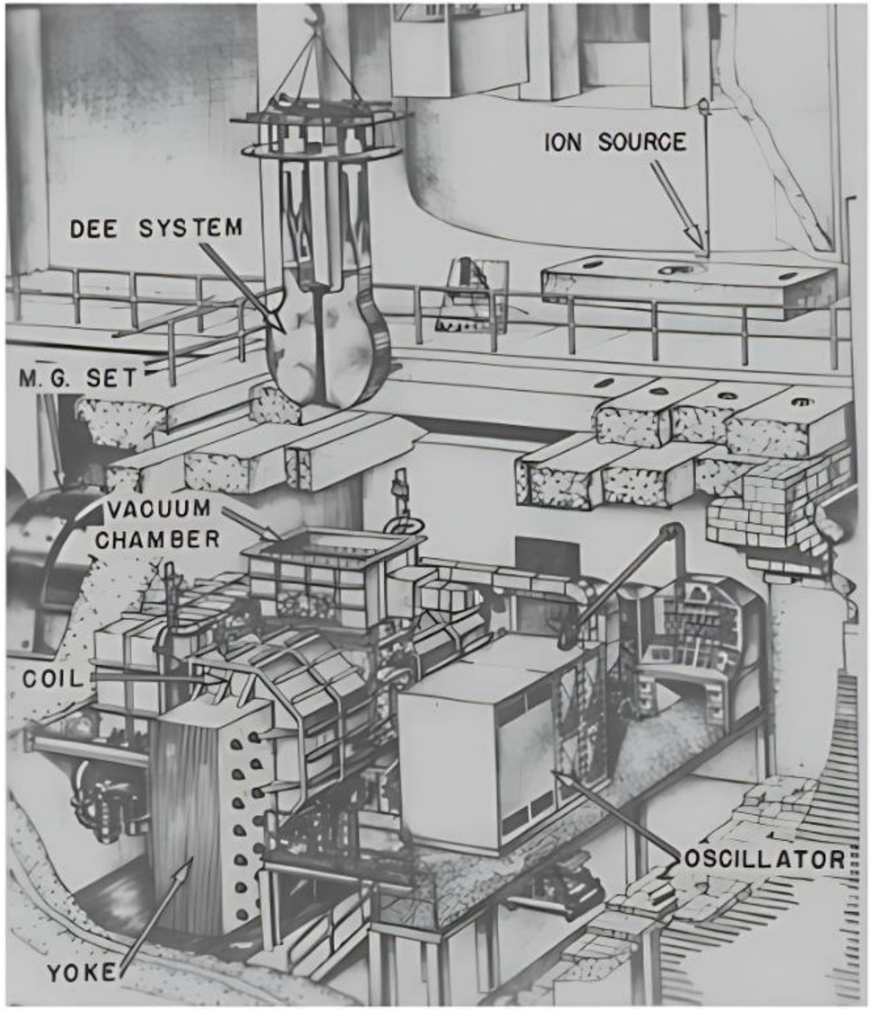
The Ulam-Teller design was based on the original Teller idea, that the heat would be generated by a fission bomb to create the conditions for fusion. Instead of nitrogen, deuterium and tritium would be the fuel, the latter produced at Hanford via the $^{7}Li(n,t)^{4}He$ reaction. The Ulam-Teller design 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 just beyond a 10-Mev temperature. It is impossible to reach such temperatures unless fission bombs or thermonuclear bombs are used which greatly exceed the bombs now under consideration. But even if bombs of the required volume (i.e., greater than 1000 cubic meters) are employed, energy transfer from electrons to light quanta by Compton scattering will provide a further safety factor and will make a chain reaction in air impossible.

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



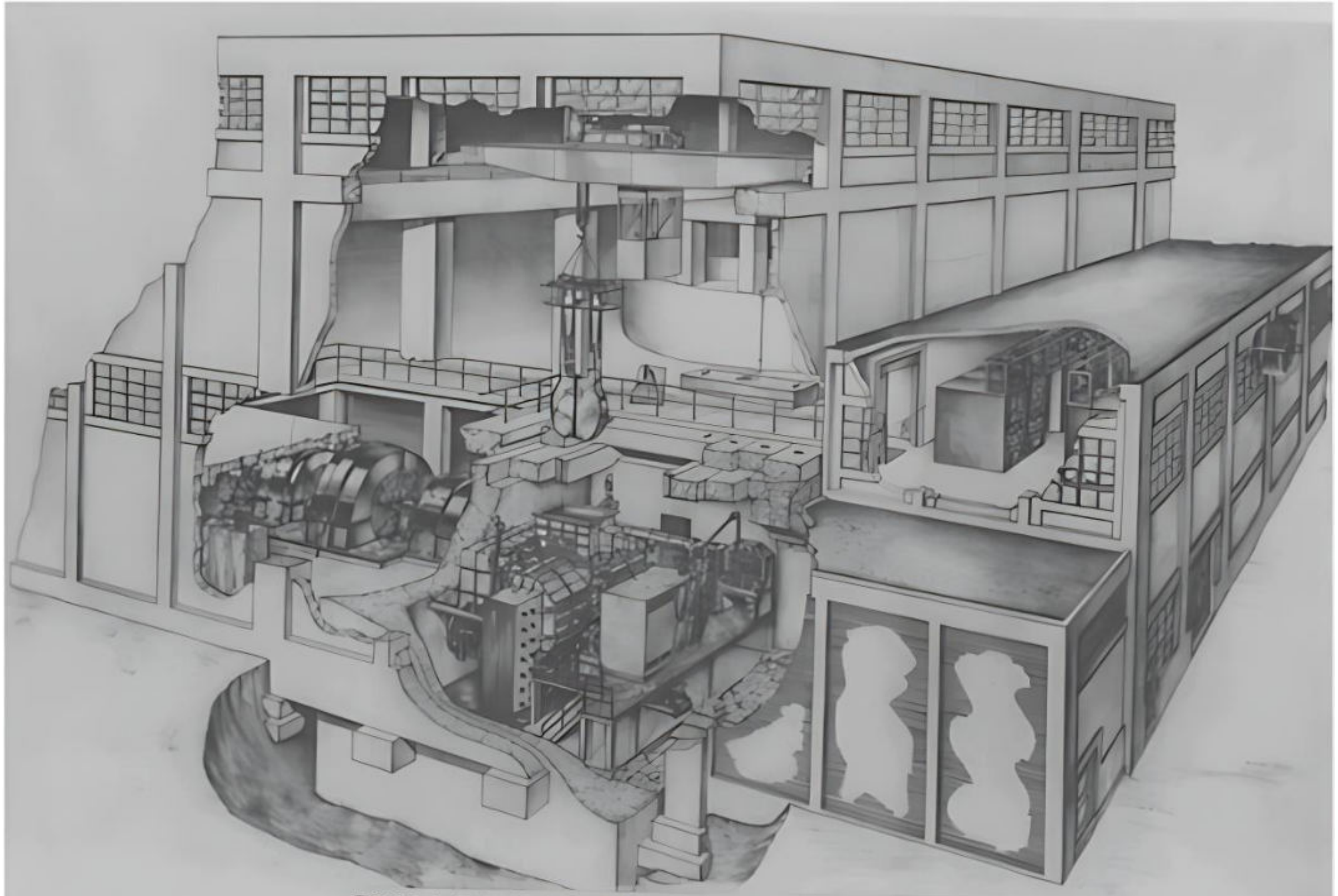
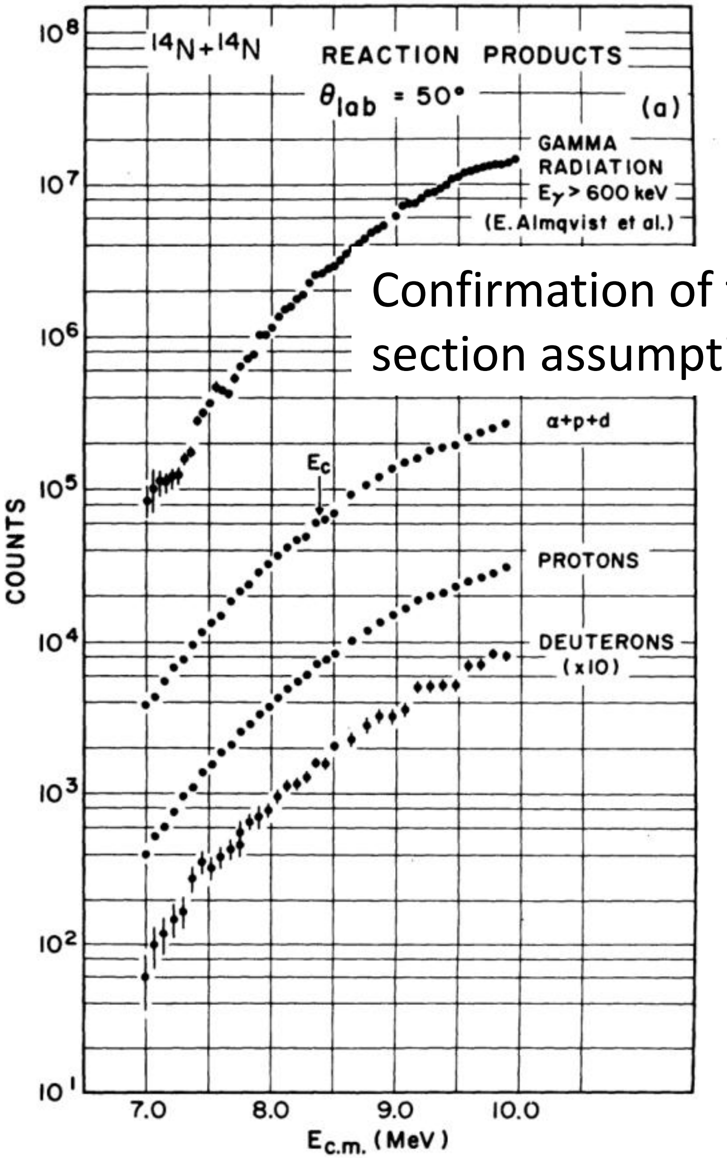


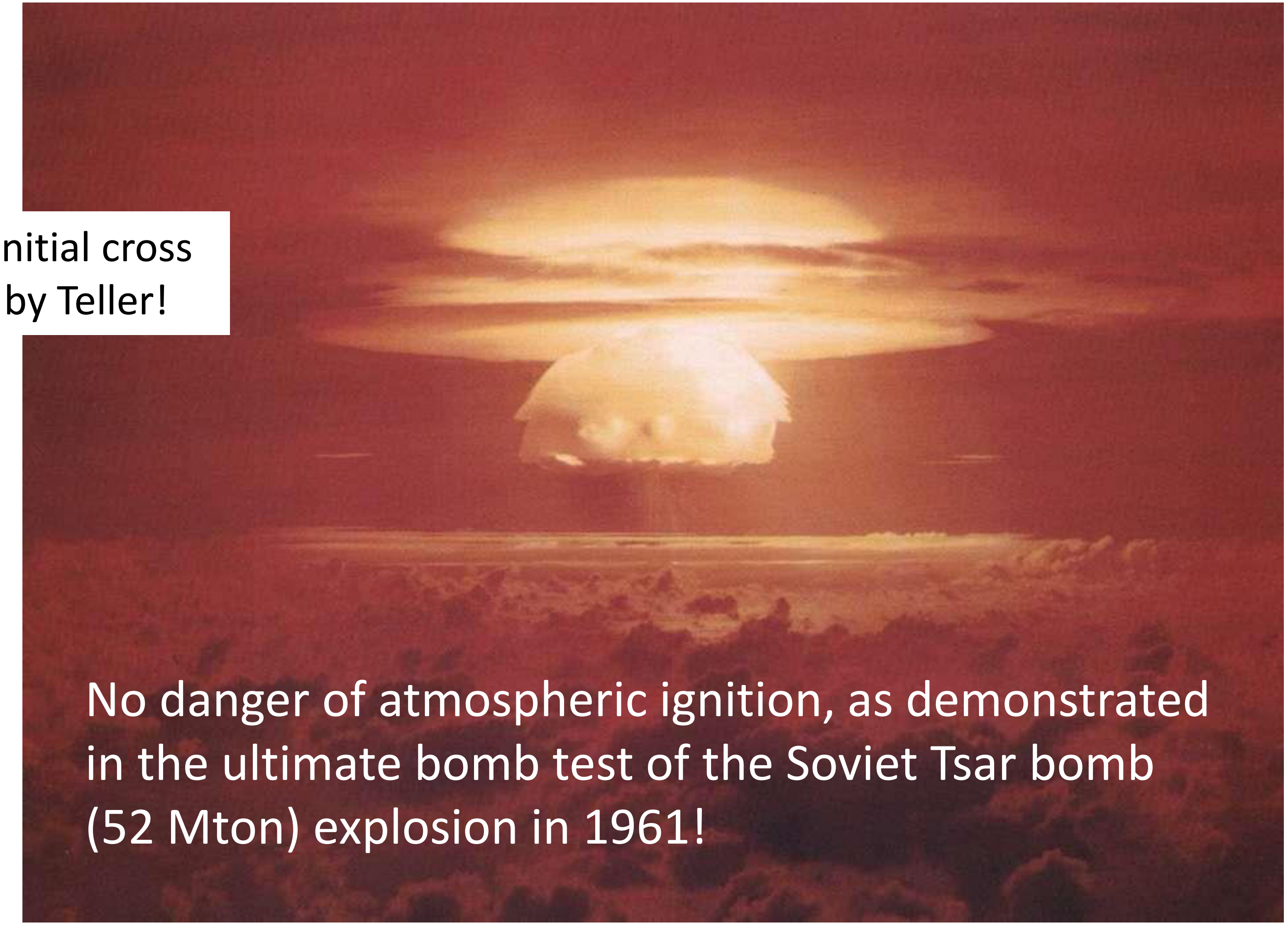
FIGURE I THE 86 INCH CYCLOTRON INSTALLATION

6

Cross Sections Studies and Confirmation



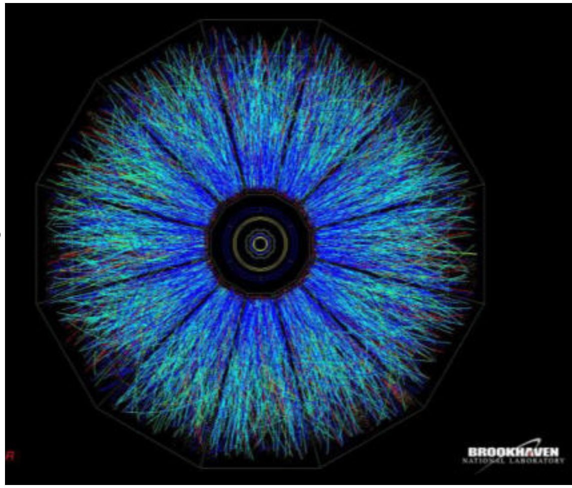
Confirmation of the initial cross section assumptions by Teller!



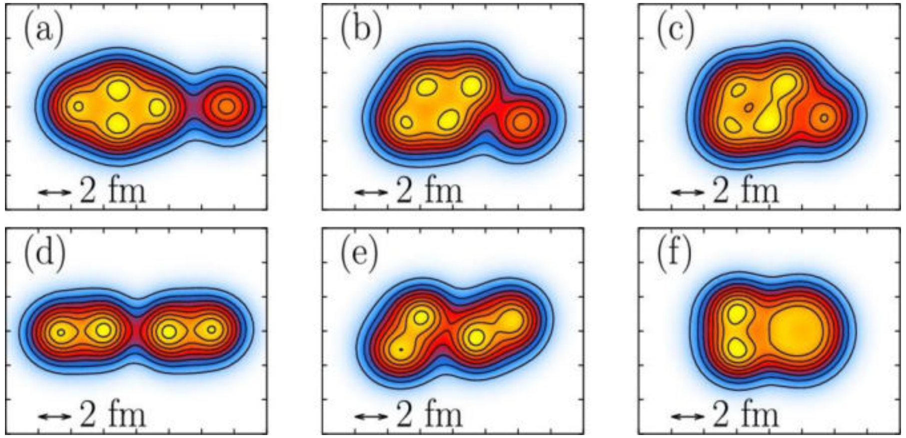
No danger of atmospheric ignition, as demonstrated in the ultimate bomb test of the Soviet Tsar bomb (52 Mton) explosion in 1961!

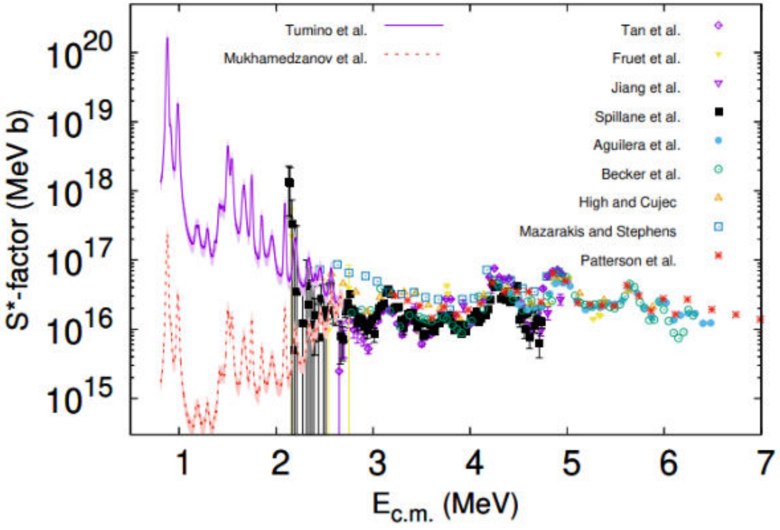
New directions towards high and low energies

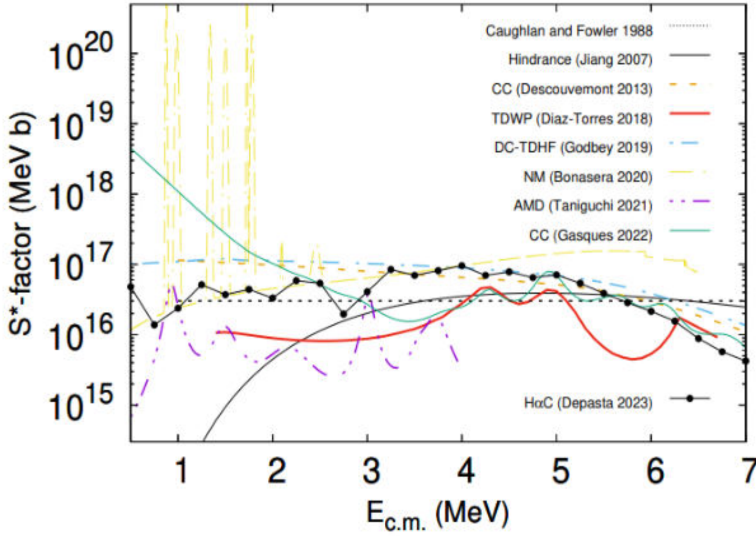
Heavy ion studies opened a new field of heavy ion fusion measurements at Oak Ridge, Berkeley, Brookhaven, leading to the construction of the Relativistic Heavy Ion Collider at BNL for heavy ion fusion at high energies.



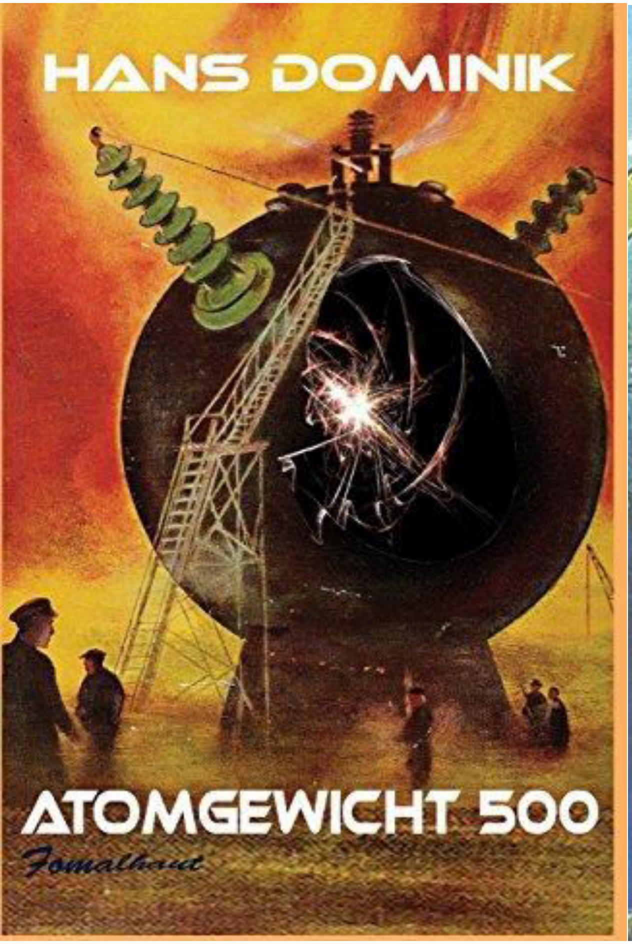
In low energy to the search for clustering phenomena in light ion fusion reactions of importance for nuclear burning in late stellar evolution and explosion! These are presently pursued at ANL, Notre Dame, Strasbourg!

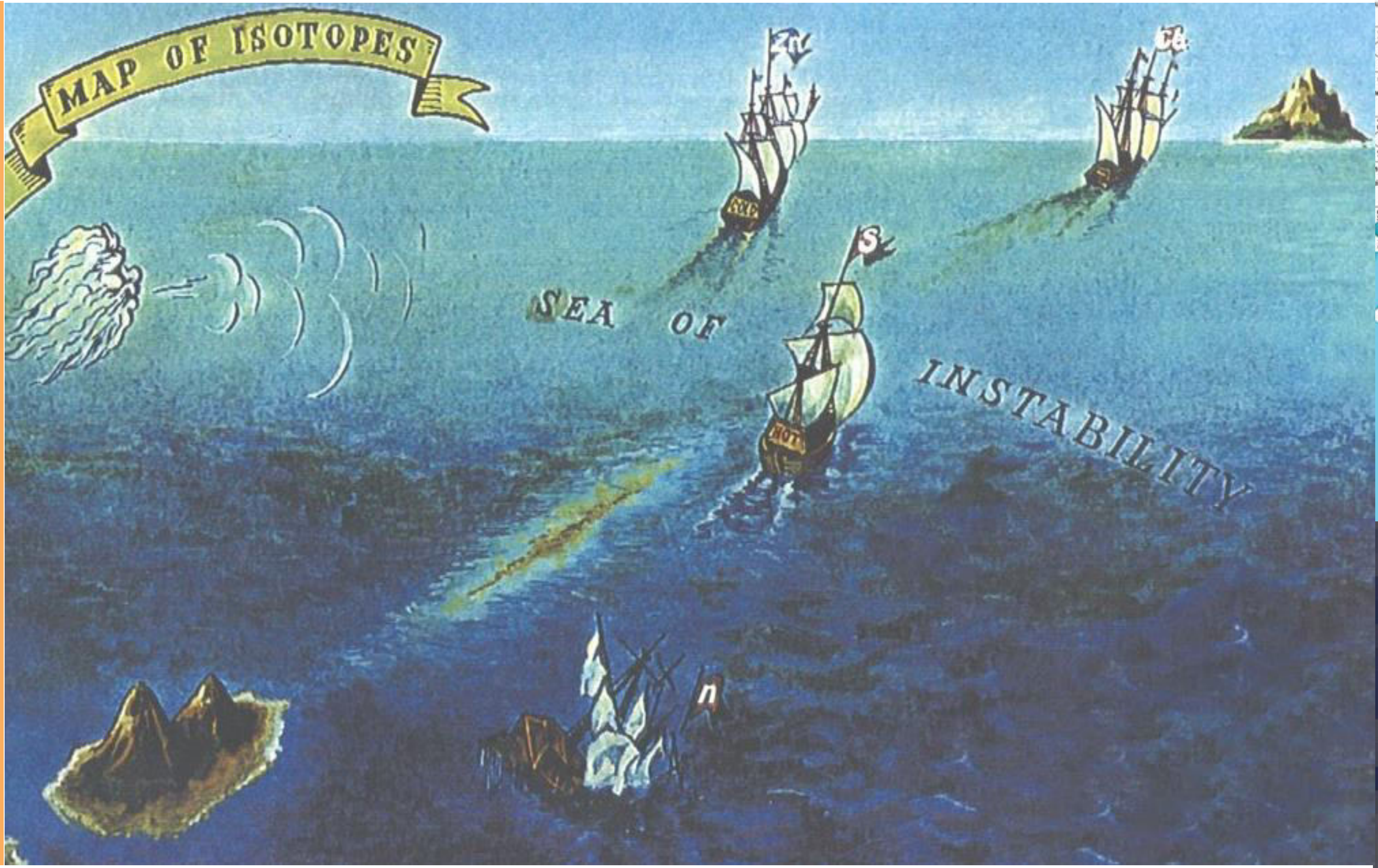


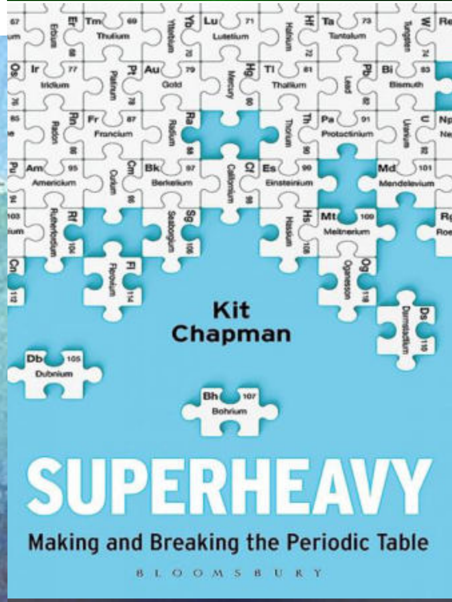


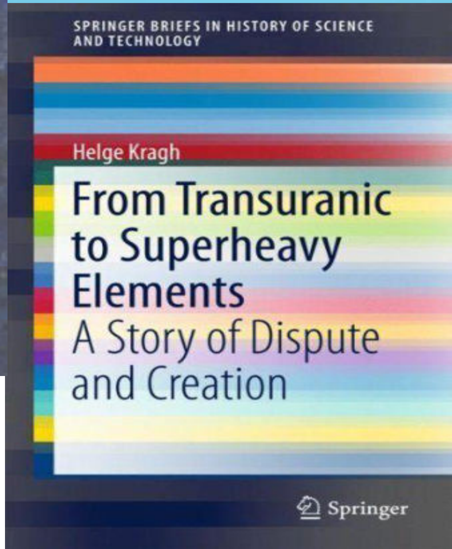


Extending the Nuclide Chart
The Dream of Discovery









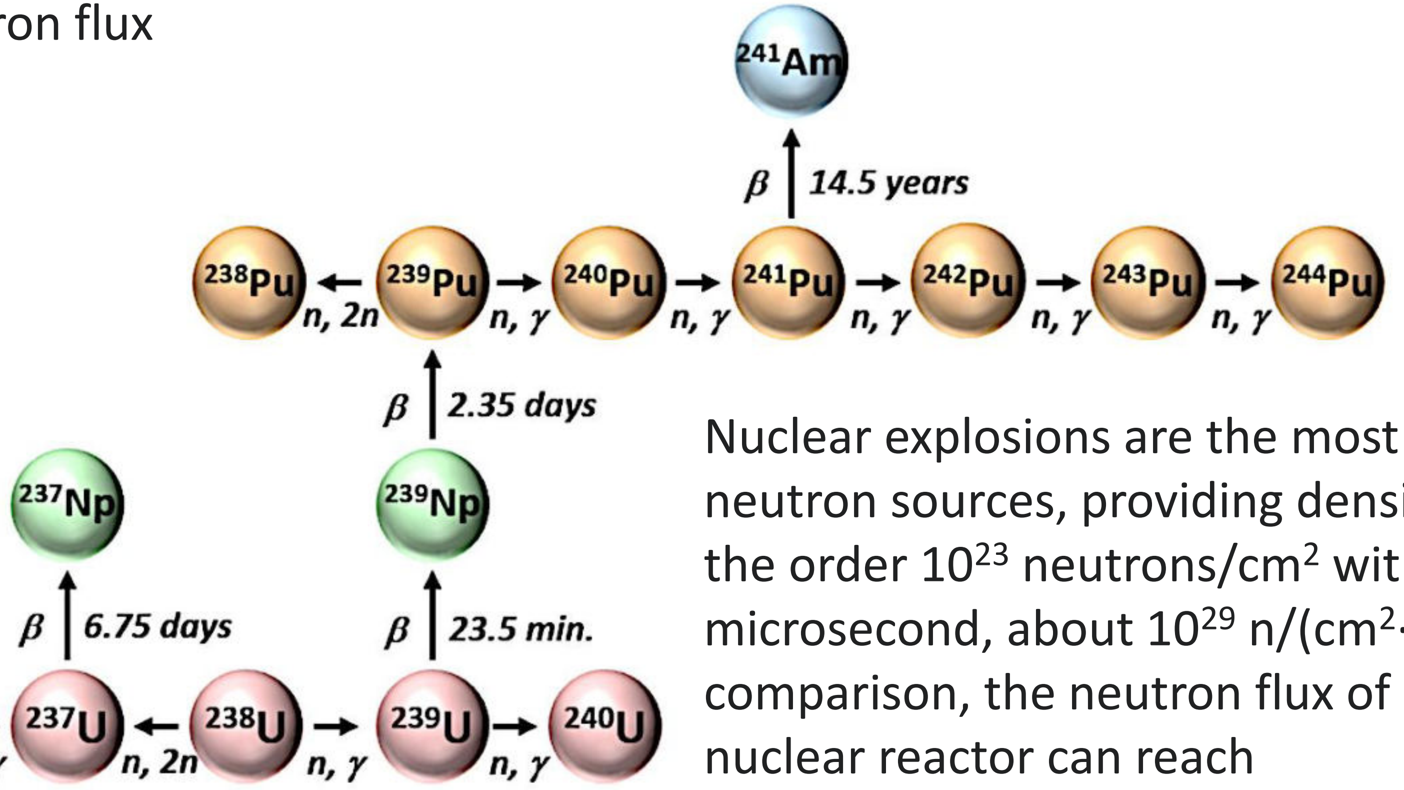
Searching for Superheavy Elements and reaching the Island of Stability

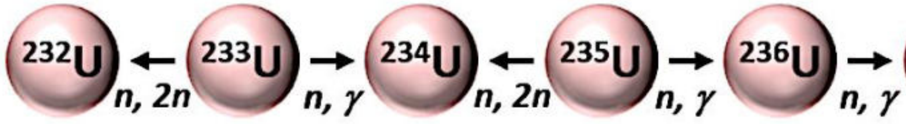
Glenn Seaborg as Head of the AEC

Seaborg received the Nobel price for the discovery of Plutonium and pushed for heavier element discoveries

Neutron Capture in the Bomb

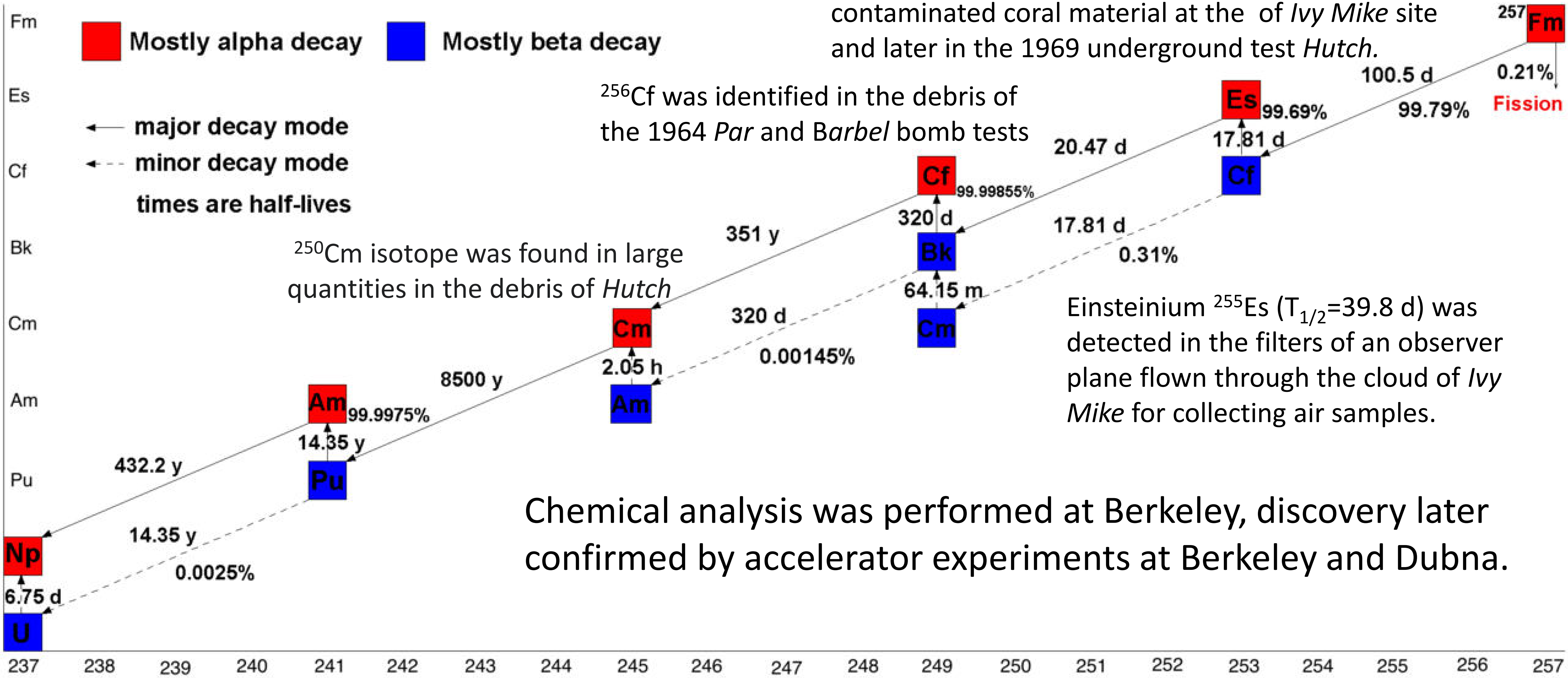
New elements were first discovered in the fallout from the 'Ivy Mike' nuclear test. The examination of the debris from the explosion had shown the production of a new isotope of plutonium, $^{244}_{94}Pu$, which would have formed by the absorption of six neutrons by a uranium-238 nucleus followed by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

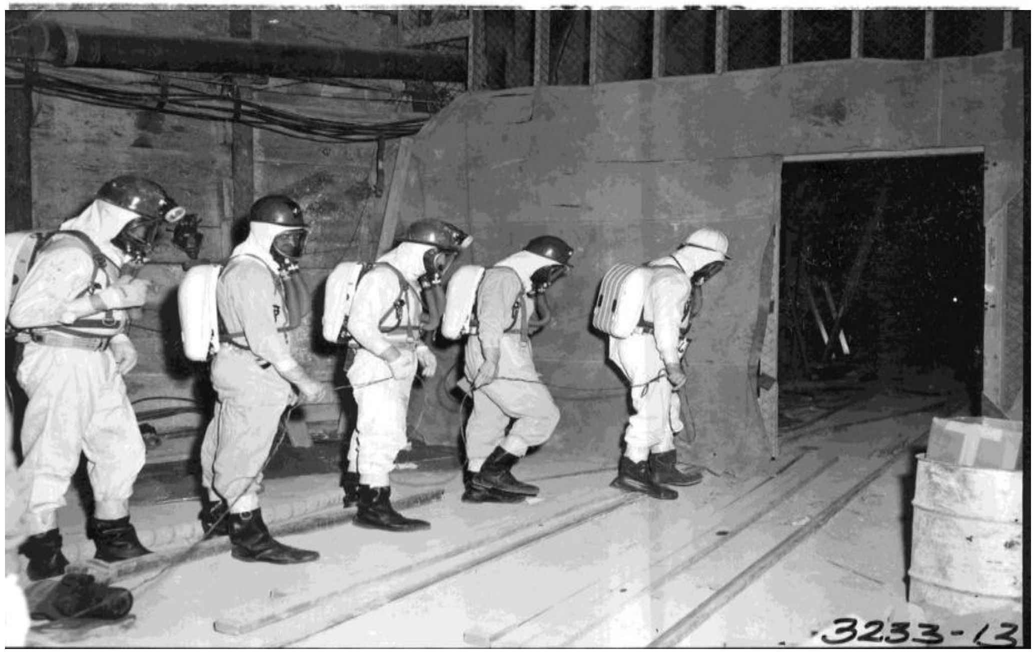
Einsteinium ^{255}Es ($T_{1/2}$=39.8 d) was detected in the filters of an observer plane flown through the cloud of *Ivy Mike* for collecting air samples.

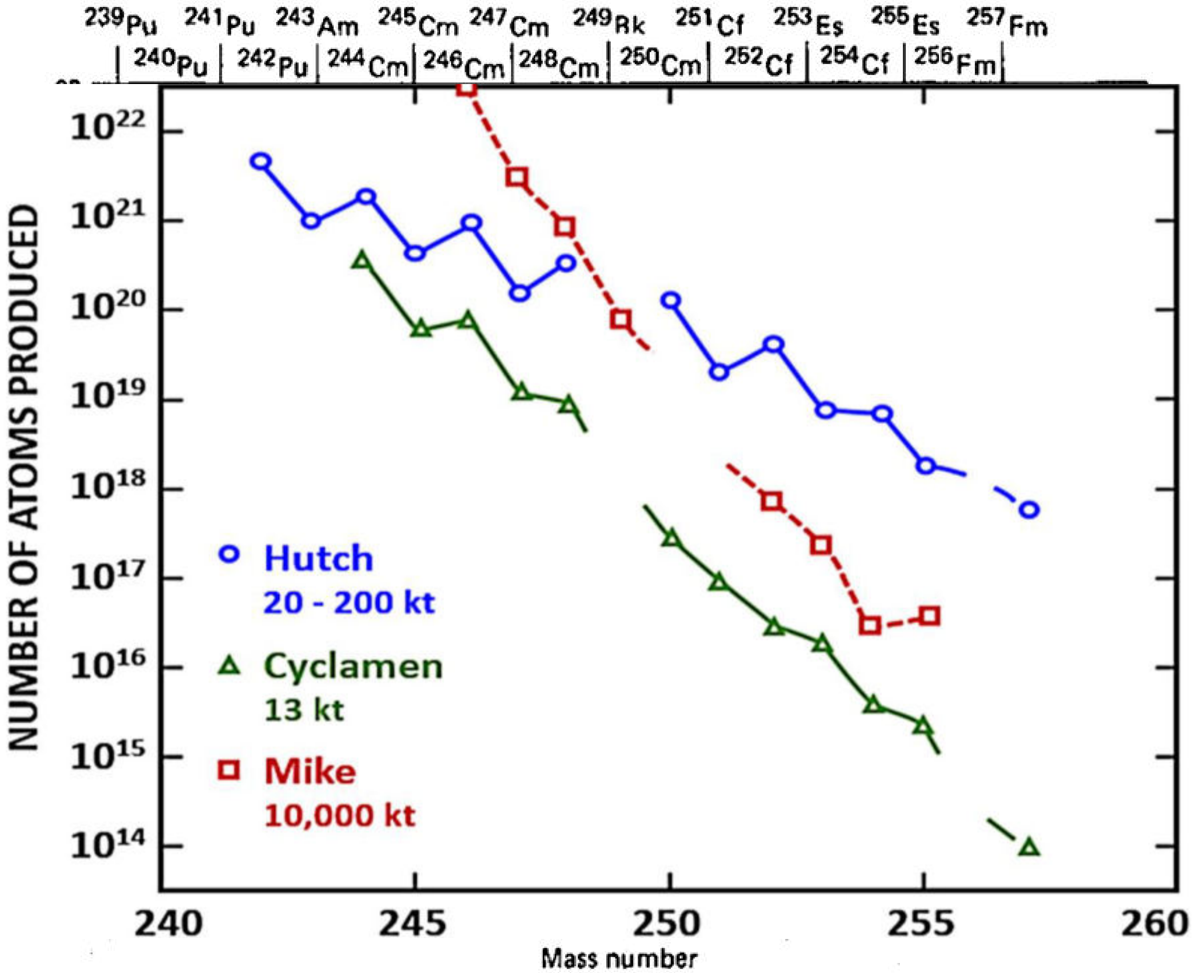
Chemical analysis was performed at Berkeley, discovery later confirmed by accelerator experiments at Berkeley and Dubna.

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.

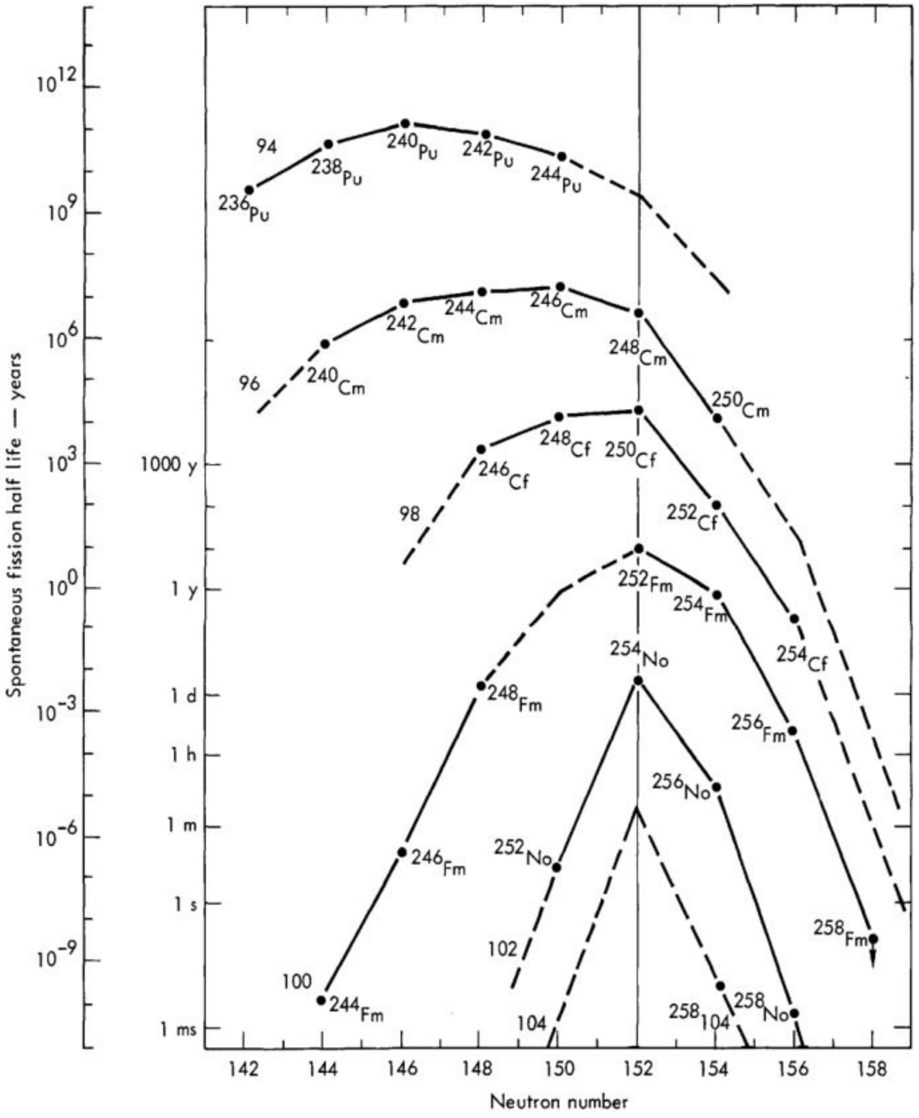




Super-heavies from Hutch

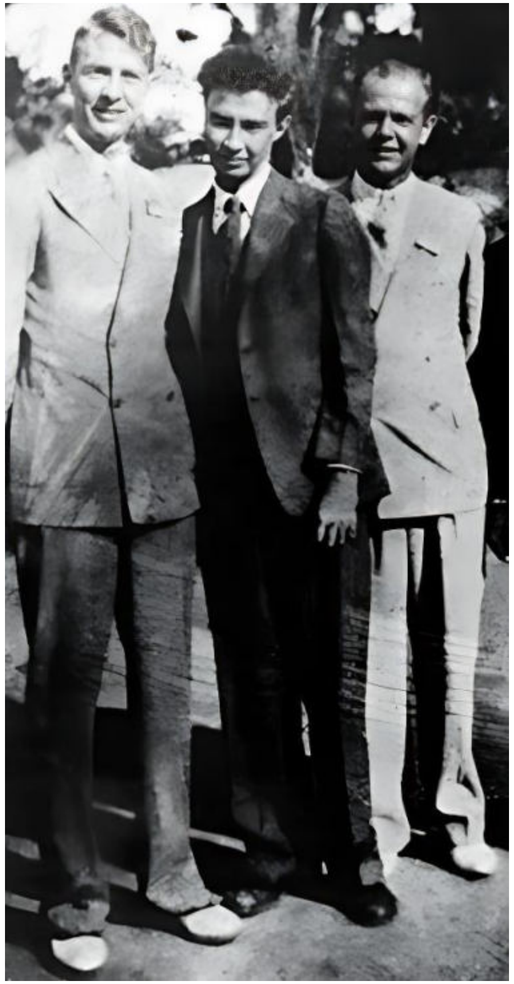
THE RECOVERY AND STUDY OF HEAVY NUCLIDES PRODUCED IN A NUCLEAR EXPLOSION —THE HUTCH EVENT“ LLNL Report: **XA04N0908**
R. W. Hoff and E. K. Hulet
Lawrence Radiation Laboratory,

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}



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.



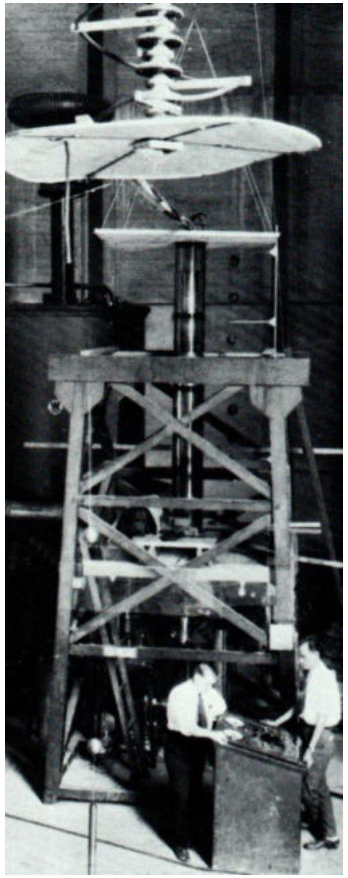
In the framework of the Manhattan Project, Fowler developed ignition systems for nuclear weapons. As part of the missile program at China Lake, he also considered so-called long-range "delivery systems" for nuclear weapons.
In 1951 Fowler became scientific director of the Vista project, which was established for the study of strategic nuclear weapon systems.

Motivated by Fred Hoyle he returned to Nuclear Astrophysics!

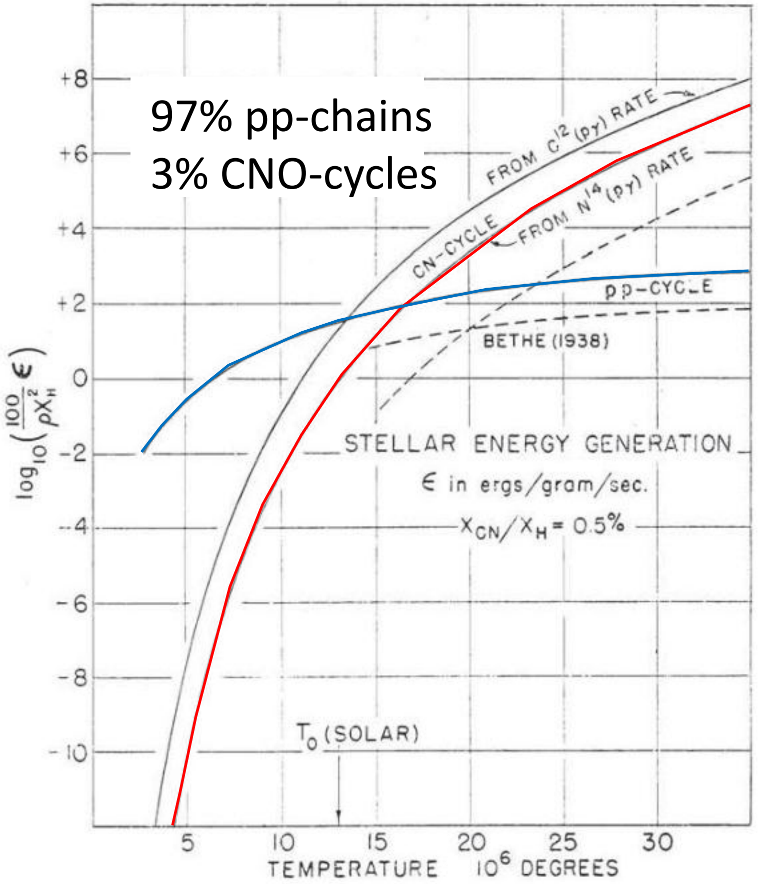
W. Patrick McGray, "Project Vista, Caltech, and the dilemmas of Lee DuBridge," *Historical Studies in the Physical and Biological Sciences* 34 (2), (2004)

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).

Willy Fowler at Kellogg in Caltech.



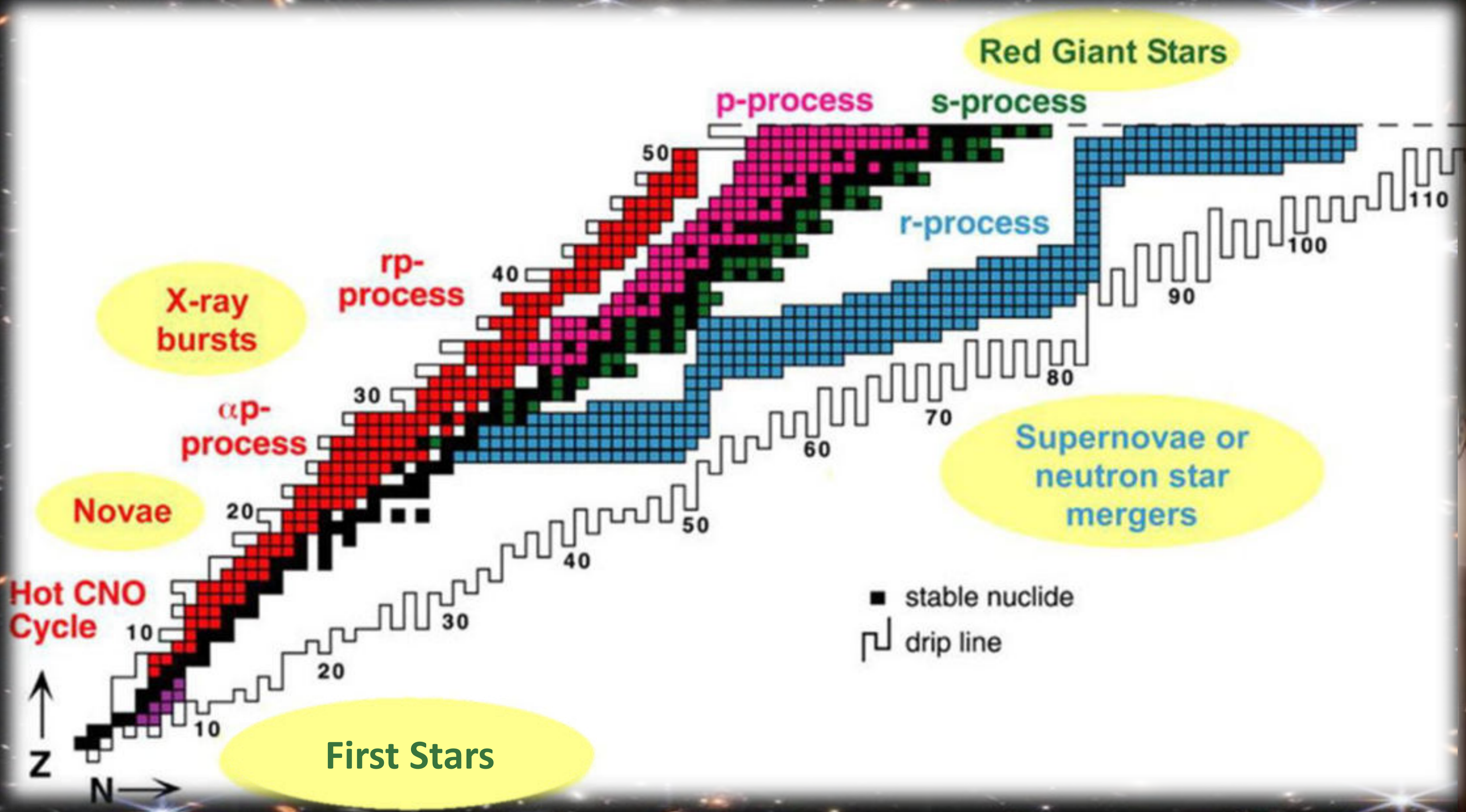
Experimental studies of the energy source of the Sun.

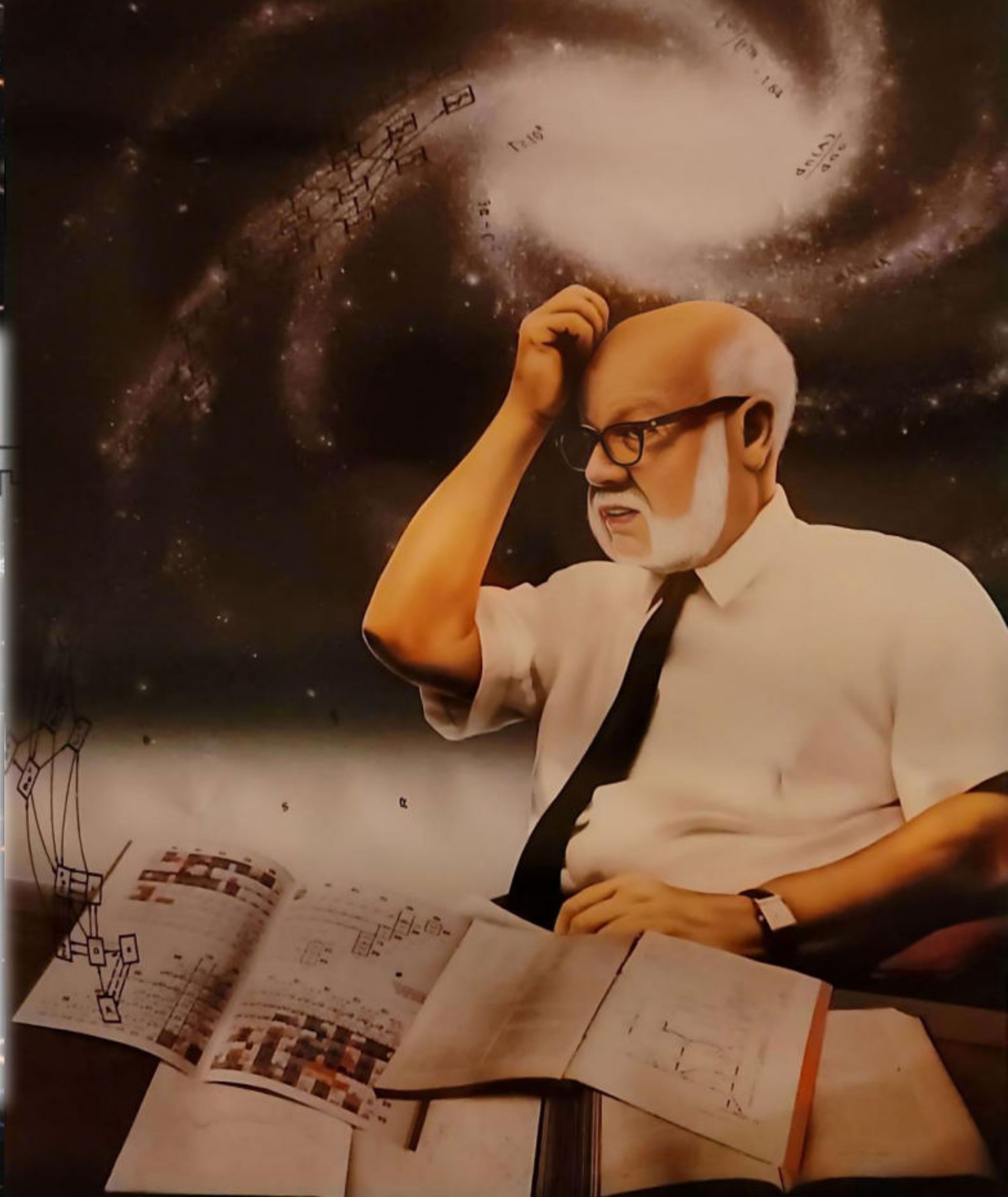


The observation of technetium in stellar spectra and the discoveries of new heavy elements in the debris triggered the idea of the neutron driven processes as the origin of the heavy elements in stars. In the seminal B^2FH paper, Fowler proposed the s- and the r-process – without identifying the site.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

From Neutron Source to the r-Process

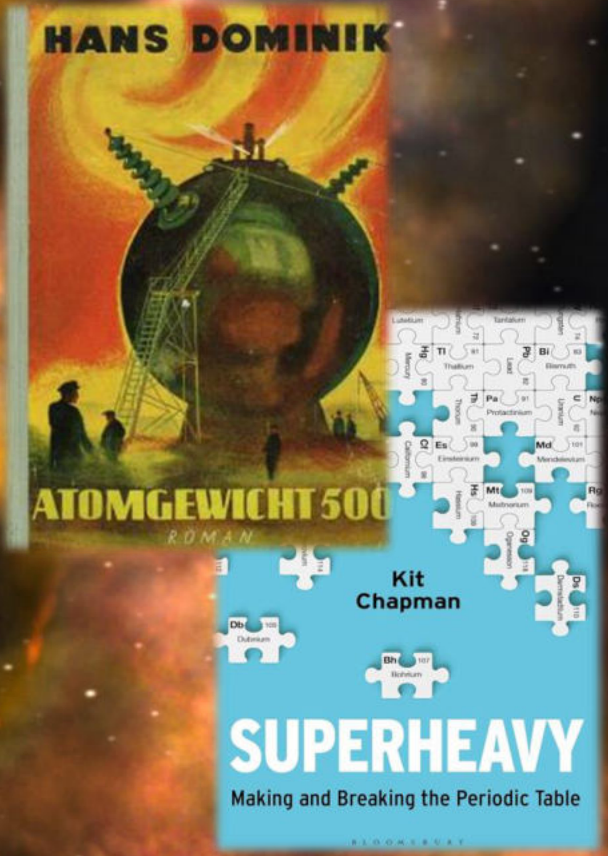
Rephrasing from Eddington 1920: “What is possible in the Nevada desert may not be too difficult in stars”



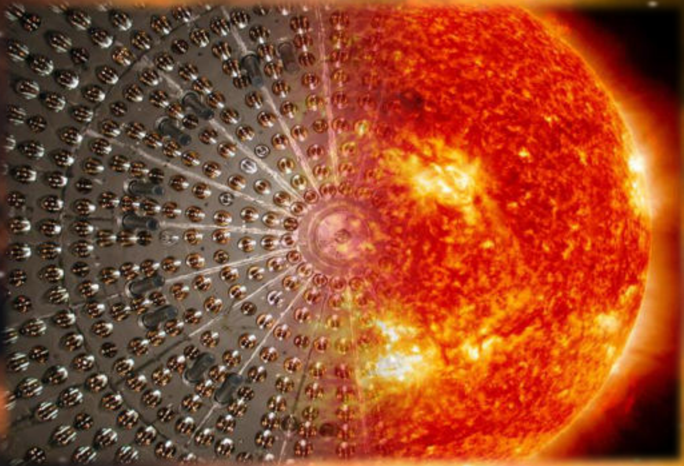


And it became the field you are studying!

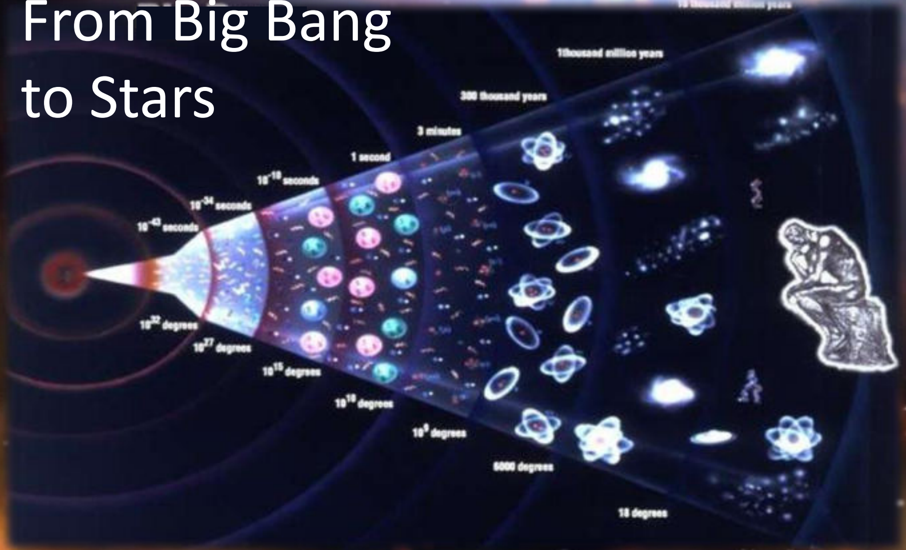
From Superheavies to Supernovae



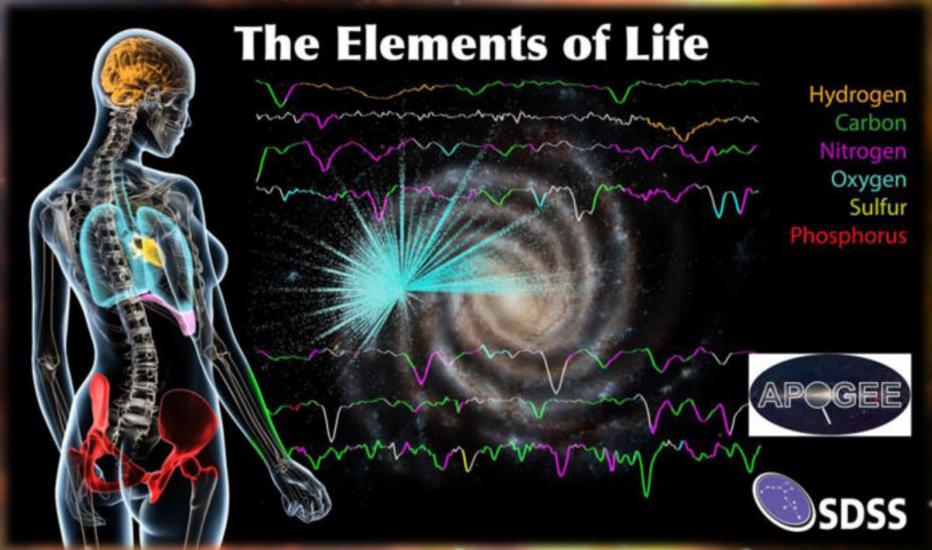
From Sun to Neutrinos



From Big Bang to Stars



From Stardust to Us



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