Hans Bethe and 20th-century physics

“the supreme problem solver of the 20th century“ (Freeman Dyson)

Dr. Adriana Banu
Department of Physics and Astronomy (JMU)
Harrisonburg, Virginia, USA

Hans Bethe's Scientific Work

"If you know his work, you might be inclined to think he is really several people, all of whom are engaged in a conspiracy to sign their work with the same name."

- John Bahcall (1934-2005)
American astrophysicist

78 Years of Scientific Publication

- *Born: July 2, 1906 - Died: March 6, 2005*

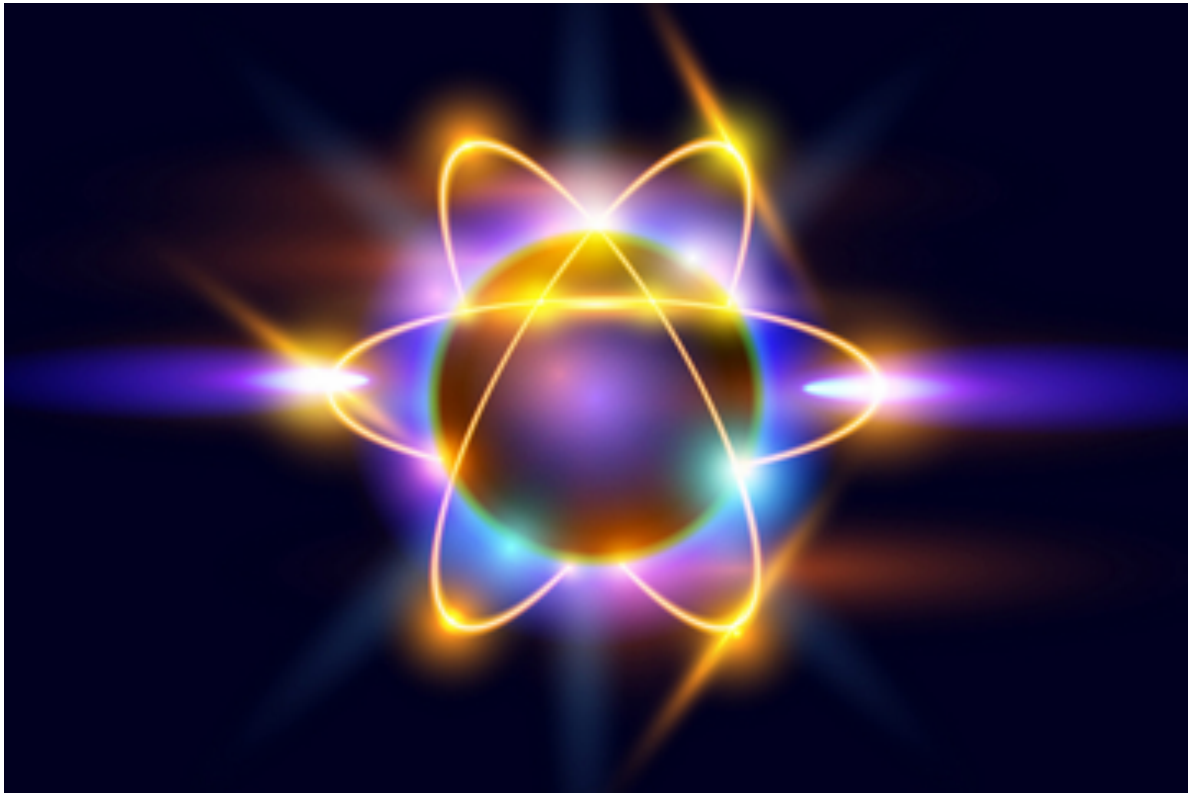
Nearly 400 publications, including several books:

- **First publication: 1924 (aged 18)**
  - with A. Bethe and Y. Terada
  - "Experiments Relating to the Theory of Dialysis"
  - Zeitschrift f. Physik. Chemie, **112**, pp. 250-269
- **One of his last few publications: 2002 (aged 96)**
  - with G. C. McLaughlin, R.A.M.J. Wijers and G. E. Brown
  - "Broad and Shifted Iron-Group Emission Lines in Gamma-Ray Bursts as Test of the Hypernova Scenario"
  - Astrophys. J., **567**, 454-462

Topics of Bethe's Publications

- Atomic physics and spectroscopy
- Interactions of fast particles with matter (scattering, annihilation, pair creation, …)
- Solid state physics
- Hydrodynamics, especially shock waves
- Nuclear physics (from 'pure' physics to bombs)
- Nuclear astrophysics (stellar energy, supernovae, and solar neutrinos)
- Nuclear weaponry, the arms race, and national security
- Energy policy, including fission power
- Gravitational wave sources (evolution and merger in binary star systems)

Before Bethe- at the dawn of the 20th century physics



Quantum Theory and Special Relativity

$$B_\lambda(T) = \frac{2hc^2/\lambda^5}{e^{hc/\lambda kT} - 1}$$

1900

Length contraction

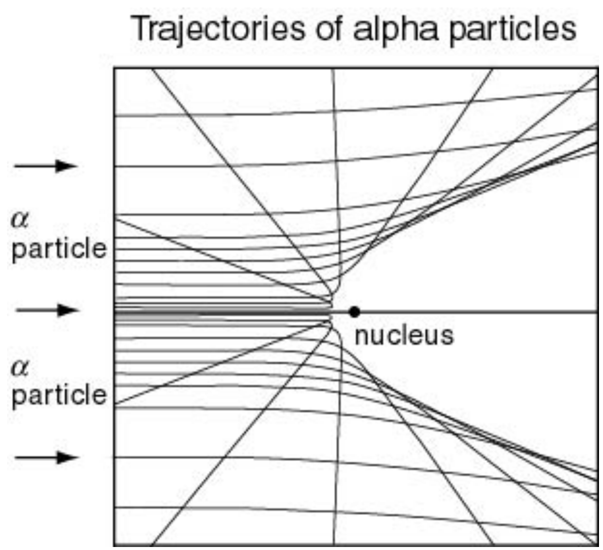
$$L' = \frac{L_0}{\gamma}$$

Time dilation

$$t' = \gamma\, t$$

1905

Rutherford, Bohr, and the Hydrogen Atom



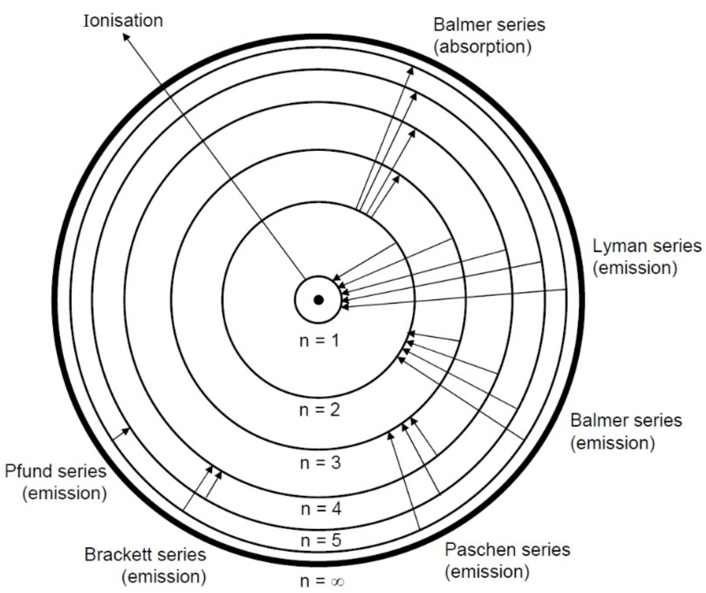
1911

1913

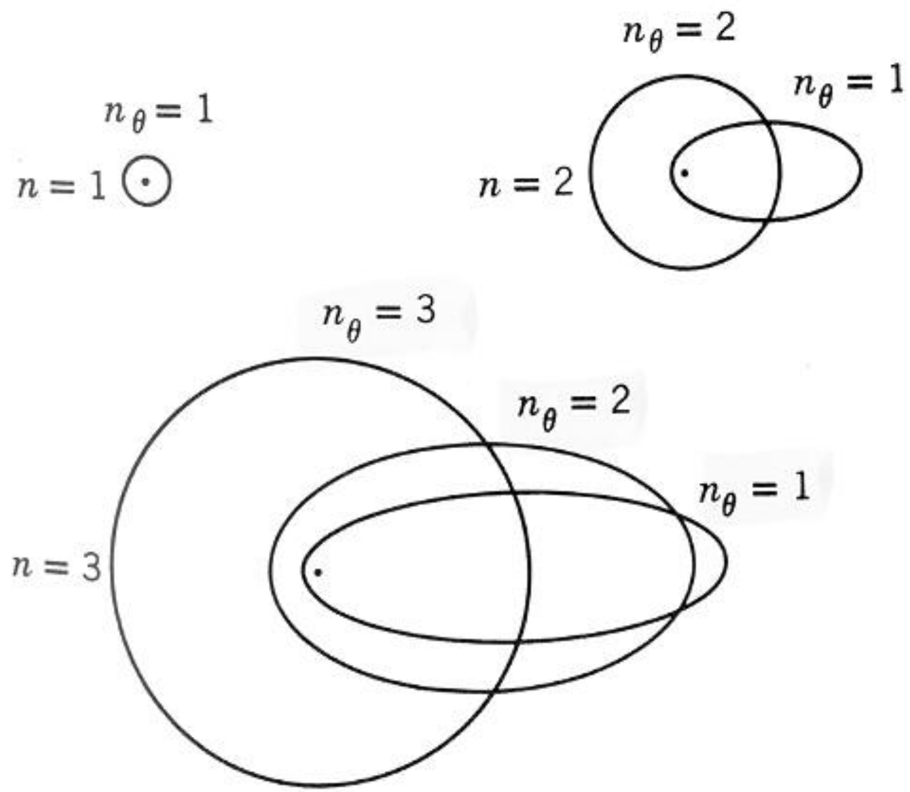
Hydrogen

The Old Quantum Theory

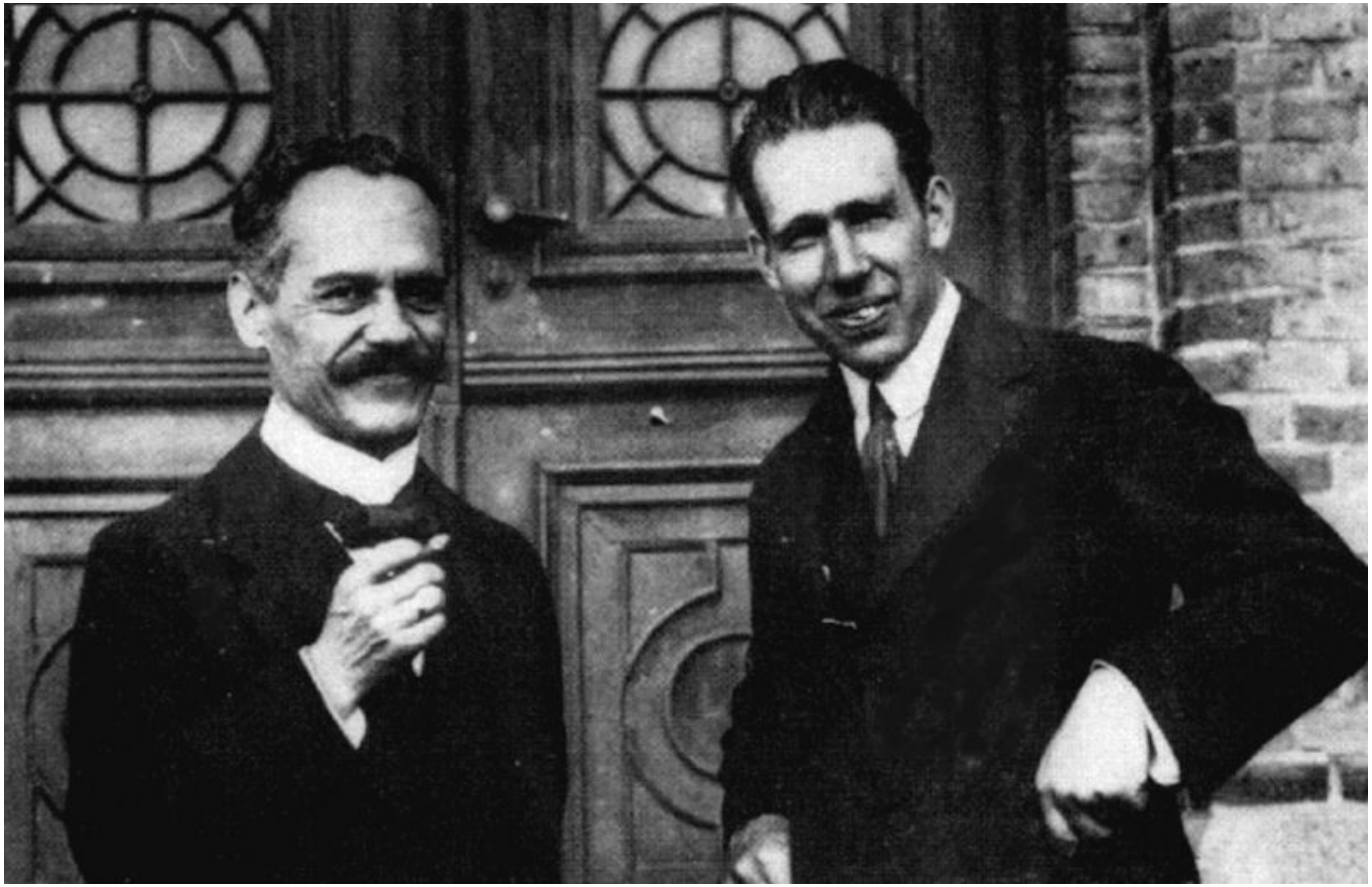
Bohr Model of the Hydrogen Atom



Spectral series	Emission	Absorption	Frequency
Lyman series	Down to n = 1	Up from n = 1	Ultraviolet
Balmer series	Down to n = 2	Up from n = 2	Visible light
Paschen series	Down to n = 3	Up from n = 3	Near infrared
Brackett series	Down to n = 4	Up from n = 4	Far infrared
Pfund series	Down to n = 5	Up from n = 5	Far infrared

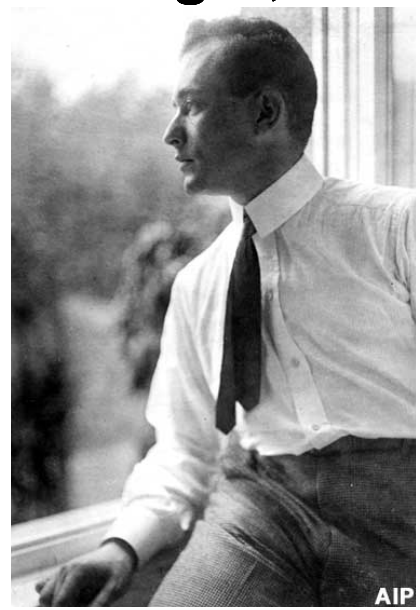


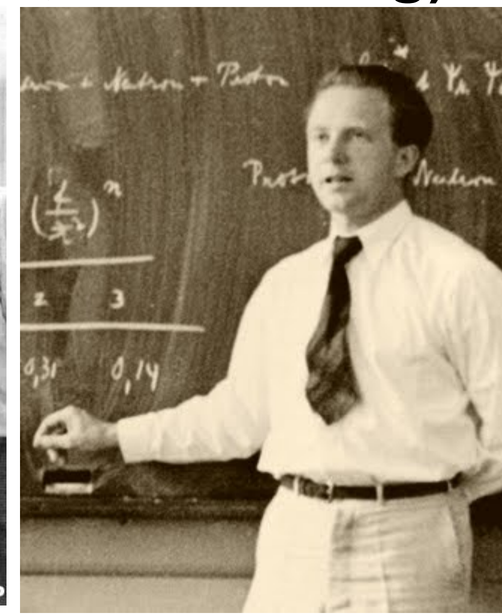
Bohr, Sommerfeld, & the Old Quantum Theory



Birth of Quantum Mechanics (1924-1928)

(left to right: de Broglie, Schrödinger, Born, Heisenberg)





$$\lambda = \frac{h}{p}$$

$$-\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r}) + V(\mathbf{r})\psi(\mathbf{r}) = E\,\psi(\mathbf{r})$$

$$\int_{-\infty}^{\infty} |\psi(x,t)|^2\, dx = 1$$

$$\Delta p\, \Delta x \geq \frac{1}{2}\,\hbar$$

1924 **1926** **1927**

Along came...Bethe

Growing Up (1906-1924)

- Born July 2, 1906 in Strassburg, Germany (now Strasbourg, France)
- His father was a *Privatdozent* of physiology at University of Strasbourg
- His mother was an accomplished musician (also had a Jewish heritage!)
- As a child Hans Bethe was “off-scale” (he started reading at the age of 4 and began writing in capital letters, by the age of 5 he fully understood fractions and could add, subtract, multiply, and divide any of them)
- As a young teenager Hans Bethe would go to his father’s laboratory and help with various chores
- His family moved to Frankfurt where Hans Bethe attended the Goethe

Bethe's Education & First Academic Jobs (1924-1929)

- **University of Frankfurt, 1924-1926**
  - Hans studied physics with Walter Gerlach and Karl Meissner, who encouraged him to move on to the University of Munich.

- **University of Munich, 1926-1928**
  - Hans studied with Arnold Sommerfeld.
  - His doctoral thesis analyzed the diffraction of electrons by crystals.
  - Published it in Ann. Phys. **87**, 55-129 (1928) – **"Theory of the Diffraction of Electrons by Crystals"**

- **University of Frankfurt and then Technical College of Stuttgart** (one semester each as an instructor), 1928-1929
  - The crystallographer Paul Ewald invited Bethe to Stuttgart as his assistant.
  - Sommerfeld recalled Bethe to Munich in the autumn of 1929.

"Calculation of Electronic Affinity of Hydrogen"

(Zeitschrift für Physik **55**, 815-821 (1929))

"The old quantum theory was unable to calculate the binding energy of a second electron to the hydrogen atom; in fact, two authors concluded that a negative hydrogen ion could not exist at all [...] I use the variational method pioneered by Hylleraas [...] and **thus find the binding energy of the extra electron [...] = 0.73 eV**. [...] It is shown that there are probably no discrete excited states of the H^- ion."

–excerpt from the abstract

"The Theory of the Passage of Swift Corpuscular Rays through Matter"

Ann. Phys. **5**, 325-400 (1930)

"**The inelastic collision of a fast charged particle (electron, proton, α-particle) with an atom is treated according to Born's theory of wave mechanics.** […] The theory is developed in detail for collisions of hydrogen atoms and, in as far as possible, for complex atoms. […] The agreement of this theory with experiment is satisfactory to good."

–from the abstract

Leading to the famous Bethe-Bloch formula!

Bethe's Rockefeller Foundation Traveling Scholarship

(supervisors: Ralph Fowler in Cambridge and Enrico Fermi in Rome)

1931

"**The best thing in Rome is unquestionably Fermi**. It is absolutely fabulous how he immediately sees the solution to every problem that is put to him, and his ability to present such complicated things as quantum electrodynamics simply [...] I am now actually sorry that I cannot stay here longer, or as the case may be, that I did not come here for all of the Rockefeller-time."

–excerpt from a letter addressed to Sommerfeld (1931)

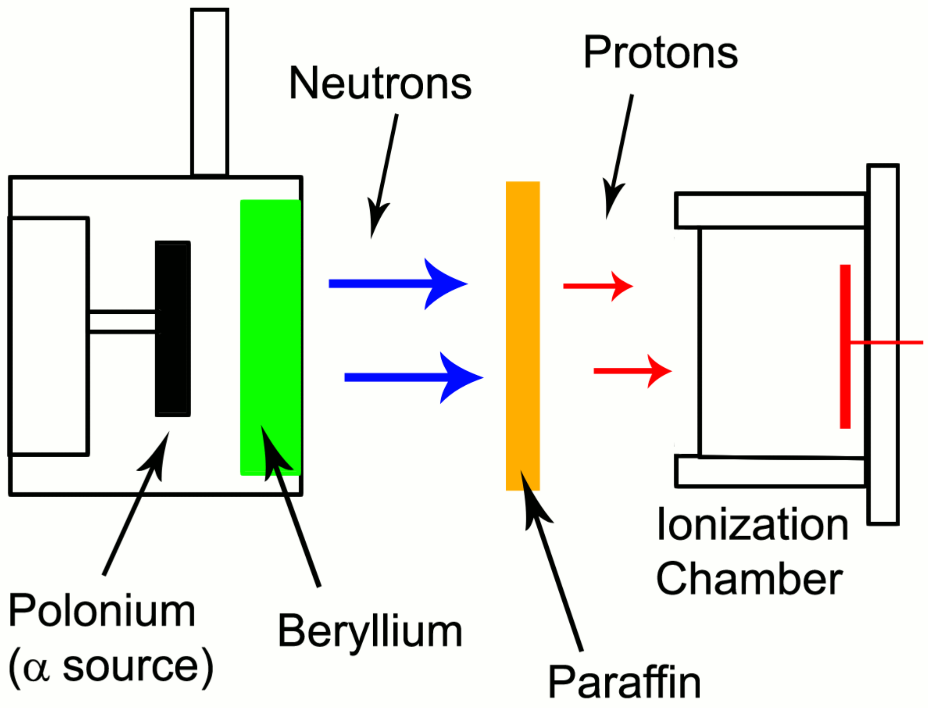
Back to Rome (1932)

- Bethe and Sommerfeld wrote a review article “The Electron Theory of Metals” for the Handbuch der Physik. This article became famous in the physics community – **it covered the basis of what is now called solid state physics.**

- Also for the Handbuch der Physik Hans Bethe wrote another review article “Quantum Mechanics of One- and Two-Electron Problems” which **became *the* presentation of quantum mechanics (nonrelativistic and relativistic)** from which an entire generation of physicists learned how to address the problems of immediate relevance to experimentalists during the 1930s.

“In 1931 Fermi was completely a theoretical physicist. But in 1932 while h still doing theoretical work, he was determined to go into experimental nu physics” – from a letter that Hans Bethe wrote to Sommerfeld (April 20, 19

Chadwick's Discovery of the Neutron (1932)



Bethe’s Dismissal from University of Tübingen

- During the winter of 1932-1933, **Bethe was Acting Assistant Professor at the University of Tübingen**, where Hans Geiger, the Professor of Experimental Physics, was his supervisor.

- In late January 1933, **Hitler became Chancellor in Germany**
- In April 1933, **Hans Geiger summarily dismissed Bethe** from his teaching position at Tubingen. (Bethe’s mother was Jewish.)
- Sommerfeld invited him back to Munich and worked hard during the summer of 1933 trying to find jobs for Bethe and other displaced academics.

Emigration to Great Britain (1933)

Academic Positions in Manchester and Bristol

(left to right: Bethe, Genia and Rudolf Peierls, Neville Mott)

"Quantum Theory of the Diplon"

(with R. Peierls)

Proc. Roy. Soc. London Ser. **A148**, 146-156 (1935)

"The diplon is the heavy isotope of hydrogen, now called deuteron. It is the simplest composite nucleus [...]

The photoelectric disintegration of the deuteron is calculated; this, in fact, was the origin of the paper: James Chadwick who (with Maurice Goldhaber) had observed the photo-disintegration, challenged the authors to give a theory of the process"

-Bethe's commentary from "Selected Works of Hans A. Bethe" (1996)

The "Neutrino"

(with R. Peierls)

Nature **133**, 532-533 (1934)

"**The authors show that it would be very unlikely that free neutrinos can be observed**: Bethe and Peierls could not foresee that there would be nuclear reactors giving neutrino fluxes enormously greater than the radioactive sources available in 1934. Using these, Reines and Cowan **(1956)** were able to observe free neutrinos, work for which Reines received the Nobel Prize in 1995. Nor could they foresee accelerators giving protons of energies of TeV which produce similarly large neutrino fluxes."

-Bethe's commentary from "Selected Works of Hans A. Bethe" (1996)

Becoming Bethe

Arnold Sommerfeld
(1868-1951)

Enrico Fermi
(1901-1954)

“If you were not to find satisfaction *in the search for knowledge,* you would despairingly put your hands in your lap and say: It is too difficult for us humans.”

Albrecht Bethe, 1899

Thoroughness & Rigor

Clarity & Simplicity

Coming to the United States (1935)

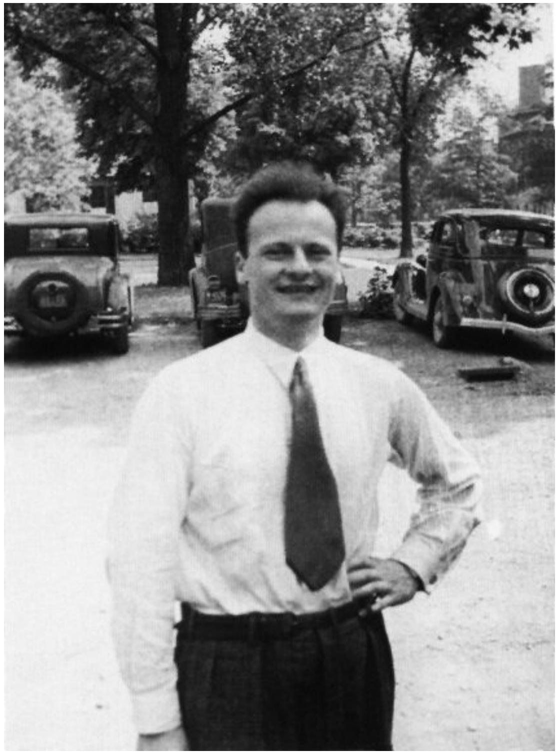
After spending Fall 1934 at the University of Bristol, he accepted a job as an assistant professor at **Cornell University in Ithaca, NY**.

Cornell University would be his home institution for the next 70 years.

“The Happy Thirties”

Assistant Professor Bethe with Cornell physics colleagues in 1935

Bethe, Livingston and Bacher:
Three Musketeers of Nuclear Physics at Cornell



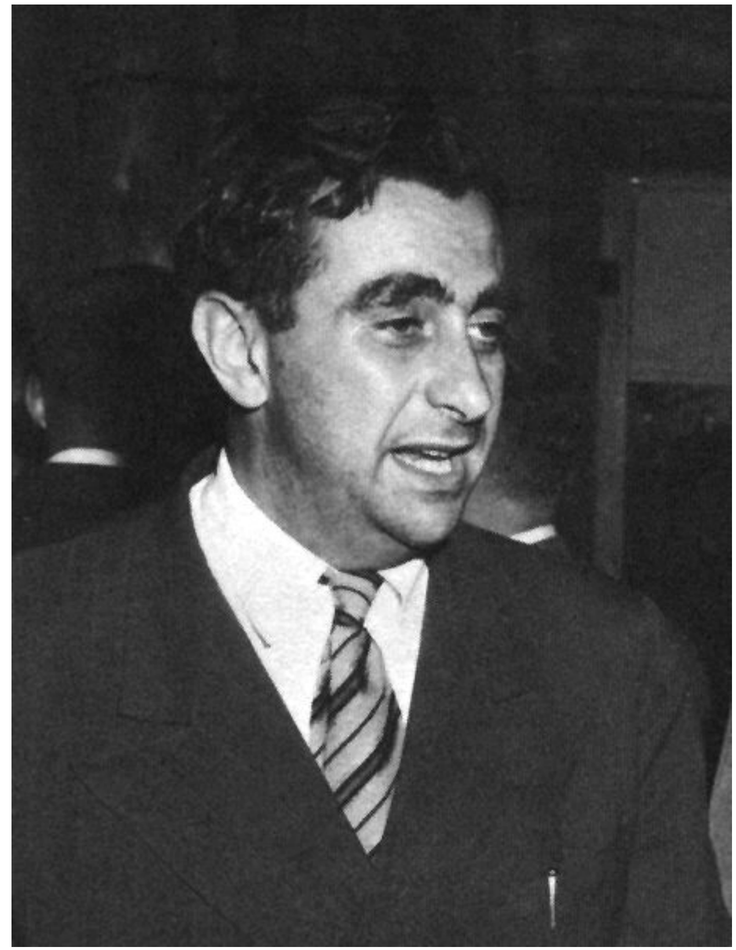
“Bethe’s Bible”

In 1936-37, Bethe published three long articles in the journal Reviews of Modern Physics:

- Nuclear Physics. Part A, **Stationary States of Nuclei** *(with R. F. Bacher; 146 pages)*
- Nuclear Physics. Part B, **Theoretical Nuclear Dynamics** (175 pages)
- Nuclear Physics. Part C, **Experimental Nuclear Dynamics** *(with M.S. Livingston; 145 pages)*

These three articles, totaling 487 pages, amounted essentially to a compendium of everything known in nuclear physics at the time – collectively they became known as “Bethe’s Bible.”

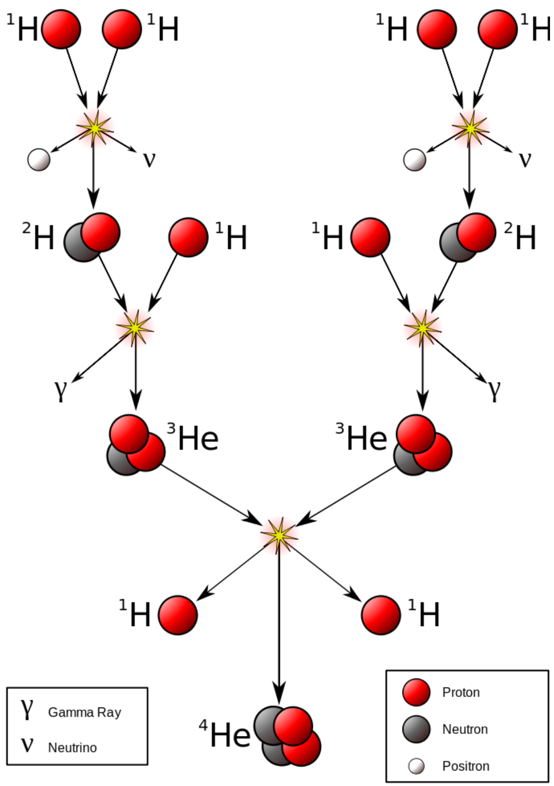
George Gamow and Edward Teller

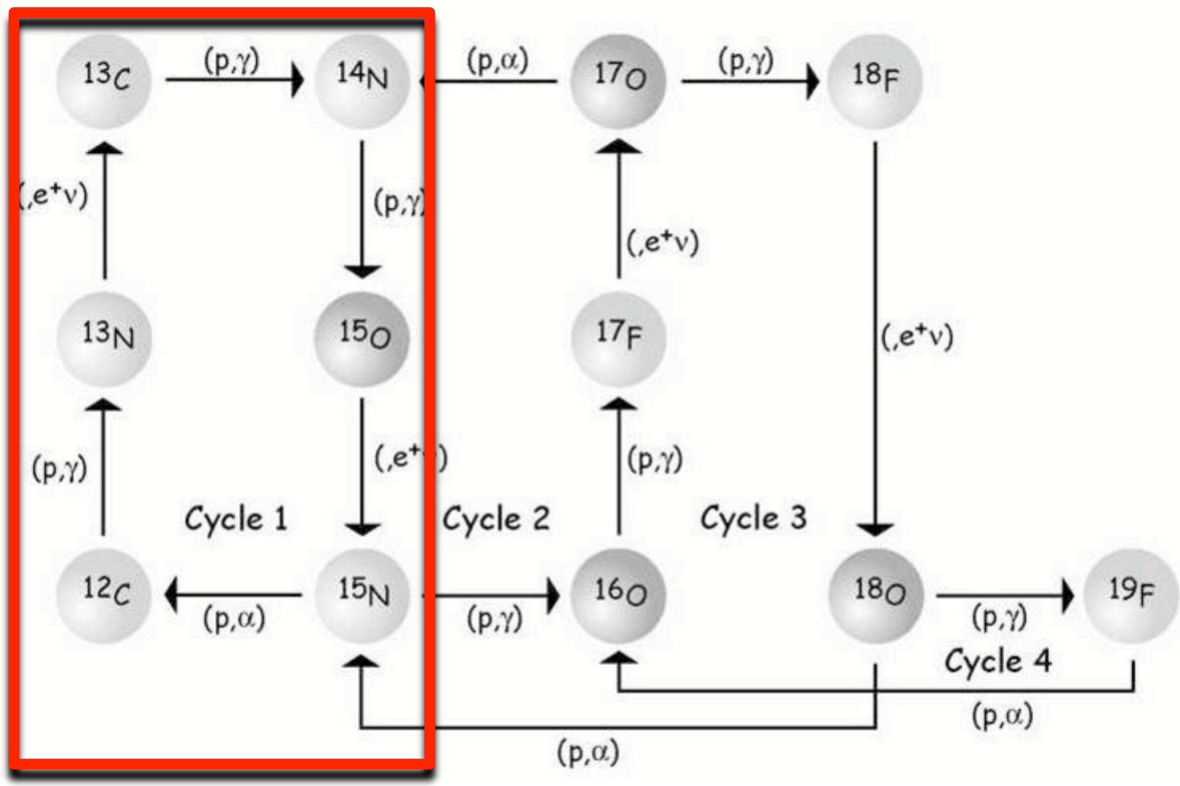


Fourth Washington Conference on Theoretical Physics: Stellar Energy and Nuclear Processes (March 21-23, 1938)

Proton-proton reactions and the CN cycle:

two sets of reactions that convert hydrogen into helium within stars





“Energy Production in Stars”

(Phys. Rev., **55**, 434-456, 1939)

“[…] ***the most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons.*** These reactions form a cycle in which the original nucleus is reproduced […].Thus carbon and nitrogen merely serve as catalysts […]”

− from the abstract

Nobel Prize in Physics (1967)

The 1967 Nobel Prize for Physics

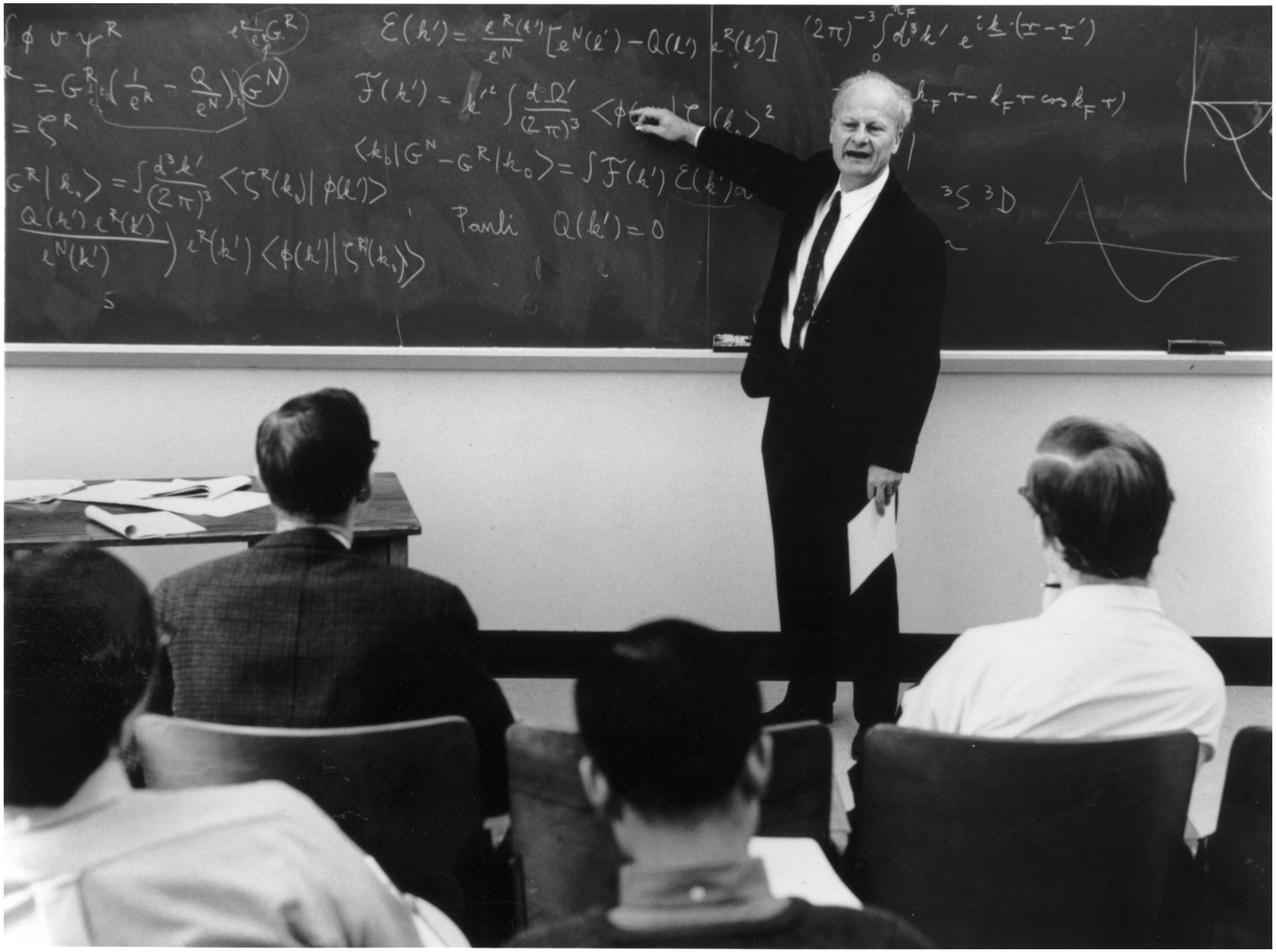
"Professor Bethe, you may have been astonished that among your many contributions to physics, several of which have been proposed for the Nobel Prize, we have chosen one which contains less fundamental physics than many of the others and which has taken only a short part of your long time in science […].

[…] Your solution of the energy source of stars is one of the most important applications of fundamental physics in our days, having led to a deep going evolution of our knowledge of the universe around us."

-from the presentation speech of Professor Oskar Klein, member of the Swedish Academy of Sciences

Stockholm, 1967

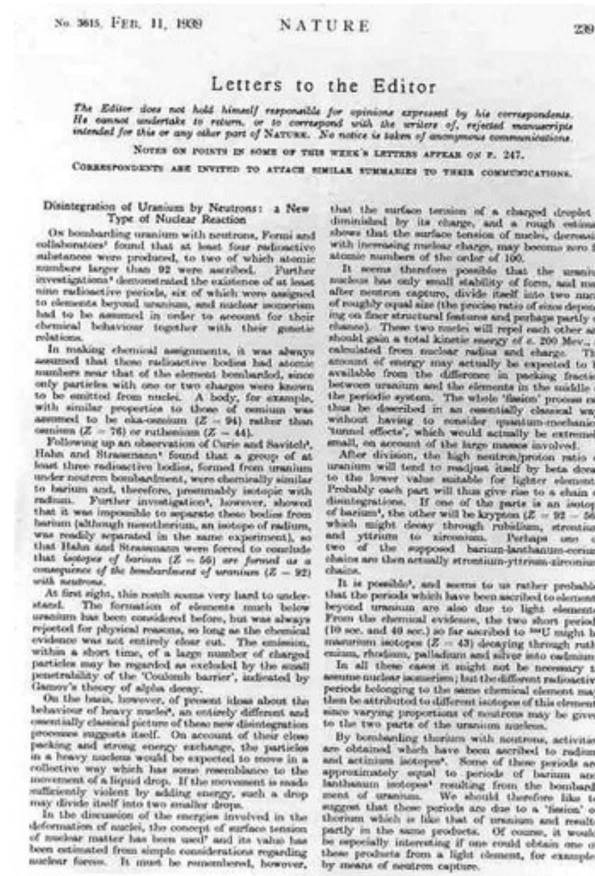
Bethe lecturing at Cornell University, 1967



Discovery of Nuclear Fission

Otto Hahn & Lise Meitner

Fritz Strassmann



No. 3615, FEB. 11, 1939 NATURE 239

Letters to the Editor

The Editor does not hold himself responsible for opinions expressed by his correspondents. He cannot undertake to return, or to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.*

NOTES ON POINTS IN SOME OF THIS WEEK'S LETTERS APPEAR ON P. 247.

CORRESPONDENTS ARE INVITED TO ATTACH SIMILAR SUMMARIES TO THEIR COMMUNICATIONS.

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

ON bombarding uranium with neutrons, Fermi and collaborators[1] found that at least four radioactive substances were produced, to two of which atomic numbers larger than 92 were ascribed. Further investigations[2] demonstrated the existence of at least nine radioactive periods, six of which were assigned to elements beyond uranium, and nuclear isomerism had to be assumed in order to account for their chemical behaviour together with their genetic relations.

In making chemical assignments, it was always assumed that these radioactive bodies had atomic numbers near that of the element bombarded, since only particles with one or two charges were known to be emitted from nuclei. A body, for example, with similar properties to those of osmium was assumed to be eka-osmium ($Z = 94$) rather than osmium ($Z = 76$) or ruthenium ($Z = 44$).

Following up an observation of Curie and Savitch[3], Hahn and Strassmann[4] found that a group of at least three radioactive bodies, formed from uranium under neutron bombardment, were chemically similar to barium and, therefore, presumably isotopic with radium. Further investigation[5], however, showed that it was impossible to separate these bodies from barium (although mesothorium, an isotope of radium, was readily separated in the same experiment), so that Hahn and Strassmann were forced to conclude that *isotopes of barium ($Z = 56$) are formed as a consequence of the bombardment of uranium ($Z = 92$) with neutrons.*

At first sight, this result seems very hard to understand. The formation of elements much below uranium has been considered before, but was always rejected for physical reasons, so long as the chemical evidence was not entirely clear cut. The emission, within a short time, of a large number of charged particles may be regarded as excluded by the small penetrability of the 'Coulomb barrier', indicated by Gamov's theory of alpha decay.

On the basis, however, of present ideas about the behaviour of heavy nuclei[6], an entirely different and essentially classical picture of these new disintegration processes suggests itself. On account of their close packing and strong energy exchange, the particles in a heavy nucleus would be expected to move in a collective way which has some resemblance to the movement of a liquid drop. If the movement is made sufficiently violent by adding energy, such a drop may divide itself into two smaller drops.

In the discussion of the energies involved in the deformation of nuclei, the concept of surface tension of nuclear matter has been used[7] and its value has been estimated from simple considerations regarding nuclear forces. It must be remembered, however, that the surface tension of a charged droplet is diminished by its charge, and a rough estimate shows that the surface tension of nuclei, decreasing with increasing nuclear charge, may become zero for atomic numbers of the order of 100.

It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size (the precise ratio of sizes depending on finer structural features and perhaps partly on chance). These two nuclei will repel each other and should gain a total kinetic energy of *c.* 200 Mev., as calculated from nuclear radius and charge. This amount of energy may actually be expected to be available from the difference in packing fraction between uranium and the elements in the middle of the periodic system. The whole 'fission' process can thus be described in an essentially classical way, without having to consider quantum-mechanical 'tunnel effects', which would actually be extremely small, on account of the large masses involved.

After division, the high neutron/proton ratio of uranium will tend to readjust itself by beta decay to the lower value suitable for lighter elements. Probably each part will thus give rise to a chain of disintegrations. If one of the parts is an isotope of barium[5], the other will be krypton ($Z = 92 - 56$), which might decay through rubidium, strontium and yttrium to zirconium. Perhaps one or two of the supposed barium-lanthanum-cerium chains are then actually strontium-yttrium-zirconium chains.

It is possible[4], and seems to us rather probable, that the periods which have been ascribed to elements beyond uranium are also due to light elements. From the chemical evidence, the two short periods (10 sec. and 40 sec.) so far ascribed to ^{239}U might be masurium isotopes ($Z = 43$) decaying through ruthenium, rhodium, palladium and silver into cadmium.

In all these cases it might not be necessary to assume nuclear isomerism; but the different radioactive periods belonging to the same chemical element may then be attributed to different isotopes of this element, since varying proportions of neutrons may be given to the two parts of the uranium nucleus.

By bombarding thorium with neutrons, activities are obtained which have been ascribed to radium and actinium isotopes[8]. Some of these periods are approximately equal to periods of barium and lanthanum isotopes[5] resulting from the bombardment of uranium. We should therefore like to suggest that these periods are due to a 'fission' of thorium which is like that of uranium and results partly in the same products. Of course, it would be especially interesting if one could obtain one of these products from a light element, for example, by means of neutron capture.

"Disintegration of Uranium by Neutrons …"

Letter to Nature, **Feb.11, 1939**

Fifth Washington Conference on Theoretical Physics:
Low Temperature Physics and Superconductivity
January 26-28, 1939

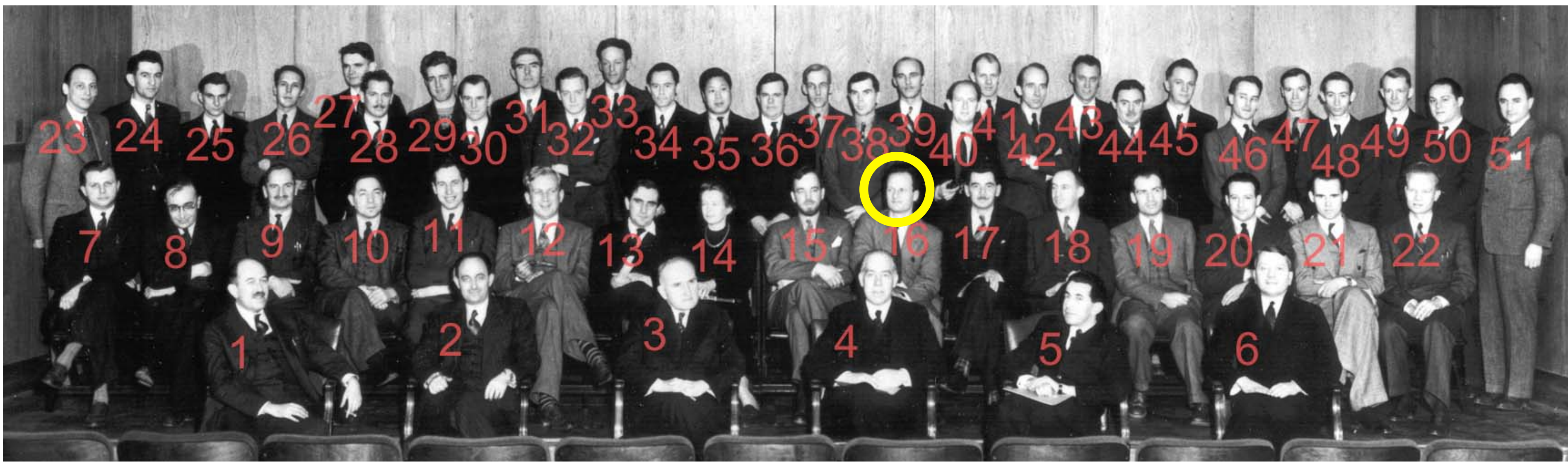


Image credit: http://home.gwu.edu/~kargaltsev/HEA/washington-conferences.html

Marriage and Citizenship

- **World War II began on September 1, 1939** when Germany invaded Poland. Although the United States did not enter the war until after the attack on Pearl Harbor, many steps were taken to prepare for likely involvement.
- **Hans Bethe and Rose Ewald were married at a civil ceremony on September 14, 1939** in New Rochelle, New York. Among those attending were Edward Teller, his wife Augusta, and the mathematician Richard Courant.
- Bethe had relatives in Germany and could not be cleared for classified work until after he became a citizen in 1941. **He received his security clearance on the "Day of Infamy", December 7, 1941** (Japanese attacked Pear Harbor).

War Work without a Security Clearance! (1940-1941)

"Deviations from Thermal Equilibrium in Shock Waves" (Bethe and Teller, 1941, distributed by Ballistic Research Laboratories, Aberdeen, Maryland)

"After the fall of France to the Nazis in June 1940, Teller and I felt that **we wanted to contribute to the Allied War Effort**. Theodore von Karman, the famous aerodynamicist, […] was a close friend of the Teller family, so we decided to […] ask his advice. He suggested the subject."

-Bethe's commentary from "Selected Works of Hans A. Bethe" (1996)

Summer Study on Fission and Chain Reactions

(Berkeley, July 1942)

During the summer of 1942, Bethe was part of a study group assembled at Berkeley by J. Robert Oppenheimer, who had been appointed **to lead the theoretical side of the effort to develop a fission bomb.**

In the center of the photograph is Robert Serber, whose lectures beginning the next year in Los Alamos would constitute the "Los Alamos Primer"

Los Alamos, New Mexico

By December 1942, Oppenheimer was suggesting to Bethe that he joins the bomb-building facility planned for Los Alamos. In April 1943, just as the Los Alamos laboratory was beginning to function, Hans and Rose Bethe relocated to New Mexico.

The Lab on the Mesa

Los Alamos Badges:

Leslie R. Groves, J. Robert Oppenheimer, Katherine Oppenheimer, Dorothy McKibbin

Los Alamos Badges:
Hans Bethe, Rose Bethe, Edward Teller, Augusta Teller

Hans was appointed **Chief of the Theoretical Division at Los Alamos**. He remained there until January 1946.

Los Alamos Badges:

Robert Bacher, Enrico Fermi, Richard Feynman, Robert Wilson

The head of the
experimental division
at Los Alamos

A Jeep Ride in the Mountains

(left to right: Hans and Henry Bethe, Enrico and Giulio Fermi)

“Little Boy” Uranium-235 Bomb Design

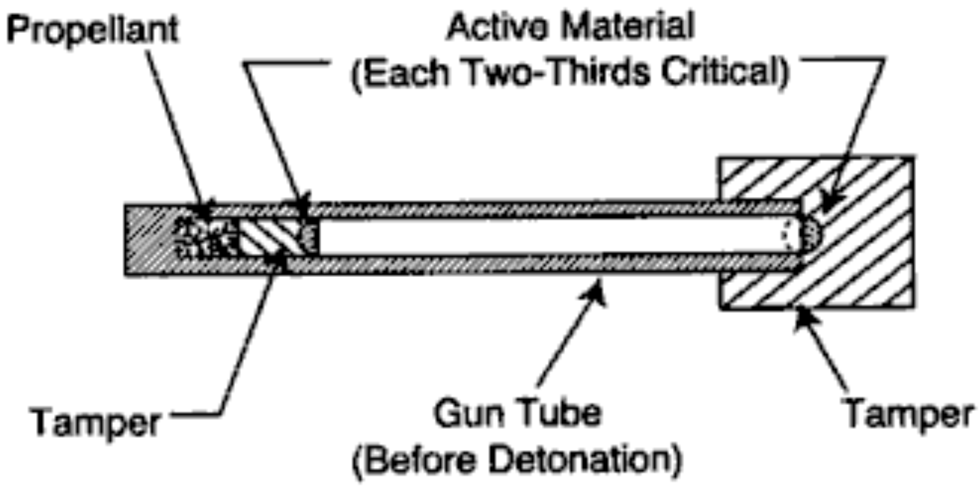
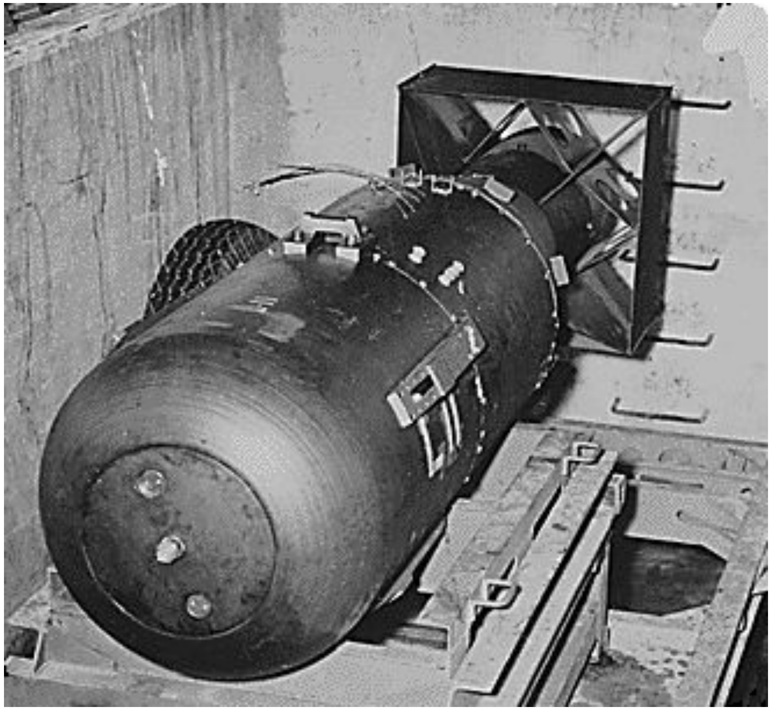


Figure 2-VII. Gun Assembly Principle



Detonated over Hiroshima (August 6, 1945)

“Fat Man”: Plutonium-239 Bomb Design

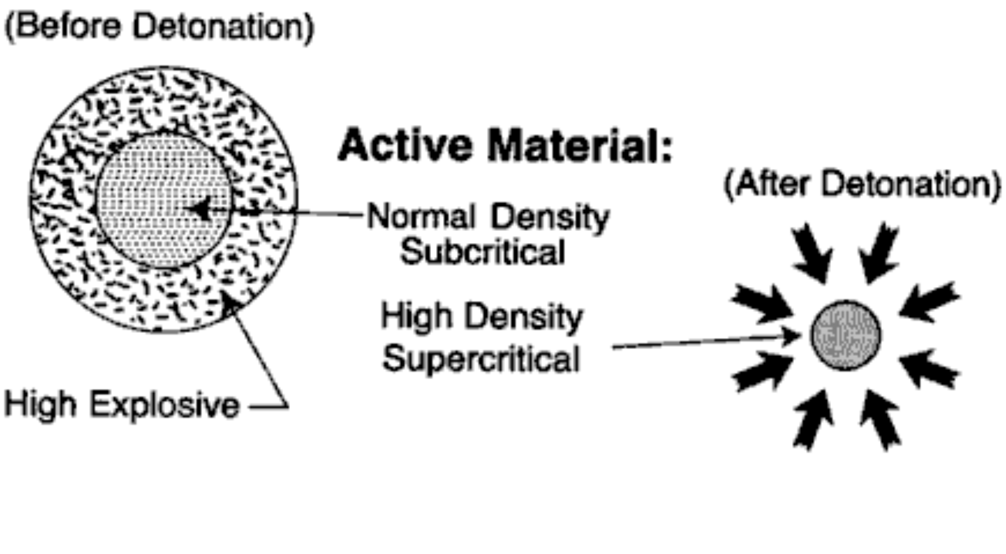
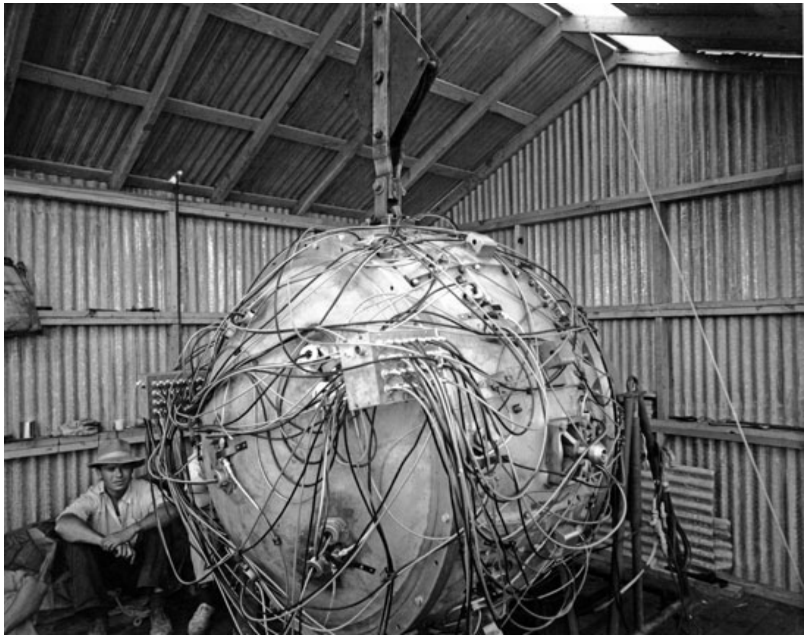


Figure 2-VIII. Implosion Assembly Principle



Detonated over Nagasaki (August 9, 1945)

Highlights on Bethe's work at Los Alar

• calculation of the critical mass and efficiency of U-235

• along with Richard Feynman, he developed a formula fo calculating the atomic bomb's explosive yield

• hydrodynamic aspects of Pu-bomb implosion (worked o the neutron initiator and on radiation propagation from an explosive atomic bomb)

The Trinity nuclear test validated the accuracy of T Division's r

See for details Richard Rhodes's books:
"The Making of the Atomic Bomb" and "Dark Sun: The Making of the Hydrogen Bomb"

Shelter Island, New York

(site of 1947 conference on theoretical physics sponsored by the National Academy of Sciences)

The Shelter Island Conference succeeded in its purpose:
it set the direction for physics to the next 30 years.

Shelter Island Conference on Theoretical Physics

(Bethe at window on right)

Physicists gathered around Feynman at Shelter Island

“The Electromagnetic Shift of Energy Levels”

(Phys. Rev. **72**, 339-341, (1947))

“[…] **the fine structure of the second quantum state of hydrogen does not agree with the prediction of the Dirac theory**. The 2s level, which […] should coincide with the $2p_{1/2}$ level, is actually higher […] by […] 1000 megacycles.”

“Schwinger and Weisskopf, and Oppenheimer have suggested that a possible explanation might be the shift of energy levels by the interaction of the electron with the radiation field.”

“We find (a shift of) **1040 megacycles**. This is in excellent agreement with the observed value of 1000 megacycles.”

Soon thereafter, Schwinger at Harvard, Feynman at Cornell, and Tomonaga at Tokyo University of Education established the theory of quantum electrodynamics (QED), for which the three shared the Nobel Prize in 1965.

Hans Bethe as Consultant and Advisor

(partial listing)

- **Consultant**:
  - Los Alamos Scientific Laboratory, 1947-2002?
  - Avco Everett Research Lab, 1955-87
- **Government advisor**:
  - Member, President's Science Advisory Committee, 1956-59
  - Member, US Delegation to Discussions on Discontinuance of Nuclear Weapons Tests, 1958-59

Hans Bethe with President John F. Kennedy

Presidential Gratitude

"You are not only an outstanding scientist, you are also a devoted public servant.

"The nation has asked for your help many times and you have responded selflessly. You have made profound contributions in the fields of atomic energy, arms control and military technology. And you have been an important source of the immense contribution which science and the university community are making to society as a whole.

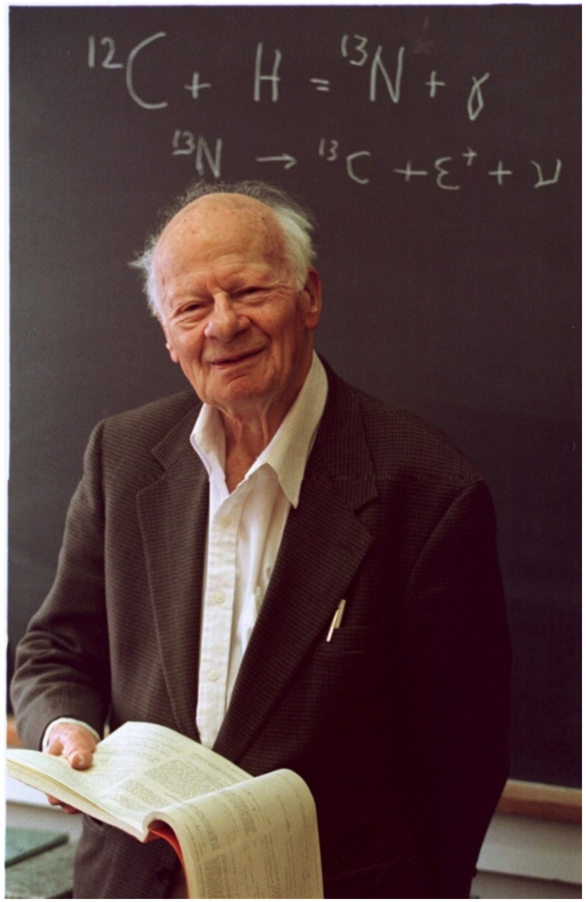
"Our country is deeply indebted to you."

-letter from President Lyndon Johnson to Hans Bethe on the occasion of Bethe's sixtieth birthday (1966)

Retirement?– Not Really

Bethe in the 1970's
(he retired in 1975)

Wearing Nobel Prize
medal (1986)



Lecturing about the
CN cycle (1996)

"Possible Explanation of the Solar-Neutrino Puzzle "

(Phys. Rev. Letters, **56**, 1305-1308, (1986))

Abstract

"Mikheyev and Smirnov have shown that electron neutrinos above a certain energy E_m may all be converted into μ neutrinos on their way out from the sun. **We assume here that this is the reason why Davis and collaborators, in their experiments, find many fewer solar neutrinos than predicted.** The minimum energy E_m is found to be about 6 MeV, the mass of the μ neutrino must be greater than that of the electron neutrino, $m_2^2 - m_1^2 = 6 \times 10^{-5}$ eV^2, and there is a very minor restriction on the neutrino mixing angle."

Hans Bethe at age 80!

Selected Bethe's astrophysics papers

- **Neutron Star Matter.** *Nuclear Phys.* **A175**, 225-240 (19
- **Neutron Star Models with Realistic High-Density Equ of State.** *Astrophys. J.* **199**, 741-748 (1975)
- **Equation of State in the Gravitational Collapse of Sta** *Nuclear Phys.* **A324**, 487-533 (1979)
- **Equation of State of a Very Hot Gas of Electrons anc Neutrinos.** *Astrophys. J.* **241**, 350-354 (1980)
- **SN 1987A: An Empirical and Analytic Approach.** *Astrophys. J.* **412**, 192-202 (1993)
- **The Supernova Shock.** *Astrophys. J.* **449,** 714-726 (19
- **Evolution of Binary Compact Objects That Merge.** *Astrophys. J.* **506**, 780-789 (1998)

Hans and Rose Bethe on a hike in 1995

Citation for Hans Bethe's Franklin Medal from the American Philosophical Society (2005)

In recognition of his role as

- A **preeminent physicist of the twentieth century**, whose productive research career has spanned eight decades.
- A **pioneer in atomic physics**, whose seminal work on stellar energy production earned him the 1967 Nobel prize.
- A **leader of the Theoretical Division at Los Alamos**.
- A **senior statesman of science and adviser to U. S. Presidents** on atomic energy.
- A **courageous critic of defense policy and passionate advocate of arms control**.
- A **beloved mentor to generations of Cornell physicists**, whose efforts helped to transform the Cornell University Physics Departments into one of the world's great centers of physics.

“Either write something worth reading or do something worth writing.”

- Benjamin Franklin

Franklin (1706-1790) was arguably the first “scientific American”.

Rose Bethe accepting the Franklin Medal from Frank Rhodes of the American Philosophical Society (March 9, 2005)

Making of Bethe

"Among Bethe's many strong points, three have been decisive in his growth as an outstanding physicist.

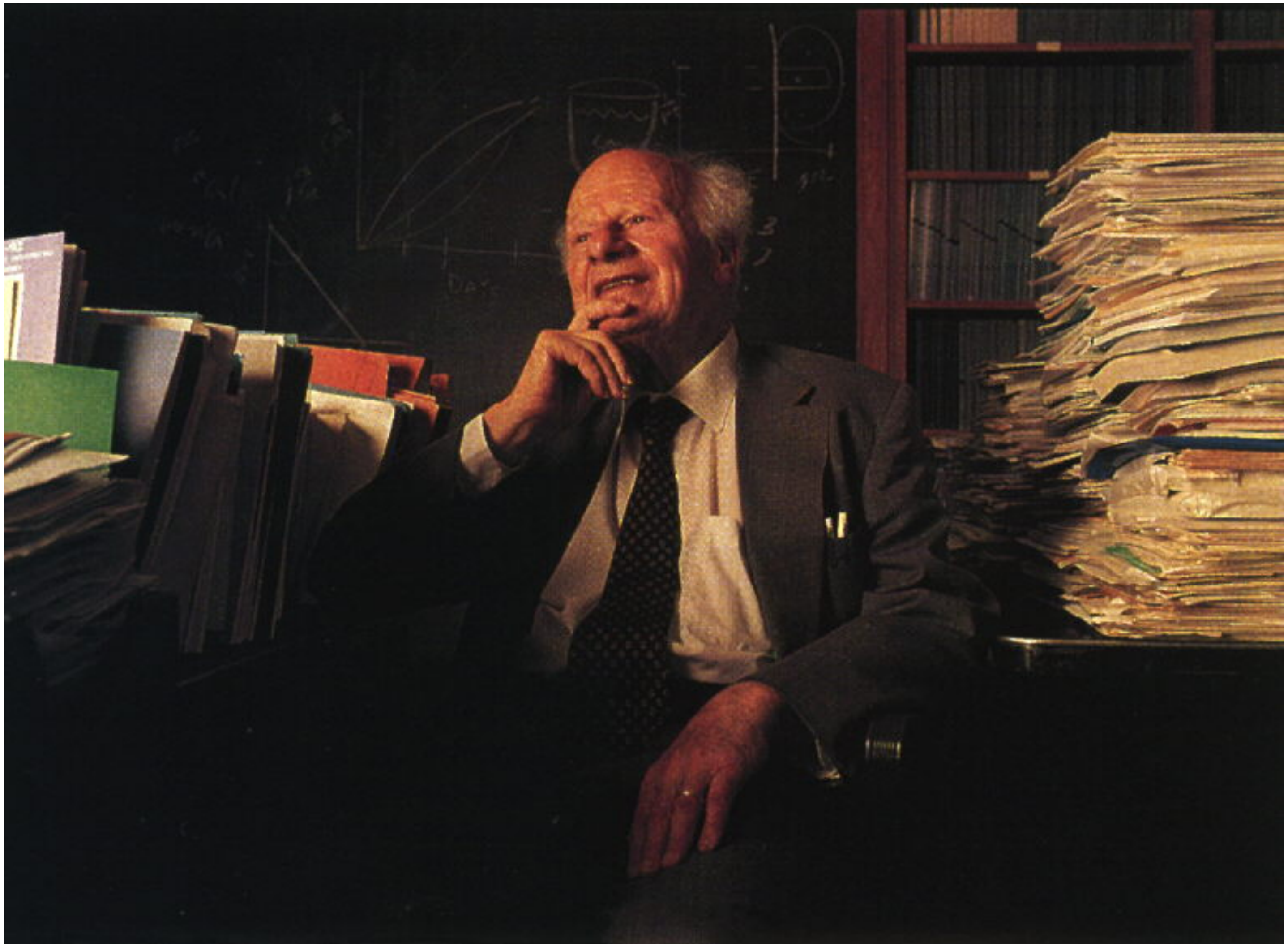
The first was his **ability to recognize his strengths and his limitations.** From early on he was very much aware that **he was not creative in the way Heisenberg, Dirac, or Schrödinger were**. He was not able to formulate radically new ideas, but, on the basis of foundational approaches of others, he could critically analyze and extend theories and formulate generative idealizations and models that would test their validity. The criteria that determined the validity of a theory always had an empirical component. **Certainly one of the characteristic features of Bethe's research in physics is its close relationship to experiments and to experimental practice**.

His second insight into his abilities was that **he came to know *when* to undertake a problem by evaluating the empirical data and theories at hand.**

The third was **being able to assess realistically whether he possessed the knowledge and the mathematical tools to tackle and solve the problem**, and whether he could at the outset say to himself: "**I can do that**.""

- From "Nuclear Forces -The Making of the physicist Hans Bethe" by Silvan S. Sc

Carry on! – “H. A. Bethe way”



Work only on problems for which you have “an unfair advan

Acknowledgements

Sincere thanks are in order to
Prof. Emeritus Dr. William Ingham (JMU
for allowing me to adapt some ideas
from his recent seminar at JMU on
Hans Bethe's legacy.

Image Sources and Recommended Web Sites

- The images in this talk were taken from a wide variety of online sources. Some of the images are copyright-free; the others appear here under the "fair use" provision of US copyright law. Three specific image sources that were used heavily:
  - the Emilio Segre Visual Archive of the Niels Bohr Library at the American Institute of Physics
  - the Cornell University Library
  - Wikimedia Commons
- Six recommended web sites:
  - AIP Center for the History of Physics: www.aip.org/history
  - Cornell University: www.cornell.edu
  - the Nobel e-Museum: www.nobel.se
  - Web of Stories: www. webofstories.com
  - Personal and Historical Perspectives of Hans Bethe: www.bethe.cornell.edu
  - Celebration of Bethe's life (2005): http://ecommons.library.cornell.edu/handle/1813/3764