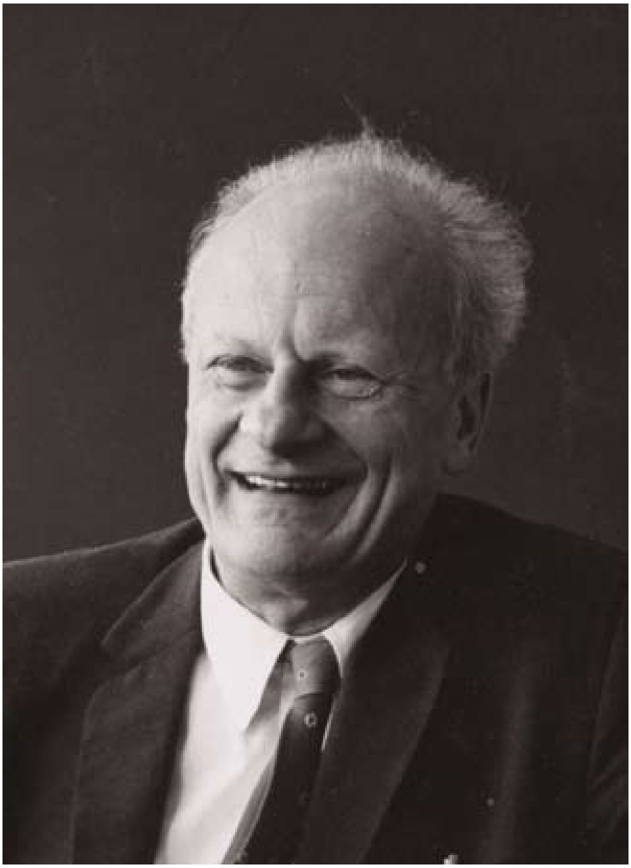
NATIONAL ACADEMY OF SCIENCES

HANS ALBRECHT BETHE
1906—2005

A Biographical Memoir by
GERALD E. BROWN AND SABINE LEE

Biographical Memoir



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H. A. Bethe

HANS ALBRECHT BETHE

July 2, 1906–March 6, 2005

BY GERALD E. BROWN AND SABINE LEE

HANS ALBRECHT BETHE, who died on March 6, 2005, at the age of 98, was one of the greatest physicists of the 20th century, a giant among giants whose legacy will remain with physics and the wider science community for years to come. He was universally admired for his scientific achievement, his integrity, fairness, and for his deeply felt concern for the progress of science and humanity that made him the "conscience of science." Bethe studied theoretical physics with many of the greatest minds within the physics community, including Sommerfeld, Ewald, and Bohr. His Jewish background made a career in Germany all but impossible, and after a brief spell in England between 1933 and 1935, he emigrated from Germany to the United States. He took up a post at Cornell University where he remained, with exceptions of his work at Los Alamos and several sabbaticals, until the end of his career. Hans Bethe was a universalist who contributed to scientific research for more than seven decades. He was awarded the Nobel Prize for his work on energy production in stars. Many other of his discoveries would have been worthy of a Nobel Prize, for instance, his

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work on the Lamb Shift or the "Bethe Ansatz." Like many of his colleagues who had contributed to the development of nuclear weapons, Hans Bethe devoted much of his time and energy to the control of these weapons, to nuclear disarmament, and to the promotion of greater understanding between East and West, most notably through his activities within the framework of the Pugwash movement.

EARLY YEARS

Hans Bethe was born in Strasbourg, in Alsace-Lorraine (then part of Germany) on July 2, 1906. His parents were Albrecht Julius Bethe (1872-1954), at the time *Privatdozent* in physiology at Strasbourg University, and Anna (née Kuhn, 1876-1966), a talented musician and writer of children's stories. Both grandfathers were physicians: on his father's side a general practitioner in Stettin, northern Germany (now Szczecin, Poland), and on his mother's side a professor at the University of Strasbourg with specialization in ear, nose, and throat diseases.

Hans Bethe showed an early interest in numbers, discovering for himself the basic principles of arithmetic, including the decimal system. He was close to his father and they often talked about scientific matters. Albrecht knew some mathematics, mainly algebra, and he taught his son the use of the slide rule. Hans would use the slide rule for the rest of his life and when the most detailed calculations were made on supercomputers, he could be found behind a stack of computer output, analyzing it with the help of his slide rule. Father and son took long walks together talking about politics of the present and about German and ancient history. These early extensive conversations instilled in Hans an awareness of political developments and a sense of responsibility for shaping the world around him, be it as a scientist, a teacher, or a political advisor.

STUDENT YEARS

In 1924 Bethe enrolled at the University of Frankfurt in chemistry. He soon discovered that chemical experiments consumed too many lab coats and he switched to physics and within physics to theory. He was fascinated by the lectures of the ebullient Walter Gerlach and later of his successor, the spectroscopist Karl Meissner, who told Hans emphatically that he must not stay in Frankfurt but should go to a place with better theoretical physics. On his recommendation, Bethe applied to Arnold Sommerfeld in Munich for admission to his seminar. In 1926 Arnold Sommerfeld was the most influential physics teacher in the world, his recent prize pupils having been the future Nobel Prize winners Wolfgang Pauli and Werner Heisenberg. Sommerfeld worked in every area of theoretical physics and his lectures formed one of the best introductions to many branches of physics.

At Sommerfeld's institute, collaboration and exchange of scientific ideas were encouraged. German graduate students and foreign postgrads shared one big room that also served as a library and a place of scientific discussion. Here Bethe met Rudi Peierls, a year younger than himself, super quick of mind and congenial in his approach to life. Soon there were joint Sunday expeditions to the Alps for walking and skiing, and, most importantly, they enjoyed each other's humor which made possible political discussions, a very necessary relief in those years of the rise of Hitler. The friendship continued throughout their lives and included scientific collaboration, at first in England and later in Los Alamos where Peierls was part of the British Delegation.

Sommerfeld's students benefited from the respect in which the theoretical physics community held this grandmaster of their discipline. New ideas and preprints of papers would land on Sommerfeld's desk for comment, and Sommerfeld passed them on to his students for discussion in his advanced seminar. Schrödinger's and de Broglie's work on wave mechanics was being developed in 1925-1926 and Bethe often argued that he entered the scene of serious theoretical physics research at an ideal time. Unencumbered by old concepts and theories, he was both keen to study and quick to appreciate the new ideas. His doctoral thesis, suggested by Sommerfeld, was a theoretical analysis of the Davisson and Germer paper on diffraction of electrons by crystals (Davisson and Germer, 1927). Since electrons have wave properties, as evidenced by their de Broglie wavelength, they diffract in crystals in a similar way to X-rays. The theory of x-ray diffraction had initially been formulated in 1912 by Max von Laue based on suggestions by Paul Ewald, and had been demonstrated in famous experiments by Walther Friedrich and Paul Knipping (Friedrich, Knipping and Laue, 1913). Sommerfeld suggested that Bethe look at a paper by Paul Ewald in which he had presented a dynamical theory of the diffraction of X-rays by crystals (Ewald, 1917). Bethe adapted Ewald's approach to the wave mechanical description of electron diffraction and found that it yielded very satisfactory results. (Bethe and Hildebrandt, 1988). Bethe started out by producing a more or less direct translation of Ewald's thesis from X-ray to electron diffraction and found out that it worked very well.

EARLY CAREER

After a short period in Frankfurt in 1928, Bethe became Paul Ewald's assistant at Stuttgart. The move to Stuttgart was a happy one, coming as it did at a time when Bethe's personal life was less than happy due to his parents' divorce in 1927. At Stuttgart Bethe was made welcome in the institute and in Ewald's family; many years later, in 1939, he married his mentor's daughter Rose.

Bethe thoroughly enjoyed his work at Stuttgart; Ewald was working on crystallography, the topic of Bethe's Ph.D. thesis. Bethe's knowledge was sought by colleagues and students alike. He was asked to lecture twice a week on the new quantum mechanics to Ewald and all of his assistants, and to the numerous visitors, who came from all over the world to study with Ewald. Werner Ehrenberg, assistant to the professor of experimental physics Erich Regener, once famously remarked: "If you want to see Hans, the line starts to form at 10 o'clock!"

In the midst of Bethe's happy situation in Stuttgart, Sommerfeld returned from a trip around the world. He wrote a postcard to Ewald saying, in effect, "Bethe is my student. Send him back to me immediately." Ewald could do little but obey his former teacher's request, and Sommerfeld created an attractive package for Bethe that allowed him to become a *Privatdozent* the following spring as well as provided a fellowship and a general travel allowance.

At Munich in the winter of 1929 Bethe wrote what he considered to be his best paper on the theory of the passage of fast corpuscular rays through matter (1930). The paper was submitted as his habilitation thesis, the research paper required to become a *Privatdozent.* It established the theory that has been of great importance for the interpretation of experiments using cosmic rays and particle accelerators. Thus, by the age of 24 Bethe had already left his mark in his chosen field of scientific research with thorough, insightful, and innovative contributions of long-lasting impact.

When Bethe was awarded a Rockefeller Fellowship for 1930-1931, he decided to visit Cambridge and Rome. In Cambridge he was welcomed particularly by Ralph Fowler and Patrick Blackett. In their company he discovered a new relaxed, yet respectful lifestyle in which in particular politics could be discussed without confrontation. In fact, it relaxed him so much that he forgot how SERIOUS science was and together with two other young visiting German scientists wrote a spoof: "On the Quantum Theory of the Temperature of Absolute Zero" in centigrade. It appeared in *Naturwissenschaften,* and he had to publish an apology as well as endure the anger of his beloved teacher, Geheimrat Sommerfeld. Later he would frequently recall how formative his work with Enrico Fermi in Rome had been for him. From him Bethe learned to look at a problem qualitatively first, and understand the problem physically before putting lots of formulas on paper. In contrast with Sommerfeld, whose method was to begin by inserting the data of a problem into an appropriate mathematical equation and solving the equation quantitatively according to the strictest mathematical formalism for those specific data, for Fermi the mathematical solution was more a confirmation of his understanding of a problem than the basis for its solution.

Although Fermi's main interest during the period of Bethe's visit was low-energy neutron scattering, he and Bethe coauthored a paper comparing three methods of treating relativistic electron-electron interactions (1932). In general, however, although Bethe took an interest in the experiments, he worked on his own. He worked out the solution of the linear chain during that period, introducing what C. N. Yang later named "The Bethe Ansatz" (1931). Of all his works, this result probably has had the most influence over a wider variety of fields.

Bethe's style of doing physics and of teaching became an amalgam of the influence of his two great teachers: Sommerfeld's mathematical rigor and Fermi's joy in the challenge of the problem at hand. Both encouraged free exchange of ideas and the close relation of theory and experiment. Bethe himself expressed his indebtedness to these two great teachers by saying, “If I am, in German parlance, my students’ doctor father, they have two doctor grandfathers.”

On his return to Munich, in collaboration with Sommerfeld, Bethe wrote one of his three great review articles “Elektronentheorie der Metalle” (1933). In fact, Sommerfeld wrote the first chapter and Bethe wrote the rest of the book.

In the summer of 1932 Bethe was offered an assistant professorship at Tübingen, but after Hitler’s ascension to power in January 1933 and the enactment of the racial laws, Bethe was dismissed from his post in April 1933. His mother being of Jewish origin, by the new laws he was no longer regarded fit to serve the state. Bethe gladly accepted a temporary lectureship at Manchester. It allowed him to leave Germany and brought him together again with Rudolf Peierls, who also held a lectureship at Bragg’s institute. Peierls was now married and living in a large house, which Hans happily shared.

Bethe often referred to the year 1933-1934 as his most productive. Working (and lodging) with Peierls was highly enjoyable for Bethe, and their collaboration produced several noteworthy papers. On the occasion of a visit to Rutherford’s Cavendish Laboratory in Cambridge, James Chadwick acquainted them with an experiment carried out with a bright young graduate student Maurice Goldhaber on the photodisintegration of the deuteron (then called diplon). Chadwick challenged them to work out the theory of this reaction. Trains took a long time to go cross-country in England at that time, about four hours from Cambridge to Manchester. Bethe and Peierls had a solution to the problem by the time they reached Manchester (1934[1], 1935).

That year they also wrote two short papers on the neutrino (1934 [2]) and a paper on neutron-proton scattering (1935). In a different collaborative effort, Bethe and Walter

Heitler wrote the paper "On the Stopping of Fast Particles and on the Creation of Positive Electrons" (1934[3]).

During an earlier visit to England, Bethe had made the acquaintance of Nevill Mott, who in 1933-1934 was a professor at Bristol. Bethe gave a talk there and intimated he would like to join the department. A few weeks later Mott offered him a fellowship at Bristol for a year. But in the summer of 1934 Bethe got a cable, seemingly out of the blue, from Cornell University offering him an acting assistant professorship, with the prospect that it might be made permanent. He accepted with some trepidation about going alone so far away from his family. But it was a good move: he remained a Cornell professor for the rest of his life, teaching for 40 years and officially retired for 30 more.

AMERICA, THE FIRST YEARS

Hans Bethe immediately felt welcome in America, and often reiterated that within a short period of time he came to feel that his growing up in Germany had been an accident and coming to America was like coming home. Starting in 1933, the physics department at Cornell had made plans to enlarge its activities, which until then had been focused on teaching, with research serving to provide thesis topics for M.A. and Ph.D. students. The new chairman of the department, R. C. Gibbs, along with one of Bethe's acquaintances from Munich days, Lloyd Smith, conceived a very different model for the department. Four new appointments were made in just two years: Lyman Parratt in X-ray spectroscopy, and three men in the very new field of nuclear physics: Stanley Livingston, who had just helped Ernest Lawrence build the world's first cyclotron, the young yet experienced experimentalist Robert F. Bacher, and to complete the team of builder, experimentalist, and theorist, Hans Bethe. Hans was welcomed warmly and very quickly felt very much at home. He was happy to continue shedding the stiff and formal life of Germany. He joined the luncheon table of physicists and chemists, where professors and students mingled freely, and he found colleagues who liked to hike the beautiful hills and gorges of the Ithaca area. He lived for a while in a fraternity house and then in Telluride House where politics was a lively topic of conversation, especially as the second Roosevelt election came up in 1936. After a summer spent in Germany, he was doubly happy to be living in America and began urging his mother to join him.

THE BETHE BIBLE

Bethe's unsurpassed ability to elucidate newly developed, complex physical knowledge had already been displayed in his *Handbuchartikel* in the early 1930s. When he joined the physics department at Cornell and found his colleagues to be more ambitious than knowledgeable in theory, he provided them with what later became known as the "Bethe Bible," three articles in the *Reviews of Modern Physics* (1936, 1937[1, 2]). Written in collaboration with his colleagues Bacher and Livingston, the articles presented a complete coverage of nuclear physics and were used like textbooks.

These review articles and a lecturing tour on which Bethe embarked soon after his arrival in the United States were evidence of his strong commitment to teaching at all levels. They also brought him a job offer from another American university and, when he chose to stay at Cornell, his promotion to full professor.

THE CARBON CYCLE

The fourth Washington Conference, jointly organized by Merle Tuve of the Carnegie Institution and John Fleming of George Washington University in March 1938 was devoted to problems of stellar energy, particularly as these related to nuclear physics. Several investigators whose work was especially concerned with the internal constitution of stars joined forces with physicists working on the problems of nuclear transformations.

Bethe and Charles Critchfield had investigated the "proton-proton chain" as a possible mode of energy production in the Sun (1938). Their work had used Eddington's value for the central temperature of the Sun, which was later found to be inaccurate, and therefore their calculations had led to an inaccurate value for the luminosity of the Sun. At Washington, Bethe heard of Strömgren's new estimates of the solar interior temperature (Strömgren, 1937), and these estimates brought his calculated predictions for solar luminosity much closer to the observed radiation, and his and Critchfield's theory of energy production in the Sun and less massive stars worked just fine.

The question of energy production in larger stars remained unsolved. The proton-proton reaction did not predict this accurately, since the rate of the reaction increases slowly as the temperatures rise, in contrast with the known phenomenon in larger stars where the core temperatures increase slowly with increasing mass, but the luminosity increases very rapidly. Bethe considered this particular problem when he left the conference. Contrary to legend he did not figure out the carbon cycle (and thereby understand the energy production in larger stars), the discovery that would earn him the Nobel Prize in 1967, on the train on the way back home from Washington. But he did start thinking about energy production in massive stars upon his return to Ithaca and he soon worked out that the reaction would have to involve heavier nuclei. Within two weeks, Bethe had worked out the six-step cycle in which carbon and nitrogen act as catalysts in producing a ^{4}He nucleus from hydrogen atoms. He did this simply by looking through the possible reactions that had been measured by Willy Fowler and his collaborators at Caltech.

$$
\begin{gathered}
{}^{12}C + H \rightarrow {}^{13}N + \gamma \\
{}^{13}N \rightarrow {}^{13}C + e^{+} + \gamma \\
{}^{13}C + H \rightarrow {}^{14}N + \gamma \\
{}^{14}N + H \rightarrow {}^{15}O + \gamma \\
{}^{15}O \rightarrow {}^{15}N + e^{+} + \gamma \\
{}^{15}N + H \rightarrow {}^{12}C + {}^{4}He
\end{gathered}
$$

The 1939 paper on “Energy Production in Stars” was a landmark paper that formed the basis of much work in astrophysics for decades. It also brought him the A. Cressy Morrisson Prize from the New York Academy of Sciences, and 29 years later the Nobel Prize.

The years immediately preceding the Second World War were an exciting time for Hans Bethe scientifically, and they were also a happy time personally. His mother arrived in the United States safely in 1939, and in September of that year, he married Rose Ewald, the daughter of his former mentor at Stuttgart. As Bethe would later recall, they were married by a judge who recited the marriage ceremony in its briefest possible form—everybody thought it was a rehearsal. But at some stage the judge said: “Now you are married.” And so they remained for more than 66 years.

THE WAR EFFORT

Keen to contribute to the war effort after hostilities had commenced in Europe in September 1939, Bethe initially had to limit himself to work that did not require security clearance. Together with his fellow noncitizen, Austrian-born George Winter, a civil engineer who had specialized in elasticity of steel, he wrote a paper on armor plate deformation and shielding. The paper was never published and as a potentially significant contribution to the war effort it was soon classified and thereby put outside Bethe's reach, who—as enemy alien—was not allowed to access such classified material! Only after the war Nevill Mott told him that it had been very useful.

A second important paper was written, at the suggestion of Hungarian aeronautical engineer and physicist Theodore von Kármán, by Bethe and Edward Teller who produced a theory of how the equilibrium of a gas is reestablished behind a shock wave. This paper was later to become the basis of much work done by aerodynamicists, as it gave insights into the use of shock waves in the investigation of properties of gases (1941). Bethe considered this paper one of the most influential either he or Teller ever wrote.

After becoming an American citizen in February 1941, in December of the same year Bethe finally received his clearance to work on classified military projects. The first such project was linked to the radar that was being developed at the Radiation Laboratory at MIT; Bethe invented the so-called "Bethe coupler," a device used to measure the propagation of electromagnetic waves in waveguides. In 1942 while working on the radar project, Bethe participated in a summer study group at Berkeley, organized by Robert Oppenheimer, which led to the creation of the Los Alamos Laboratory in 1943. Like many others, Bethe joined the Manhattan Project out of fear that Nazi Germany might be developing a fission bomb. As head of the theoretical division in Los Alamos, Bethe led the effort to assess theoretically the performance of the evolving designs of what ultimately became the Hiroshima and Nagasaki bombs. Never before or after did he work so intensely. He was ideally suited for his role at Los Alamos. He coupled deep theoretical insight into nuclear physics with organizational talent and stamina.

The wartime experiences had changed Hans Bethe profoundly, not merely in his evaluation of the interrelationship of science and politics. As a division leader within the Manhattan Project he had learned to organize work for others, to keep people happy working together creatively amidst the tense wartime atmosphere, and he had had to deal with issues of "nonscientific" personnel management. As a result he became more confident in human relations. Likewise, his already considerable range of scientific knowledge expanded further into chemistry, metallurgy, explosives, electronics, and others. He also realized the role science would play in government policy and politics after the war and the urgency of increased understanding of science and numbers by the general public. In January 1946 he returned to Cornell.

QED AND THE LAMB SHIFT CALCULATION

After the end of the Second World War, the U.S. National Academy of Sciences sponsored a series of conferences in theoretical physics. The first of these meetings, the Shelter Island Conference of June 1947 on the Foundation of Quantum Mechanics revisited Quantum Electrodynamics (QED). Invited participants, including Oppenheimer, Bethe, Weisskopf, Feynman, Lamb, Teller, and Schwinger, discussed the experiments of Lamb and Retherford to measure the fine structure of the energy levels of the hydrogen atom (Lamb and Retherford, 1947). Lamb and Retherford had measured what later became known as the "Lamb Shift," the frequency of a microwave field that induced transition between the lowest two excited states of the hydrogen atom.

According to QED, the observed energy of an electron was the sum of two unobservable quantities, the bare energy as an energy of the electron if it were uncoupled from electromagnetic field and the self-energy, which results from electromagnetic coupling. At Shelter Island, Hendrik Kramers presented a model of the electron where all parameters in the theory were made to refer only to observable quantities, by incorporating the infinite contribution of the electromagnetic self energy into the parameter that corresponded to the observed mass. At the conference, it was suggested by Oppenheimer, by Weisskopf, and by Schwinger that Kramers' ideas could be applied to calculate the Lamb shift. Hans Bethe, on a relatively brief train journey from New York to Schenectady after the conference, made use of these ideas to calculate quantum mechanically the level shift for a non-relativistic electron and found substantial agreement with the experimental value. The Lamb Shift calculations were a fine example of what I (G.E.B.) call the "H. A. Bethe way." When confronted by any problem Bethe would sit down with paper, pen, and his slide rule and calculate the problem in the most obvious way. Most importantly, he would not be deterred by anyone who would tell him—as most colleagues would—that the situation was much more complicated than you thought. Bethe could identify the essential physics and see the light at the end of the tunnel. Once he had focused on that light, he would move toward it, undeterred by temporary obstacles and helped by his formidable mathematical mind and his prodigious memory, which gave him a command and control over the entire discipline that was second to none.

While making seminal contributions to the development of QED, Hans Bethe was also heavily involved in particle physics in the early 1950s. Under his leadership Cornell became a world center for high-energy particle physics. During a sabbatical at Cambridge in the mid-1950s, he gave a substantial lecture course on fields and particles, closely related to the two-volume study of *Mesons and Fields* (1955), which he had written together with Sam Schweber and Frederic de Hoffmann.

Bethe's outstanding abilities and his significant contributions to the progress of physics were widely recognized by that time. This was evident in the numerous prizes and awards he received. He was elected to the National Academy of Sciences in 1944. The award of the 1947 Henry Draper Medal was followed by the Max Planck Medal in 1955, the Ben Franklin Medal in 1959, the Enrico Fermi Award and the Eddington Medal in 1961, the Rumford Prize in 1963, the Nobel Prize for Physics in 1967, the Order Pour le Merite for Arts and Sciences of the German Government in 1984, the Los Alamos National Laboratory Medal and the Bruce Medal in 2001, and—awarded posthumously—the Benjamin Franklin Medal, 2005, to name but the most important honors.

LOS ALAMOS REVISITED: THE H-BOMB AND THE SHAPING OF PUBLIC POLICY

In 1942 Edward Teller had suggested to focus nuclear weapons research on the development of a hydrogen bomb, and although not a priority, work on thermonuclear weapons was actively pursued during the war years. Bethe viewed the H-bomb an unnecessary and undesirable escalation of destructive capability and he opposed the development with all means at his disposal. He had hoped to be able to prove that such a bomb would not be technically feasible. When he realized, however, that this was not the case, and after a decision had been made to develop such a device, he returned to Los Alamos in an attempt to make his influence felt within the establishment (Edson, 1968).

Following his initial work on the atom and the hydrogen bombs and throughout the four decades of the Cold War, Bethe advocated and worked tirelessly to create effective tools for verifying and validating negotiated agreements to slow down the arms race between the two superpowers. (Drell, 2006) As one of the original members of the President's

Advisory Committee, Bethe proposed a study of the possibility and implications of a ban on nuclear weapons tests. His chairmanship of the interagency panel created to assess the American ability to detect Soviet nuclear tests allowed him to gain the expertise to actively participate in the 1958 Geneva talks on test bans, work that culminated, five years later, during J. F. Kennedy's presidency, in the conclusion of the Limited Test Ban Treaty between the United States, the Soviet Union, and Great Britain.

Bethe's guiding principle in his government service was that he did not have the right to withhold his help. This help included insisting on truth over wishful thinking, but leaving the final decision-making to the elected politicians. However, as a citizen he had the obligation publicly to speak his mind which led him to write and to follow numerous invitations to speak.

When ballistic missile defenses were proposed, first in the 1970s, then again with the "Star Wars" proposal in the 1980s, Bethe argued against them, both on policy grounds and as useless in practice because the antimissiles could be defeated by decoys. Together with Richard Garwin, he wrote a substantial article for the *Scientific American* (1968) showing the scientific problems of Star Wars. Together with Kurt Gottfried, he also wrote several op-eds published in *The New York Times* (1982 [1,2]) discussing the policy implications.

It is indicative of Bethe's continual grappling with moral issues that on the occasion of the 50th anniversary of Hiroshima he addressed the scientists assembled at Los Alamos to convince them that one should not work on the further improvement of nuclear weapons. Given the changed context brought about by the collapse of the Soviet Union he urged that fellow scientists collectively take a Hippocratic oath not to work on designing new nuclear weapons.

He was a man of reason with great faith in the power of reason to create a peaceful world. Among his friends it earned him a soubriquet "conscience of science."

THE NUCLEAR MANY-BODY PROBLEM

In 1955 Nevill Mott invited Bethe to spend his sabbatical leave at the Cavendish Laboratory in Cambridge, England, and be a visitor at Caius College. It turned out to be a year of reunion with old friends and family, of professional and pleasure travel in England and on the continent, and in his research the emphasis shifted to the nuclear many body problem in a more focused way. This work involved the use of the *G*-matrix theory developed by Keith Brueckner in order to "tame" the extremely strong short-range repulsions entering into the nucleon-nucleon interaction (Brueckner et al., 1954; Brueckner, 1954, 1955 a,b; Brueckner and Levinson, 1955). Brueckner's pioneering approach to solving the two-body scattering problem in the nuclear medium by rearranging perturbation theory in such a way that the contribution to the total energy at each order was proportional to the number of particles allowed a better understanding of nuclear properties. Energies per particle were manifestly finite. The challenge of calculating these nuclear properties was yet another one for which Bethe's abilities, experience, and knowledge were ideally suited. His approach, based on a diagrammatic expansion of perturbation theory in a series ordered by the number of interacting particles, had "Hans Bethe" written all over it. In one substantial paper (1956) Bethe gave a self-contained and largely new description of Brueckner's method for studying the nucleus as a system of strongly interacting particles with the aim of developing a method that was applicable to a nucleus of finite size while at the same time eliminating any ambiguities of interpretation and approximations required for computation. Thus

Bethe—using the work of Brueckner and collaborators—produced an orderly formalism in which the evaluation of the two-body operators *G* would form the basis for calculating the shell model potential *V (r)*. As in other scientific contexts, analytic solutions to specific problems were a source of additional insight for Hans Bethe. Therefore, with Jeffrey Goldstone he went on to investigate the evaluation of *G* for extreme infinite height hard core potential, and he encouraged his graduate student David Thouless to investigate the problem: what properties of *G* would produce it given the empirically known shell potential *VSM (r)*.

Then, progressing from Goldstone's work and the Goldstone diagrams (Goldstone, 1957), Bethe took the logical next step and investigated three-body correlations, in the course formulating what is now known as the Bethe-Faddeev equations. Using Ludwig Faddeev's work on scattering of systems of three particles (Faddeev, 1960) he generalized the approach and formulated the problem in terms of the three-body wave function. He developed the tools to evaluate the three-body contributions to the binding energy, and after combining it with Wong's idea of a "soft repulsive core" (Wong, 1964), he arrived at binding energies that were in much better agreement with observations than previous estimates (1965, 1967).

CONSULTING FOR INDUSTRY & THE GOVERNMENT

Following WWII, Bethe became active in industrial R&D. He consulted on the design of nuclear reactors, starting in the mid forties at General Electric, later at Detroit Edison, where a breeder reactor was attempted, and still later at General Atomics, where he worked on improving the efficiency and safety of reactors. In the 1950s he began a long association with AVCO Corporation, an aerospace company, working initially on nose cones for missiles and spacecraft reentering the atmosphere, later primarily on making magneto-hydrodynamics commercially feasible.

The twenty-five years after WWII were busy and productive years for Bethe. He was able to share his knowledge and ability with others who were intent on building a better world; he did good physics and had many good students who became his friends.

In the 1970s, when the oil embargo created the first energy crisis, Bethe became interested and active in proposing solutions. He remained convinced that nuclear power was the key to immediate solutions, and that all other sources not derived from fossil fuel or water were then too expensive or needed thirty to forty years of R&D to become economically useful.

ASTROPHYSICS AGAIN

I (G.E.B.) had got to know Hans Bethe in the 1950s, when I was a lodger—at Birmingham—at the home of his close friend from Munich days, Rudolf Peierls. Their comradeship affected many physicists who benefited from their numerative collaborative efforts and from the Birmingham-Cornell pipeline that ensured the cross-Atlantic transfer of knowledge and personnel. Not long after Bethe had begun working on the nuclear many-body problem during his 1955 Cambridge sabbatical, I began work on applying finite nuclei to effective range interactions he had obtained for infinite nuclear matter, and I often visited him at Cornell to discuss these topics. I soon learnt why Hans had had no long-term collaborators earlier in his life, aside from Peierls. Even after he retired, it was nearly impossible to keep up with him. He did not work rapidly, but he could always identify the essential physics immediately and saw the light at the end of the tunnel. Once identified, he would move toward that light like a bulldozer, undeterred by temporary obstacles.

At his retirement party from Cornell University in 1975 I approached Hans with the proposal of a collaboration. But it was not until three years later, when he visited Copenhagen where I was professor at NORDITA, that we got started. I proposed to work out a theory of supernovae and while at Copenhagen Bethe read through the existing literature on the core collapse of massive stars. He quickly realized that all supernovae calculations contained an error. The consensus was that the core collapse ended when the core density reached less than 10 percent of the nuclear density, whereas in fact it continued to densities well in excess of nuclear density. Together with Jim Applegate and Jim Lattimer, Bethe and I wrote the paper, nicknamed "babble" by William Fowler, and generally referred to as such in the astrophysics community. It derived the equation of state in stellar collapse from simple considerations, notably Bethe's early insight that the entropy per nucleon remains small in the order of 1 (in units of $k_{Boltzmann}$) during the entire collapse (1978).

Babble turned out to be the beginning of a long and fruitful astrophysical collaboration between us. For 19 years we spent the month of January together on the West Coast, at Santa Barbara, Santa Cruz, or Caltech, producing more than 20 joint papers in the process. At the outset I would bring up ideas and what he called the "don't know how," and Hans would provide his seemingly inexhaustible 'disc storage' of problems he had worked through or thought about. Hans started his research of the day, as he had done for decades, with a stack of white paper on the upper-left-hand corner of his desk, fountain pen and slide rule in hand. Then he would begin working out whatever problem he had planned to do, remembering all constants, and would fill the white sheets at a nearly constant rate. He headed straight toward the light at the end of the tunnel. If he ran into a barrier, he would go around, over, or under it, filling more of the paper. In short: the Bethe Way!

In the evening I would bring up the problems I wanted Hans to think about the next morning. The master bedroom always had a large bath, as Hans felt his mind to be clearest in the morning in the bath. He would come after his bath to the massive breakfast: sliced meat from the roast or joint or chicken supper the evening before, hot bread rolls, raspberry jam, and lots and lots of weak tea. Over breakfast he outlined the line of attack we should use on the problem at hand. He would estimate what we could get done by noon, and he was in less than good humor if he missed his goal, because he wanted to set out for lunch by noon. In the late afternoon after coming home from the Institute, over tea we would crosscheck our solutions for the problem we had worked during the day. Hans would have done his numerical work with his slide rule; I would have done mine with a $16.00 calculator. Usually we agreed on the results.

When asked once how he wanted to be remembered, after some puzzlement at the question, he said "as a scientist." It would therefore have pleased him that in 2008 a younger generation of physicists in Germany, where the immediate post-war generation repudiated him as one of the evil geniuses of the atomic bomb, wished to perpetuate his name through the Bethe Center for Theoretical Physics at Bonn University and the Hans Bethe-Strasse in the neighborhood of the natural science campus of the University of Frankfurt am Main.

Hans Bethe defied the notion that physics is a young person's pastime. He published significant papers in every decade from the 1920s into the 21st century. As John Bahcall remarked: "If you know his work, you are inclined to think that he is many different people, all of whom have gotten together and had formed a conspiracy to sign their papers under the same name"(Bahcall, 2005).

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