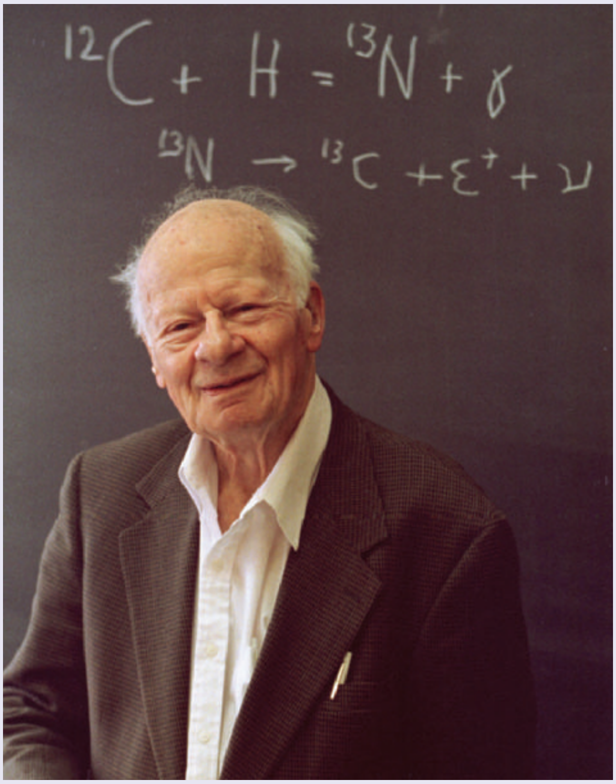
Obituary

Hans A. Bethe (1906–2005)

Were we asked to characterize Hans Bethe with one word, we would choose strength — strength of intellect and strength of character. From the moment he reached the frontier of physics research, it was evident that he possessed exceptional intellectual strength and the personal resources to put his talents to outstanding use. The true extent of his moral strength would only emerge when his role in the birth of the nuclear age posed a host of ethical choices.



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Giant of physics who grappled with the moral implications of nuclear weapons.

Bethe, who died on 6 March, was born in 1906 in Strasbourg, Alsace-Lorraine — then part of the German Empire — and went to school and university in Frankfurt am Main. In 1926, he joined Arnold Sommerfeld's famous school of theoretical physics in Munich just as Erwin Schrödinger's wave mechanics theory was appearing. Bethe absorbed the new theory quickly because, as he recalled, he was not burdened by knowing the recipes of the 'old' quantum theory.

By 1931, his rapidly growing publication list included three classic papers: the spectrum of an atom in a host lattice, one of the first applications of group theory to quantum mechanics; the quantitative description of how charged particles lose energy when traversing matter, important to the interpretation of nuclear data; and the exact spectrum and wavefunctions of a linear chain of interacting spins. All three papers solved difficult problems, and all were marked by formidable mathematics deployed with virtuosity. In the solution to the spin problem, Bethe introduced the now-famous 'Bethe ansatz', a tool used by armies of theorists to this day.

Bethe's amazing ability to analyse and synthesize a huge and still-growing body of intricate knowledge was first displayed in the 1933 edition of the *Handbuch der Physik* in two encyclopaedic articles: on one- and two-electron systems; and, with Sommerfeld, on the theory of metals.

But 1933 was also a personal watershed for Bethe. His parents were Protestants, but his mother had been Jewish at birth, and so he was dismissed by the Nazis from his university post. He moved to England, but, after two very productive years there, left Europe to join Cornell University in New York, and never looked back. He was to stay at Cornell, despite many offers, for the next 70 years. In 1947, when asked to succeed Sommerfeld in Munich, he declined, writing that he felt "as if I was born in Germany only by mistake, and only came to my true homeland at age 28".

Bethe's involvement with nuclear physics began in England in collaboration with Rudolf Peierls, his close friend since their days as students of Sommerfeld. At this time he devised the first theory of order–disorder phase transitions that took short-range correlations between atoms into account. Also in England, with Walter Heitler, he calculated the cross-section for electron–positron pair production, which played a central role in cosmic-ray physics and the discovery of mesons.

Bethe's mastery of the rapidly expanding field of nuclear physics produced innumerable invitations to speak, and he decided it would be more efficient to write a review than to spend so much time travelling across North America in trains. The result was the 'Bethe Bible', three book-length issues of *Reviews of Modern Physics*, written in part with experimental colleagues at Cornell, and for years an indispensable text for students and experts alike.

That nuclear processes must be responsible for energy production in stars was accepted by the 1930s, but specific reactions that could account for observations remained to be identified.

The first step, following a suggestion by Carl-Friedrich von Weizsäcker, was Bethe's 1938 paper with Charles Critchfield on the fusion of two protons into deuterium and the subsequent reactions that eventually lead to helium. Their results seemed to be in conflict with the solar models of the day; after the models were corrected, the agreement was close. But the proton reaction could not account for energy production by more massive stars. This led Bethe to look into other processes for converting hydrogen into helium, resulting in his discovery of the carbon–nitrogen cycle, in which carbon is not destroyed but is used repeatedly as a catalyst. His monumental carbon-cycle paper was published in 1939, and led in 1967 to Bethe receiving the first Nobel prize on a topic in astronomy.

The discovery of fission in 1938 and Germany's invasion of Poland ended what Bethe called "the happy thirties" of physics. Well before the Japanese attack on Pearl Harbor in 1941, Bethe and his good friend Edward Teller were eager to help with the defence of their new home. As they were not yet allowed to do secret work, they asked Theodore von Kármán what they should do. The result — "Deviations from thermal equilibrium in shock waves", the analysis of the role of molecular structure in fluid dynamics under extreme conditions — was immediately stamped 'secret'. Bethe was very proud of this work, written in part in a mountain cabin during the Bethes' annual summer pilgrimage to the West, and only declassified long after the war.

Bethe participated in secret studies of both the fission and fusion weapon concepts before the start of the Manhattan Project to develop the atomic bomb. But, being a supremely practical man, he at first doubted that nuclear weapons could be invented in time to influence the course of the war. Robert Oppenheimer and Teller changed his mind, and he went to the US government's newly founded Los Alamos nuclear laboratory in 1943 where he became head of the Theoretical Division. Because so many of the phenomena involved in nuclear explosions were not yet accessible to empirical study, theoretical physics was indispensable to the bomb project, especially after it turned out that a plutonium bomb would have to use a tricky implosion mechanism. Bethe, with his unequalled command of physics and serene but commanding persona, became the maestro of Oppenheimer's theoretical orchestra — which did not lack prima donnas.

At the end of the war, Bethe returned to Cornell, bringing Richard Feynman and Philip Morrison with him. Robert Wilson, who had led the experimental nuclear physics division at Los Alamos, and other veterans of the bomb project soon joined them. This established Cornell as a leading centre of theoretical and experimental particle physics, with Bethe as teacher and mentor of scores of students and postdocs. He himself started the spectacular postwar development of quantum electrodynamics (QED), the quantum-mechanical description of the electromagnetic interaction. This he did with the first, somewhat slapdash but essentially correct, calculation of radiative corrections to the hydrogen spectrum. He worked it out on the train ride from the conference where Willis Lamb's experiment disagreeing with QED, as the theory was then understood, was first announced. QED was then taken over by a brilliant young generation: Feynman and Freeman Dyson at Cornell, and Julian Schwinger at Harvard.

But there could be no return to the ivory tower of the "happy thirties". For so central a character in the drama that culminated in the bombing of Hiroshima and Nagasaki, politics was bound to be an inescapable presence. In this setting, Bethe assumed a variety of roles: as an expert technical consultant in further weapons development, and an opponent to such development; as an adviser to the highest levels of government, and an outspoken critic of government policy; and as a defender of colleagues under attack by influential demagogues. That he played all these roles shows how difficult he found it to square his deep moral and ethical convictions, and his desire to influence fateful events, with the realities of the context in which he now lived. As he put it, "sometimes I wish I were a more consistent idealist".

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Presidential adviser: Bethe receives the Enrico Fermi medal from President John F. Kennedy in 1961. Bethe's wife Rose, his companion through 66 years of marriage, looks on.

Bethe never regretted his role in the wartime bomb project, for he had feared that Nazi Germany was developing such a weapon; but he was deeply worried by what he had helped to unleash. Soon after 1945, he joined Albert Einstein and others in a public-education campaign. He publicly opposed the development of a hydrogen bomb on moral grounds, but participated in its research in the hope that he could prove it impossible. After Stanislaw Ulam and Teller discovered how it could be done, he remained involved because he believed the Soviets would also invent it. The H-bomb controversy finally led to the sham process that removed Oppenheimer's security clearance, and to his irrevocable split with Teller.

As a member of the President's Science Advisory Committee (PSAC) from its start in 1957, Bethe advocated a ban on nuclear tests. After a long struggle, in which he played a central part, this came to partial fruition in 1963 with the atmospheric test ban. PSAC studies convinced Bethe that it was futile to attempt a defence against ballistic missiles. After President Lyndon Johnson rejected this assessment, he and Richard Garwin went public with their views. Bethe was to take the same vigorous public role in opposing President Ronald Reagan's 'Star Wars' plans. And in Los Alamos on the fiftieth anniversary of Hiroshima, he called on scientists everywhere to desist from work on creating and developing further nuclear weapons.

Between 1940 and 1970 Bethe did not work explicitly on astrophysics but had a strong indirect influence by supporting Willy Fowler, who was turning nuclear astrophysics into an empirical science at the California Institute of Technology in Pasadena. Bethe was the role model for Fowler's enterprise, interacting constantly with him and sending him young postdocs — including one of us (E.E.S.). During the early 1970s, Bethe worked on the equation of state of high-density nuclear matter, which is needed to understand the dynamics of neutron stars. Of particular interest was how matter 'stiffened' above normal nuclear densities.

Soon after his official retirement, Bethe returned to astrophysics and did cutting-edge research on three different topics until well beyond the age of 90. In close collaboration with Gerald Brown, a major focus was work on the formation of type II supernovae. This process starts with the collapse of a massive star and ends with its outer layers exploding, leaving a neutron star at its centre. Their calculations made use of Bethe's work on high-density equations of state. Unresolved controversies remain because of the many competing mechanisms for forcefully reversing the collapse, including neutrino transport, convection carrying energy outwards and exothermic nuclear reactions in intermediate layers. One of Bethe's greatest contributions, exploiting ingenious skills he first developed at Los Alamos, was showing how auxiliary calculations could be done simply and semi-analytically.

Bethe also made important contributions, in part with John Bahcall, to unravelling the solar neutrino problem — the fact that the flux of neutrinos coming from the Sun is considerably smaller than solar models predict — after it became clear that the theory of the neutrino had to be modified to take neutrino oscillations into account. Later on, Bethe and Brown studied various kinds of binary stars, including the merger of a neutron star and a small black hole, which is of interest for gravitational wave detectors.

The accomplishments of Hans Bethe were prodigious; it is impossible to do justice to them here. We offer this as a snapshot of him as a scientist devoted to the country that had embraced him, even though its current path disturbed him deeply, and as a man who loved his students and colleagues, his children and his wife Rose — his constant companion and foremost adviser in all the difficult decisions he had to face.

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