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EDWARD TELLER
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A Biographical Memoir by

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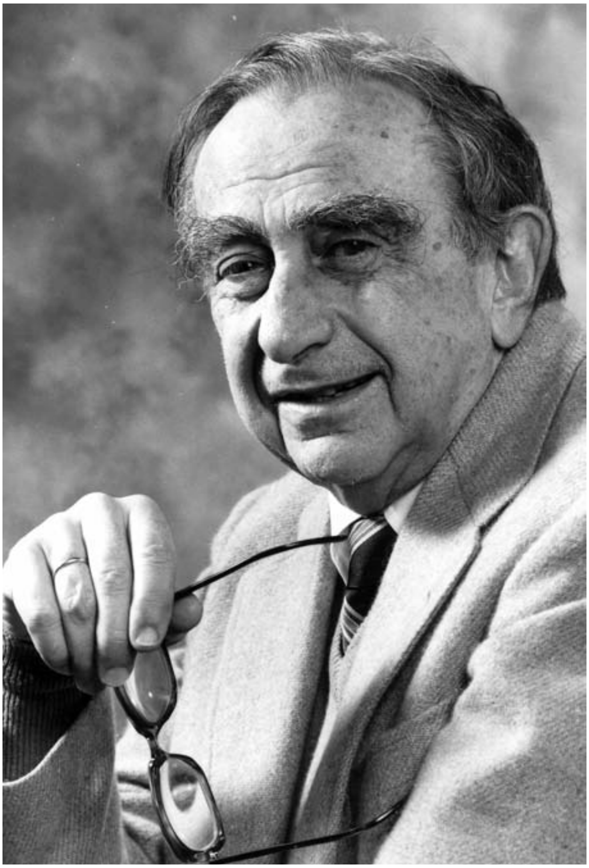
Biographical Memoir



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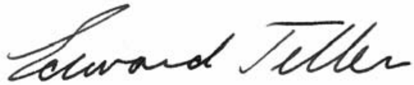

EDWARD TELLER

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BY FREEMAN J. DYSON

AT THE END OF HIS LONG LIFE Edward Teller with the help of his editor Judith Shoolery published his memoirs (2001), a lively and poignant account of his adventures in science and politics. Hostile reviewers of the memoirs pointed out that some details of his stories are inaccurate. But Teller writes in his introduction, "Our memories are selective; they delete some events and magnify others. Just the simple act of recalling the past affects the recollection of what happened. That some of my remembrances are not the commonly accepted version of events should not be surprising." Memoirs are not history. Memoirs are the raw material for history. Memoirs written by generals and politicians are notoriously inaccurate. A writer of memoirs should make an honest attempt to set down the course of events as they are recorded in memory. This Teller did. If some of the details are wrong, this detracts little from the value of his book as a panorama of a historical epoch in which he played a leading role. I have used the memoirs as the basis for this brief summary of his career.

Teller was born in 1908 into a prosperous middle-class Jewish family in Budapest. He lived through the turbulent years of World War I, the dismemberment of the Austro-Hungarian Empire, the short-lived Communist regime of Bela

Kun, and the devastating currency inflation that followed, protected by loving and resourceful parents. All through his life, from childhood to old age, he had a gift for friendship. His memoirs are full of stories about his friends and the tragic fates that many of them encountered. He cared deeply for them as individuals and described them with sympathetic understanding. He escaped from sharing their fate when he emigrated from Hungary to Germany in 1926, from Germany to Denmark in 1933, to England in 1934, and to America in 1935. He always retained an acute sense of the precariousness of human life and the fragility of political institutions. He was one of the lucky survivors of a great tragedy, when barbarians overran Europe and destroyed the world of his childhood. He saw America as the last refuge, for himself and for the civilization that he cherished. That was why he saw it as his inescapable duty to keep America armed with the most effective weapons, with bombs for deterring attack, and with missiles for active defense.

The springtime years of Teller's professional life, the years when he was happiest with his work and his friends, were the seven years between 1926 and 1933 that he spent as a student in Germany. His stay in Germany started badly. Riding a trolley car in Munich to meet some friends for a hiking trip, he overshot the meeting place, jumped off the moving trolley car, and fell under the wheels. His right foot was chopped in half. As he lay in the road assessing the damage, he thought how lucky he was not to be one of the millions of young men who had lain wounded on the muddy battlefields of World War I a few years earlier. At least he was alive, with a clean wound and the certainty of being rescued. The surgeon in Munich reconstructed what was left of his foot so that he could still walk on the heel. With the help of a prosthesis he became agile enough to go hiking in the mountains and to play a respectable game of

Ping-Pong. He observed that his mother suffered more than he did from the accident. As she sat grieving by his bedside at the hospital, he tried unsuccessfully to cheer her up. For her it was a deeply tragic event, while for him it was merely a nuisance that did not touch the important things in his life. The accident gave him confidence. As he liked to say when I got to know him 20 years later, if it doesn't kill you, it makes you stronger. The accident gave him a good excuse to leave Munich and go to Leipzig to work with Heisenberg.

The years 1926-1933 were the time when German science was blazing with creative activity while the Weimar Republic was crumbling. When Teller joined the group of young people working at Leipzig with Heisenberg as leader, Heisenberg was 28. He had invented quantum mechanics in 1925 and then invited all and sundry to join him in using quantum mechanics to understand the workings of nature. Quantum mechanics described the behavior of atoms, and so it should be able to explain everything that atoms do. It should be possible with quantum mechanics to explain all of atomic physics, most of solid-state physics, most of astrophysics, and all of chemistry. There were enough good problems, so that every student could find something important to do. Teller, having been trained as a chemist, chose chemistry as the subject to be explained with quantum mechanics. He started well by beating Heisenberg at Ping-Pong. He and Heisenberg remained friends for life. After World War II, when many American physicists condemned Heisenberg for staying in Germany through the Hitler years, Teller went out of his way to befriend him. He knew that Heisenberg had never been a Nazi, and he respected Heisenberg's decision to stay loyal to his country and share its fate.

In Leipzig Teller wrote a Ph. D. thesis (1930) on the hydrogen molecule ion, the simplest of all molecules. He was able to calculate not only the ground state but also the excited quantum states of the molecule, using an old-fashioned mechanical calculator. But he did not enjoy working alone. He much preferred the give-and-take of working together with friends. Almost all his work after the thesis was done jointly with others. During his years in Germany he collaborated fruitfully with Lev Landau, George Placzek, and James Franck, solving various problems on the borderline between physics and chemistry. As he himself said, he was a problem solver rather than a deep thinker. He enjoyed solving problems, whether or not they were important. The years 1926-1933 were harvest time for problem solvers. In those years the problem solvers laid the foundations for most of modern physics and chemistry. Teller's main contributions during this time were to explain diamagnetism in solids (1931), and to explain spectra of polyatomic molecules (1933). Both these problems required the application of quantum mechanics to systems involving many electrons.

When Hitler took power in 1933, Teller moved to Copenhagen. There he met George Gamow, a young Russian who had been the first to apply quantum mechanics to nuclear physics. In 1934 Gamow moved to George Washington University in Washington, D.C, and Teller moved to London with his newly wed wife, Mici. She was a childhood friend from Budapest who loved and sustained him through all his joys and sorrows, and remained by his side for 66 years until her death in 2000. In 1935 Gamow invited Teller to join him at George Washington University, and Mici, who had spent two years in America as a student, encouraged him to accept. During the years 1935-1939 that Gamow and Teller were together in Washington, they almost recreated the golden age of German physics in America. They found many of their European friends already in America, and quickly made new friends among the natives.

Gamow was four years younger than Heisenberg and almost as brilliant. But Gamow had no skill as an organizer and no desire to be a leader like Heisenberg. He produced brilliant new ideas at a rapid rate, and left it to Teller to work out the details. He also left to Teller the chores of administration, organizing meetings, and taking care of students. Teller worked happily with Gamow and also with other collaborators. The most important results of Teller's research during this time were the Gamow-Teller theory of weak interactions (1936) and the Jahn-Teller theory of polyatomic molecules with electrons in degenerate states (1937). The Gamow-Teller theory was in competition with an alternative theory due to Fermi. This was one of the very few occasions on which Fermi guessed wrong. The Gamow-Teller theory was Teller's first venture into nuclear physics. Twenty years later it became the basis for a unified theory of weak interactions.

One of Teller's friends in Washington was Merle Tuve, an American and a first-rate physicist who built particle accelerators and used them to do nuclear experiments at the Department of Terrestrial Magnetism of the Carnegie Institution. Tuve was one of the pioneers of accelerator physics, and made the first accurate measurements of the nuclear interaction between two protons. After Teller had spent a summer teaching in Chicago, the University of Chicago was thinking of offering him a permanent job. The Chicago physicists wrote to Tuve asking for his opinion of Teller. Tuve wrote back, "If you want a genius for your staff, don't take Teller, get Gamow. But geniuses are a dime a dozen. Teller is something much better. He helps everybody. He works on everybody's problem. He never gets into controversies or has trouble with anyone. He is by far your best choice." Teller quotes this letter in his memoirs and remarks, "I do believe it described me as I was during those happy years in Washington." He looked back on those years with nostalgia as a time when he could do science with everyone and be friends with everyone, before the bitter struggles over nuclear politics took him away from science and tore apart his friendships.

The record of Teller's publications confirms Tuve's statement. Teller in the first half of his life had an unusual gift for fruitful collaborations. I have taken 1952 as the point of division between the two halves of his life. In 1952 he moved from the University of Chicago to the new weapons laboratory that he founded at Lawrence Livermore National Laboratory in California. That was the year when he stopped being an academic scientist and became a full-time nuclear entrepreneur. In the bibliography of his technical publications there are 146 papers. Before 1952 he wrote 7 papers alone and 77 with collaborators. In that period most of his papers describe research done with one collaborator. Many of the leading physicists of that time appear as collaborators. After 1952 he wrote 42 papers alone and 20 with collaborators. In that period most of the papers are reviews or lectures, describing plans for the future or surveys of the past. The transition from a gregarious to a solitary pattern of intellectual life is painfully clear.

In January 1939 Gamow and Teller were hosts at the meeting of theoretical physicists, which was held annually at George Washington University. That year's meeting was supposed to be devoted to low-temperature physics. On the first morning of the meeting Gamow introduced Niels Bohr, who had just arrived on a ship from Denmark, and Bohr told the assembled physicists the news of the discovery of fission of uranium in Germany a month before. In the evening of the same day Merle Tuve invited everyone to his laboratory to see a demonstration of the intense bursts of ionization produced by uranium fission in a Geiger counter. The age of nuclear energy had arrived, and Teller was involved in it from the first day.

In February 1939 Teller's friend Leo Szilard called him from New York to announce that he had found abundant secondary neutrons emitted in uranium fission. This meant that an explosive nuclear chain reaction was certainly possible. In March 1939 an informal strategy meeting was held in Princeton. Present were Bohr, Wheeler, Wigner, Weisskopf, Szilard, and Teller. One American, one Dane, one Austrian, and three Hungarians. Two decisions were made; first to keep further discoveries about fission secret so far as possible, second to try to bring the situation to the attention of responsible people in the American government.

In June 1939 Teller moved from Washington to Columbia University to help Fermi and Szilard with their project to build the first nuclear reactor. In New York a few weeks before the outbreak of World War II, Heisenberg came to visit Teller. He was on his way back to Germany from a lecture tour in America. He had many offers of jobs in America and could easily have stayed. Teller asked him why he was going back to a country that was clearly headed for disaster. Heisenberg replied, "Even if my brother steals a silver spoon, he is still my brother." Teller understood that nothing he could say would cause Heisenberg to change his mind.

A few days later Szilard, who could not drive a car, came to see Teller and asked him for a ride. Szilard had written a letter to President Roosevelt informing him of the discovery of fission and the possibility of nuclear bombs. The letter asked the President to set up a channel of communication between the government and the physicists working on nuclear chain reactions in America. Szilard's plan was to persuade Einstein to sign the letter. Teller was needed as a chauffeur to bring Szilard and the letter to Einstein's summer home on Long Island. Einstein signed the letter, and Szilard successfully delivered it to Roosevelt. As a result, an official Advisory Committee on Uranium was established, and the bureaucratic machinery that later grew into the Manhattan Project slowly began to grind.

Teller worked on nuclear energy from 1939 to 1945: two years at Columbia University helping Fermi design the first nuclear reactor, two years at the Metallurgical Laboratory in Chicago helping to design the Hanford plutonium production reactors, and two years at Los Alamos National Laboratory working on bombs. In all three places he worked on a variety of projects. His wide knowledge of physics and chemistry made him useful as a liaison between different parts of the enterprise. The one thing that he could not and would not do was to sit down and do precise theoretical calculations. His thesis work, calculating the states of the hydrogen molecule ion, had given him a lifelong distaste for lengthy calculations. At Los Alamos this brought him into collision with Hans Bethe, the head of the Theoretical Division, who was Teller's boss. Bethe asked him to do a massive calculation of the physics and hydrodynamics of an imploding bomb. Teller refused, saying that if he tried to do such a calculation he would not make any useful contribution to the war effort. Teller's friendship with Bethe never recovered from this disagreement. Oppenheimer moved Teller out of Bethe's division and made him leader of an independent group. After that, Teller reported directly to Oppenheimer, and Oppenheimer kept him busy with a variety of assignments more suited to his temperament. Teller enjoyed working for Oppenheimer and considered him an excellent director.

During the wartime years Teller worked only intermittently on hydrogen bombs. This work started in the summer of 1942 when Oppenheimer held a meeting in Berkeley to explore the possibilities. The meeting concluded that if a fission bomb could be made to work, it could probably be used to ignite a hydrogen bomb. After the meeting Teller found reasons why the ignition would not work. He became seriously interested in the problem and continued to think about it. During his two years at Los Alamos he spent about one-third of his time working on hydrogen bombs. The result of his efforts was a very sketchy design called the Classical Super. The question whether the Classical Super would work could only be decided by massive calculations, using electronic computers that did not yet exist. There matters stood from 1945 to 1950.

From 1946 to 1952 Teller was a professor at the University of Chicago. He enjoyed the return to academic life and especially enjoyed interacting with a brilliant bunch of students, including Chen Ning Yang, Tsung Dao Lee, Marshall Rosenbluth, and Marvin Goldberger. Two of his closest friends, Enrico Fermi and Maria Mayer, were colleagues. During these years he worked with Fermi on the capture of negative mesons in matter (1947), with Mayer on the origin of the chemical elements (1949), and with Robert Richtmyer on the origin of cosmic rays (1949). I met Teller for the first time in March 1949 when I gave a colloquium in Chicago with Fermi and Teller sitting side by side in the front row. I spoke about the new theories of quantum electrodynamics. I made some very polite remarks about Schwinger's theory and then explained why Feynman's theory was better. As soon as I finished my talk, Teller asked a question and answered it himself. "What would you think of a man who cried, 'There is no God but Allah, and Mohammed is his prophet,' and then at once drank down a great tankard of wine? I would consider him a very sensible fellow." Afterward I was able to meet with Teller alone and he talked happily about all the things he was doing.

I quote now from a letter that I wrote to my parents in England, dated March 11, 1949.

> Teller to me has always been an enigma. He has done all kinds of interesting things in physics, but never the same thing for long, and he seems to do physics for fun rather than for glory. However, during the last few years there have been reports that he has been engaged in perfecting the most fiendish engines of destruction; and I have always wondered how such a man could do such things. In Chicago I found without difficulty the answer. I started a long argument with him about political questions, and it appears that he is an ardent supporter of the 'World Government' movement, an organization which preaches salvation in the form of a world government, to be set up in the near future with or without Russia, and to have sovereign powers over the economic and social policies of its member nations. Teller evidently finds this faith soothing to his conscience; he preaches it with great charm and intelligence; all the same, I feel that he is a good example of the saying that no man is so dangerous as an idealist.

In the same letter there is a passage describing the community of physicists in Chicago.

> The most striking thing about all these people, and also their wives whom I met as I went from house to house and from family to family, is how happy they seem to be. All of them say they have never found any place on earth so pleasant to be in as Chicago. There seems to be an exceptionally free and easy atmosphere, rather like Cornell, and with the added advantages of a metropolitan city.

These were the golden years of physics in Chicago, when Fermi was king and Teller was his court jester. Teller enjoyed those years to the full. But during those same years he could not stop thinking about the question that he had left unanswered when he left Los Alamos in 1946. Could a hydrogen bomb be made to work? In June 1949 he returned to Los Alamos to continue his lonely effort to understand what Nature allows us to do. In August the first Russian nuclear bomb was tested, and in January 1950 President Truman announced that work on the "so-called hydrogen or super bomb" would continue. After the President's announcement Teller wrote to Maria Mayer from Los Alamos. "Whatever help and whatever advice I can get from you—I need it. Not because I feel subjectively that I must have help, but because I know objectively that we are in a situation in which any sane person must and does throw up his hands and only the crazy ones keep going."

In 1950 electronic computers were able to simulate in a rough fashion the Classical Super design for a hydrogen bomb and showed that it did not work. George Gamow drew a famous cartoon of Teller trying to set fire to a wet piece of rock with a match. But to Teller the downfall of the Classical Super came as a liberation. For eight years his thoughts had been fixed on the Classical Super, which required deuterium to burn at low density, so that radiation could escape from the burning region and not come to thermal equilibrium with the matter. The idea was to achieve a runaway burn, with the temperature of the matter remaining much higher than the temperature of the radiation. The computers showed that runaway burn did not work. So Teller started to look seriously at the opposite situation, with deuterium at high density and the radiation trapped in thermal equilibrium with the matter.

Teller quickly found that at high density, deuterium could burn well in thermal equilibrium. From that point it was a short step to design an arrangement by which a fission bomb could compress deuterium to high density and then ignite it. Teller's colleague Stanislas Ulam at Los Alamos thought of a similar arrangement at the same time, and so the idea became known as the Teller-Ulam design. It was successfully tested in 1952 and has been the basis for American hydrogen bombs ever since. Andrei Sakharov had the same idea in 1954, and it quickly became the basis for Russian hydrogen bombs too. Many years later Teller and Sakharov met. They did not agree about political questions but expressed a deep respect for each other. Sakharov remarked in his memoirs that Teller's treatment at the hands of his American colleagues was "unfair and even ignoble."

In 1951 Teller returned briefly to his academic life in Chicago, but in 1952 he moved permanently to the Livermore laboratory, a brand-new weapons laboratory that his friend Ernest Lawrence had organized in California to give some competition to Los Alamos. He stayed at Livermore for 23 years, attracted a brilliant group of young collaborators, and saw the laboratory quickly rise to become an equal partner with Los Alamos in weapons development and in many other enterprises. Livermore was more adventurous than Los Alamos and more willing to try out crazy ideas. A much larger fraction of Livermore bomb tests failed, but Teller considered failed tests a badge of honor rather than a disgrace. In the end the Livermore-designed weapons proved to be as rugged and reliable as those designed at Los Alamos.

Soon after Teller moved to Livermore he was invited to testify at the Oppenheimer security hearings in Washington. At the hearings he was asked whether he considered Oppenheimer to be a security risk, and answered, "Yes." For this the majority of physicists, including many of his friends, never forgave him. The estrangement caused Teller tremendous grief. The community of physicists was split in two, and Teller became a symbol of the division. At the time when this happened I was puzzled and shocked by the violence of the reaction against Teller. To me it seemed that the main question was whether the security rules should be applied impartially to famous people and unknown people alike. It was a question of fairness. If any unknown person had behaved as Oppenheimer behaved, telling a lie to a security officer about an incident that involved possible spying, he would certainly have been denied clearance.

The question was whether Oppenheimer, because he was famous, should be treated differently. Should there be different rules for peasants and princes? This was a question concerning which reasonable people could disagree. I tended to agree with Teller that the rules ought to be impartial. And I saw no reason why people who disagreed with him should condemn him for speaking his mind. Teller's estrangement from the community of physicists became worse when three of his closest friends, Enrico Fermi, John von Neumann, and Ernest Lawrence, happened to die prematurely within a few years after the Oppenheimer hearings. Each of them died in his fifties and should have remained vigorously active for at least another 20 years. The loss of all three made Teller even more isolated as he started his new life at Livermore.

In the summer of 1956 I had one of my happiest experiences, working with Teller on the design of a safe nuclear reactor. Teller's friend Frederick de Hoffmann, a young physicist from Los Alamos, had started a company called General Atomic in San Diego to manufacture reactors for civilian use. Teller and I came for the summer with a group of physicists and chemists and engineers to help the company get started. Teller had been saying for many years that the essential problem for public acceptance of nuclear power was safety. He proposed that General Atomic should start by building a spectacularly safe reactor. His definition of safe was that you could give the reactor to a bunch of children to play with and be sure that they would not get hurt. Safety must be guaranteed by the laws of nature and not by engineered safeguards. For three months Teller and I argued furiously about the design. Every day Teller would think of some brilliant new idea and the rest of us would do calculations to show why it would not work. Finally we found a scheme that worked and used it to design a small reactor called TRIGA, short for Training, Research, and Isotope-production, General Atomic.

The TRIGA was designed, built, licensed, and sold within two years. The company sold 75 of them, mostly to hospitals for making short-lived isotopes, and they have never run into any safety problems. Teller and I had hoped that big power reactors using the TRIGA design could give rise to a nuclear power industry without safety problems. Unfortunately, the nuclear power industry was stuck with designs borrowed from the submarine-propulsion reactor program of Admiral Rickover, and never considered the TRIGA design as a serious competitor. Many years later Teller and his colleagues at Livermore developed designs for safe nuclear power reactors that could be buried deep underground, operated with a single loading of fuel for 50 years, never refueled, and never unloaded. Teller remained always hopeful that nuclear power would one day be so safe that the public would finally accept it.

Teller pushed hard to develop at Livermore other programs besides weapons development. He started a very successful educational program informally known as Teller Tech, which brought graduate students to the University of California campus at Davis. The students were enrolled in the College of Engineering at Davis and received Ph.D. degrees in applied science from Davis, but spent half their time at Livermore. Courses were taught by leading scientists at Davis and at Livermore. Teller enjoyed doing his share of the teaching. Many of the graduates remained at Livermore as members of the staff, while others went on to distinguished careers in universities and in industry.

Roughly one-half of the Livermore budget went into weapons. In addition, there was a large program to build controlled fusion reactors, both magnetic and inertial. There was a program to develop a supersonic nuclear ramjet that could fly nonstop around the world at low altitude. And there were two projects that were particularly dear to Teller's heart, the PLOWSHARE program to use nuclear explosions for peaceful purposes, and the strategic defense program to shoot down enemy missiles using X-ray lasers and brilliant pebbles. The PLOWSHARE program aimed to use nuclear explosions to excavate large masses of dirt or rock cheaply, the main purpose being to create artificial harbors and canals. To minimize the contamination of the landscape by radioactive fallout, the PLOWSHARE experts designed bombs whose explosive yield came mostly from fusion and as little as possible from fission. The X-ray laser was a device that could convert a substantial fraction of the energy of a fission bomb into a collimated beam of X rays. It was supposed to kill missiles a long way away by firing X rays at them with extreme accuracy. The brilliant pebble was a small interceptor rocket that was supposed to kill a missile by direct impact.

In the end neither the PLOWSHARE program nor the strategic defense program fulfilled Teller's hopes. None of the places that were candidates for PLOWSHARE excavations welcomed the idea with enthusiasm. Nobody had any urgent need for new harbors and canals, and as environmental regulations became more stringent the chance that any PLOWSHARE project would ever be approved became increasingly remote. Livermore's proposals for strategic defense also ran into difficulties. The X-ray laser was designed to destroy missiles in the boost phase while they were still accelerating with rocket power, but the X rays could not penetrate any considerable depth of atmosphere. As a result, the missiles could defeat the defense by accelerating more rapidly and shortening the boost phase. The brilliant pebbles were supposed to weigh a couple of pounds and turned out to weigh a couple of hundred pounds. Extravagantly large numbers of them would be required to be sure of having one at the right place and time to intercept a missile. However, the Strategic Defense Initiative that President Reagan started in 1983 embodied some of the Livermore proposals, and Teller gave it strong support.

After the Strategic Defense Initiative had spent a lot of money and accomplished very little, Teller and I went together to the Pentagon to talk with General Abrahamson, who was then running the program. Teller and I agreed that strategic defense was in principle a good idea, and that secrecy was in principle a bad idea. The SDI was a technically flawed program whose failures were concealed by excessive secrecy. Teller and I went to the general to tell him that the only way to make SDI technically effective was to abolish the secrecy and bring it out into the open. If the program were open, it might receive the expert criticism and the influx of new ideas from the outside that it desperately needed. Teller delivered the message with his usual eloquence, and the general responded by saying that of course he agreed with us, and he would be removing the secrecy within a few weeks. Needless to say, nothing of the kind ever happened. Teller remained publicly supportive of SDI but privately furious at the general for deceiving us.

In 1975 Teller retired from Livermore and became a senior fellow at the Hoover Institution on the campus of Stanford University. Here he spent the sunset years of his life, in close touch with the work of the laboratory at Livermore, writing books, and giving lectures, politically active to the end, still fighting for strategic defense and nuclear energy. At the end of his memoirs is a chapter titled "Homecoming," describing his seven visits to Hungary between 1990 and 1996. In Hungary he felt immediately at home after an absence of 54 years. He had never stopped speaking Hungarian with his wife, so that he remained fluent in the language. He was welcomed not only as a national hero but as a long lost brother. He was as proud of Hungary as Hungary was proud of him. His homecoming gave his life the happy ending that was denied to him in America.

SELECTED BIBLIOGRAPHY

1930

Über das Wasserstoffmolekülion. *Z. Phys.* 61:458-480.

1931

Der Diamagnetismus von freien Elektronen. *Z. Phys.* 67:311-319.

1933

With G. Herzberg. Schwingungsstruktur der Elektronenübergänge bei mehratomigen Molekülen. *Z. Phys. Chem.* 21:410-446.

1936

With G. Gamow. Selection rules for the beta-disintegration. *Phys. Rev.* 49:895-899.

1937

With H. A. Jahn. Stability of polyatomic molecules in degenerate electronic states. I. Orbital degeneracy. *Proc. R. Soc. A* 161:220-235.

1947

With E. Fermi. The capture of negative mesotrons in matter. *Phys. Rev.* 72:399-408.

1949

With M. G. Mayer. On the origin of elements. *Phys. Rev.* 75:1226-1231.

With R. D. Richtmyer. On the origin of cosmic rays. *Phys. Rev.* 75:1729-1731.

2001

With J. L. Shoolery. *Memoirs: A Twentieth-Century Journey in Science and Politics*. Cambridge: Perseus.