LLNL-CONF-415308

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Edward Teller Biographical Memoir

S. B. Libby, A. M. Sessler

August 4, 2009

Edward Teller Centennial Symposium
Livermore, CA, United States
May 28, 2008 through May 28, 2008

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

Edward Teller Biographical Memoir

Stephen B. Libby[1*] and Andrew M. Sessler[2]**

[1]Lawrence Livermore National Laboratory
Livermore, California 94551

[2]Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

Introduction

Edward Teller died on September 9, 2003 in Stanford, California at the age of 95. He was both one of the great theoretical physicists of the twentieth century and a leading figure in the development of nuclear weapons and broader defense advocacy. Teller's work in physics, spanning many decades of the twentieth century, includes some of the most fundamental insights in the quantum behaviors of molecules and their spectra, nuclei, surfaces, solid state and spin systems, and plasmas. In the defense arena, Teller is best known for his key insight that made thermonuclear weapons possible.

Teller took great pleasure in being counted as one of the five "Martians," brilliant émigré scientists of Hungarian – Jewish origin, all renowned for their key roles in the development and application of science in the twentieth century. The other four were Theodore von Kármán, John von Neumann, Leo Szilárd, and Eugene Wigner.

Teller was both a great scientific collaborator and physics teacher at all levels, known for his openness, generosity, personal warmth, and powerful physical intuition. Many of his graduate students went on to illustrious careers.

Involved in nuclear matters from the beginning, Teller was an early figure in the Manhattan project. In fact, in 1939, shortly after the discovery of fission, he accompanied his old friend Leo Szilárd to ask Einstein to write to President Roosevelt recommending that the United States begin to investigate the potential for nuclear arms. Later, after the Second World War, in 1952, Ernest Lawrence and Teller co-founded the Lawrence Livermore Lab in order to accelerate the development of thermonuclear weapons.

Because of his strong advocacy of defense programs, and particularly because of his role in nuclear arms, Teller was often seen as a controversial figure supporting unpopular positions on both the national and international stage. Yet, he was also not without his strong supporters and was surely influential. While any assessment of his science would easily arrive at the conclusion that his impact was great and still growing in surprising ways, a full assessment of his political role is more complex and may have to wait for a future removed from the passions of our age.

Edward Teller was elected to the National Academy of Sciences for his many important contributions to physics. Thus, it seems appropriate to us, in this Memoir, to concentrate upon this aspect of Teller's life. Therefore, the bulk of this memoir is in the section on Scientific Contributions.

The other part of Teller's life, the public aspect, has been described in many books and articles. We refer to some of them, and it would certainly be remiss not to touch upon this aspect of his life, but it seems not appropriate, or even necessary (given all the sources and critiques) to go into detail. In the later sections we very briefly – so as to give a complete picture of the man – describe the public aspects of Teller's life.

Finally, in the Concluding Section, we sum up the many sides of this remarkable, larger-than-life person.

Early Years (1908-1925) (Budapest)

Edward Teller was born in Budapest, Hungary on January 15, 1908, the second child – his two-year-old sister was Emmi – of Max Teller and his wife Ilona Deutsch Teller. His father, Max, a distinguished lawyer, was associate editor of the law journal of Hungary. His mother, Ilona, was trained as a concert pianist and, although she never performed in public, she was a very accomplished pianist. The Jewish community of Budapest was rich in culture and accomplishment, and Teller's parents were very much a part of this community.

Teller's love of music, his life-long playing of the piano, and his deep appreciation for German language and culture were received from his mother. His father had little influence upon Teller as a youth, but did play a role in his education and career choice. The years of Teller's youth in Hungary were very difficult years, and it is quite understandable that simply adequate providing for the family required his father's full attention. When Teller was only 10 years old, his father recognized his son's talent in mathematics and arranged for him to receive special tutoring from a professor of mathematics.

World War I produced severe hardship for the Tellers (and it was followed by a period of communism - only four months long, but most horrible for almost everyone) and then anti-Semitism (for the Jews were blamed for the terrible communist period). The Treaty of Trianon went into effect in the fall of 1919 and trapped Ilona and her two children in Lugos, Hungary – where they had gone for the summer and they had to stay on as the children caught chicken pox – for Lugos had become Lugoj, Romania. After eight months they were allowed to return to a greatly reduced Hungary. (The very extensive, and cultured, Austro-Hungarian Empire, having precipitated World War I, was disassembled). Thus, by the age of 12 Teller had experiences – hunger, run-away inflation, communism, anti-Semitism, and the collapse of his culture -- that would shape his life.

From age 7 to 14, Teller was greatly influenced by an au-pair girl, Magda Hesz, who knew English well, was of very sunny disposition, and only ten years older than he. Teller's mother was devoted to her children, but she was a sad person and a worrier. (For example, she had Magda walk to school with Teller until he was age 15 and Magda left for the US.) Teller was also influenced by the mathematics professor, mentioned above, and by a very fine piano teacher that he had during the brief time he was trapped in Lugoj.

At age 9, Teller entered the Minta gymnasium; prior to that his mother had almost exclusively supervised his time. Teller's experiences during his school years were similar to that of most youngsters: he was fearful at first, bullied a bit, then eventually accepted. During that time he met a friend's younger sister, Augusta Hárkányi, called Mici. Later, in 1934, Mici became Teller's wife. Their children, Paul and Wendy, were respectively born in 1943 and 1946. Also, probably due to his father's efforts, he became friendly with three young Jews, Eugene Wigner, Johnny von Neumann and Leo Szilárd all of whom were to become great scientists.

At age 17, in June of 1925, Teller graduated from gymnasium. His father wanted him to continue his studies in Germany, for the war had decimated Hungarian universities and anti-Semitism was everywhere and becoming even worse, effectively preventing Hungarian Jews from attending Universities. In contrast, the German Universities were still at the forefront of world scientific development and were also open to Jewish students. Teller wanted to study mathematics, his father wanted a practical course; they settled on chemistry. Teller's mother insisted he was too young to leave home, but finally allowed him to go to Germany in January 1926.

(This section based on "*Memoirs" by Teller and Shoolery*)

University Years (1926-1930) (Germany)

In early 1926, almost at age 18, Teller enrolled in Karlsruhe Technical Institute, which was chosen by his father with care and attention: with the I.G. Farben chemical company located in the same town, it was very good in chemistry. He was brought there, and settled into lodgings by his parents, but just a few months later moved into quarters with a grand piano. He found great pleasure in playing the piano, especially as he now was not taking lessons and under no compulsion to practice.

He majored in chemistry, but studied a great deal of mathematics; in fact he was really undertaking a double major. He found that he did not enjoy chemistry laboratory work and that he much preferred mathematics and physics. He broached a possible change of majors with his father, who then spoke with his teacher, a distant relative of his who was a professor of physics, as well as to the director of the Hungarian equivalent of General Electric (where Teller had worked during vacations). All were positive and Teller's father allowed him to switch. At the end of the semester in April 1928, Teller left chemistry for good and went to the University of Munich to study under Arnold Sommerfeld.

That summer he was able to see his-wife-to-be, Mici, a student at the University of Budapest, as she had a summer job in Germany teaching mathematics. However, one day that summer, Saturday, July 14, 1928 was a tragic day for Teller. Returning from a hike with his backpack on, he jumped off a moving streetcar, lost his balance, and his right foot was severed as the trolley rode over it. His parents and sister arrived quickly, he underwent surgery, and took many months to recover, first in Germany and then in Budapest. During that time he was visited by fellow students including Hans Bethe (2 years his senior) and then, when back in Budapest, a few hours each day by Mici. His family took good care of him, although he much preferred Mici's cheer to his mother's sadness. By the fall, Teller was fitted with prosthesis and fully recovered.

Sommerfeld had gone abroad for the year, so Teller switched schools, still again, this time to Leipzig to work with Werner Heisenberg. Heisenberg was only 6 years older than Teller, but at that time already world-known as one of the greatest physicists of the century. Teller arrived, at age 20, a few weeks late but ready, now, to do physics in a big way. Under Heisenberg were a good number of students that were to become great physicists. These included Friedrich von Weizsäcker, Lev Landau (exactly Teller's age, and already a superb physicist), Felix Bloch, Friedrich Hund, Rudolph Peierls, J.H. van Vleck, and Robert Mulliken. Teller fit well into the group and ended up making tea for the crowd, when they met once a week. Heisenberg, at that time a bachelor, spent much time with the students, doing physics, enjoying socializing and playing ping-pong. Teller was profoundly influenced by Heisenberg, and revered him all his life. It is interesting to note, as Teller did, given the controversy in subsequent years about Heisenberg's activities under the Nazis, that nationality, religion, and political opinion played no role in Heisenberg's interaction with his group in Leipzig

Within a few weeks of arriving, Heisenberg put Teller to the task of sorting out, a controversy about the ground state of the hydrogen molecular ion. Teller was able to quickly determine the right answer. Heisenberg then put Teller to the task of determining the higher energy levels and this work became his PhD thesis that he received in January 1930 just as he turned 22 and only 2 years after formally turning to physics.

(This section based on "*Memoirs" by Teller and Shoolery*. See also "*The Martians of Science*," by Hargittai)

Scientific Contributions

Edward Teller began his work in theoretical physics just after the formulation of quantum mechanics by Bohr, Heisenberg, Born, Schrödinger, Pauli, Jordan and Dirac. With the avenue open to the detailed understanding of atomistic phenomena, he and his contemporaries, trained in Germany, who included Van Vleck, Oppenheimer, Bethe, Bloch, Landau, Herzberg, and many others, successfully applied the new framework to the analysis of diverse areas of physics and chemistry. Teller's own work eventually included key early steps in quantum chemistry, molecular spectroscopy, quantum theory of magnetism, and nuclear physics. Later, he made key contributions to statistical mechanics, and the physics of solids, surfaces, and plasmas. In many cases, his contributions are widely known parts of the canon of twentieth century physics: examples include Gamow-Teller transitions, the Lyddane-Sachs-Teller relation, the Jahn-Teller effect and theorem, Goldhaber-Teller resonance, the "BET" equation of state, the Ashkin-Teller model, and the MR^2T^2algorithm. It is also interesting to remark that several of his papers that were initially somewhat less well known, such as the papers on diamagnetism, level crossings, many body valence bases, and the dissipation of sound have significant present ramifications.

When Teller began his work in Leipzig in 1929 as Heisenberg's student, he began the study of molecules again, but now from a theoretical physicist's perspective. Born, Oppenheimer, Heitler, London, Pauling, Hund, and others were then laying down the foundations of quantum chemistry. Teller was soon to become a leading figure in the field. Appropriately, Teller's thesis was about the simplest molecule, the hydrogen molecular ion. Heisenberg drew Teller's attention to the disagreement between the calculations of Carl Jensen Burrau and A. H. Wilson on the binding of the H_2^+ ion. In a detailed analysis applying both considerable analytic and numerical power, Teller resolved the argument in Burrau's favor and went on to study the excited states. Teller always enjoyed telling a story from that time that illustrated his close relationship with Heisenberg. When he was working on his thesis, Teller lived in Heisenberg's house and worked on his numerical calculations on a noisy mechanical calculator at all hours. Heisenberg would politely inquire on the status of the calculations and finally declared the thesis complete when he tired of the machine's racket.

Teller's next foray into molecular physics was influenced by a puzzle he remembered from his earlier training in Chemistry at Karlsruhe. It appeared that the spectroscopic shifts of the excited states of methyl halides were in contradiction with the basic separation of scales implied by the Born-

Oppenheimer approximation. In collaboration with his friend László Tisza, whom he had known since their days competing in the Hungarian Eötvös competitions, he carried out the first example of a detailed analysis of the consequences of vibrational-rotational coupling in polyatomic molecules. The paradox was resolved, and Teller began a series of papers giving a comprehensive analysis of these couplings and their spectroscopic consequences in general molecules.

Important collaborators in molecular physics from that time, first in Leipzig, then Göttingen, Copenhagen, and London, and finally in Washington include Gerhard Herzberg, James Franck, Lev Landau, Herta Sponer, G. Pöschl, George Placzek, E. Bartholme, Karl Weigert, Bruno Renner, R. C. Lord, F. O. Rice, G. Nordheim, A. Sklar, Robert Mulliken, B. M. Axilrod, Karl Herzfeld, George F. Donnan, Bryan Topley, R. F. Haupt, R. J. Seeger, Hermann A. Jahn, and Tisza.

An important theme in Teller's thinking that was to have significant, surprising later consequences in many branches of physics and chemistry began with the analysis of situations where the Born-Oppenheimer approximation breaks down. Under normal circumstances, if the electronic states are well separated in comparison to the matrix elements of the vibronic coupling due to the nuclear motion, the corrections are perturbative. The Jahn-Teller effect arises in the opposite extreme: when the electronic terms are degenerate, for example, if there is orbital electron symmetry. Then, they found that the molecule inevitably deforms in a non-perturbative way causing the terms to be concomitantly split, resulting in a unique ground state. Normally, under this circumstance, the conditions for the Jahn-Teller deformations involve the zero eigenvalues of a matrix that is linear in the nuclear perturbations – whence the problem becomes one of group theoretic classification of the relevant polyatomic "wiring" as discussed in Jahn and Teller's 1937 paper.

Teller always credited Landau with stimulating his thinking in this direction and said that the famous result should be called the "Landau-Jahn-Teller effect." Teller also set his student, Bruno Renner, to study the exceptional cases (such as the CO_2 molecule) where the deviation from perfect degeneracy is quadratic in the nuclear motion and then the orbital electron symmetry can be maintained.

The Jahn-Teller effect turned out to be widespread in polyatomic and condensed matter systems. A currently famous example is the deformation of the CuO_6 octahedral complex in the K_2NiF_4 type unit cell of Müller and Bednorz's undoped perovskite high Tc superconductor precursor La_2CuO_4.

Another fascinating example of the breakdown of the Born-Oppenheimer separation of scales discussed by Teller is connected with a generalization of the well-known 1929 result of Eugene Wigner and John Von Neumann on quantum mechanical level repulsion in the case of a single real Hamiltonian tuning parameter. In molecular physics, the issue is whether one can enforce electronic level crossings by, for example changing the separation of two constituent atoms as would occur dynamically in a scattering experiment. In the diatomic case, there is one real length parameter, and the Wigner-von-Neumann theorem says that level crossings are avoided. Teller realized that, for example in three body interactions such as the simple case of H^3, level intersections, now controlled by two real degrees of freedom, could occur. Many years later, in 1962, Teller's old colleague Gerhard Herzberg and H. Christopher Longuet-Higgins analyzed the consequences of Teller's result for the global behavior of the wave functions in systems with this type of level crossing and discovered that it was multi-valued, thus producing the first molecular physics example of Berry's topological phase.

Teller first met Lev Landau in Leipzig and they worked together a few years later in Copenhagen. In addition to their fruitful discussions of the symmetry of complex molecules, they also developed a quantum mechanical description of sound dispersion and attenuation based on the idea of the dephasing of sound modes due to their coupling to internal degrees of freedom of the molecules in the medium. This led to immediate predictions of the damping rate dependence on molecular composition and temperature.

Later, in 1941 during the early years of the Second World War, before either Teller or Hans Bethe had official connections with the Manhattan Project, they carried these ideas further in a detailed study of the deviations from thermal equilibrium in shocks under the auspices of the Army Aberdeen Research Laboratories. Their work proved critical to subsequent work on hypersonic ballistics in atmospheres. Bethe says in his commentary on their report, that they were motivated to contribute to the defense effort and approached von Karman, who suggested the problem. Shortly after that, when Teller was at Columbia University, Arthur Kantrowitz carried out the first experiments to measure these deviations from equilibrium in shocks and Teller sponsored his thesis on the subject. Kantrowitz later went on to become a leading authority on hypersonic flight and was the inventor of hypersonic molecular beam sources.

Teller continued to have a close relationship with Heisenberg after leaving Leipzig for Göttingen in 1930. On a return visit to Leipzig, Heisenberg posed to Teller the conundrum offered by Lev Landau's 1930 quantum computation of the diamagnetic susceptibility of a free electron gas. The problem of diamagnetism was known to be outside the realm of classical physics because of an argument due to Bohr and van Leeuwen. There should be no classical diamagnetism at all since in a classical computation of the partition function, the influence of an external vector potential can be absorbed into the momentum sum. Heisenberg challenged Teller to give a more transparent physical argument explaining why Landau was correct. Teller did so in terms of the quantum population and current of what one would now call the skipping orbit or "edge state," at the boundary of the sample. It is interesting to remark that Teller's edge state picture later reappeared usefully in the de Haas - van Alphen effect, and the quantum Hall effect.

Also, in Göttingen, in 1932, Teller worked out, with the Russian physicist Georgi Rumer and Hermann Weyl the rules for suitable expansions of many spin wavefunction bases in terms of simpler spin eigenfunctions in a manner similar to Pauling's contemporaneous idea of valence bonding. While this theorem is not as well known as some of Teller's other papers, it is interesting to note that it was independently rediscovered at least twice: by Penrose, and then by Temperley and Lieb. More recently, this theorem has been useful in the analysis of spin chain states pertinent to Mott insulators.

One other result from Teller's time in Göttingen might be mentioned. With Herta Pöschl, he discovered a class of one-dimensional potentials that allowed for an analytic solution to anharmonic behavior. Subsequently, these reflection-less "Pöschl- Teller potentials have appeared in diverse areas of mathematical physics, most recently in the study of squeezed optical states.

After the Nazis came to power in 1933, conditions for Jews in Germany rapidly deteriorated and Teller left the country taking two temporary positions in 1934-1935, first to Bohr's Institute in Copenhagen, and then University College in London (the latter position made possible by the Rockefeller Foundation). The "Jahn-Teller" theorem, the culmination of the European phase of his career was worked out there. In 1935, George Gamow recruited Teller to a professorship at George Washington University, in Washington, D.C. There, his research focused on nuclear physics, early forays into astrophysics, the physics of dense plasmas, and solid state and statistical physics.

At George Washington University, Teller's fruitful collaboration with Gamow included their famous discovery of the "Gamow-Teller" transitions in beta-decay. This paper, written in 1936, reflects the rapidly developing, heroic period of nuclear physics in the 1930s. Two years earlier, Enrico Fermi had proposed his theory of beta decay, exploiting both Pauli's neutrino hypothesis and an analogy with electromagnetic interactions. One of the consequences of Fermi's theory was that non-zero nuclear spin changes ΔJ were inevitably accompanied by final state multipole suppression factors of at least two orders of magnitude. Gamow and Teller soon realized that these Fermi selection rules were at variance with some of the decay schemes of the "thorium active deposit," and proposed a second set of decay matrix elements allowing for spin flips upon decay. In modern relativistic notation, they proposed to amend Fermi's Hamiltonian with the added pieces:

$$\boldsymbol{H} = \sum \boldsymbol{C}_A(\overline{\Psi_p}\gamma^\mu\gamma_5\Psi_n)(\overline{\Psi_e}\gamma_\mu\gamma_5\Psi_\nu) - \boldsymbol{C}_T\tfrac{1}{4}(\overline{\Psi_p}[\gamma^\mu\gamma^\rho - \gamma^\rho\gamma^\mu]\Psi_n)(\overline{\Psi_e}[\gamma_\mu\gamma_\rho - \gamma_\rho\gamma_\mu]\Psi_\nu) + \boldsymbol{h.c.}$$

Here, "axial" and "tensor" couplings were assumed to be of same order of magnitude as their scalar and vector analogs in Fermi's original theory.

"Gamow-Teller" transitions complemented Fermi's original matrix elements, playing a very important role in the rapidly developing field of nuclear and particle beta decays, leading eventually to Lee and Yang's discovery of parity violation, the proposal of the V-A theory of the fundamental weak interaction (which require the Gamow-Teller terms) and finally to the standard model.

Interestingly, in a short 1937 follow on letter, Gamow and Teller point out, for the first time in the literature, the possible existence of weak neutral currents.

It is also interesting to recall that their proposal, while playing a key role in fundamental physics, had an immediate, dramatic consequence in astrophysics. At that time, Hans Bethe was developing the theory of stellar nucleosynthesis, and realized that the Sun was too cool to be driven by his CNO cycle. Immediately after Gamow and Teller proposed their 'spin-flip' modification of the Fermi theory, Bethe, with Gamow, and Charles Critchfield (Teller's student) realized that the Sun could be powered by the “pp chain” with the basic reaction being the weak interaction $p + p \rightarrow D + e^+ + \nu_e$. This reaction is pure “Gamow-Teller” because of the Pauli principle and the deuteron’s angular momentum (one).

Teller’s work in nuclear physics during the pre-war period at George Washington also included his 1937 papers with Julian Schwinger laying out the phase-shift analysis, including interference effects, for low energy neutron scattering off hydrogen molecules. During this time, Teller also worked with Wigner, John Wheeler, L. Hafstad, and his student Critchfield on forces and collective and rotational excitations in nuclei.

With Gamow, Teller also carried out one of the earliest studies of the temperature dependence of thermonuclear reaction rates and applied their ideas to an investigation of energy production in red giant stars.

During the late 1930’s Edward Teller also began to turn his attention to statistical and solid state physics. With his student Stephen Brunauer, and Paul H. Emmett, a chemist and catalysis expert at the Department of Agriculture, he gave a widely applied theory of physio-adsorption of gaseous species on substrates. The “BET” model isotherm extended Langmuir’s analysis of monolayer adhesion to the formation of puddles of adsorbate whose depth was controlled by balancing the simultaneous tendencies in equilibrium to evaporate and adhere. The “BET” model is typically applied to the determination of adsorbate areas in catalysis.

In 1941, Teller with his co-workers Robert G. Sachs (later Director of Argonne National Laboratory), and Russell Lyddane gave a general rule for the ratio of asymptotic values of the dielectric constant of a polar crystal like NaCl in terms of the frequencies of transverse and longitudinal optical phonon modes:

$$\omega_T^2/\omega_L^2 = \varepsilon(\infty)/\varepsilon(0)$$

This simple rule comes about from the realization that the poles and zeroes of the dielectric function are constrained by Gauss's law. Of wide applicability, the divergence of $\varepsilon(0)$ as ω_T goes to zero has important implications for ferroelectricity.

The Lyddane-Sachs-Teller relation also had an important consequence, by analogy, in nuclear physics. In 1948, several years after LST, Maurice Goldhaber, thinking about Baldwin and Klaiber's experiments showing a ubiquitous rapidly varying photo-nuclear cross-section at high energy, realized that they might be explained by a collective resonance phenomenon similar to the "reststrahl" band in polar crystals. He sought out Teller, and together they predicted universal, giant photo-resonances in nuclei.

In the early years of the war, during Teller's time on the faculty at Columbia, he supervised Julius Ashkin's thesis on a generalization of the 2-dimensional Ising model allowing for two different bond strengths. They were motivated by the desire to discover variants of the basic Ising ferromagnet that retained Kramers-Wannier duality mapping between low and high temperature phases. In the context of the mathematical physics of phase transitions, their model came to take its place in the set of exactly soluble two-dimensional models. Philosophically, it is interesting to note, that when one of us, SBL, told Edward about the beautiful work done in the 1980's analyzing two dimensional phase transitions (such as in the Ashkin-Teller model) with conformal symmetry, he was fascinated, but also eager to know if there was any practical application. This was a typical reflection of Teller's conviction that the most interesting basic discoveries have practical applications.

While at George Washington University, Teller began to think about what are now termed "high energy density" plasmas: that is, plasmas of densities above that of air (10^{-3} gr/cc) and pressures exceeding 100 kilobars. This subject, with its obvious ramifications for astrophysics, the Manhattan project, the hydrogen bomb, and more recently, "inertial" fusion was to interest him for the rest of his life. In 1939, with David Inglis, he proposed a theory of the lowering of the continuum in dense plasmas. Based on the intuitively appealing idea that the Rydberg states of excited ions in plasmas meld into the continuum as their Stark splittings due to neighboring ions approach the level spacing, the theory is still widely applied in treatments of the opacity and equation of state of plasmas. Later, as an outgrowth of the concern with equations of state of hot dense matter in the Manhattan project, he, with Richard Feynman and Nicholas Metropolis extended the Thomas-Fermi model of the atom to finite temperatures, producing a practical equation of state model for high energy density plasmas.

Teller's interest in the Thomas-Fermi method was not restricted to its implications for equations of state. In a short paper, written in 1962 honoring his old friend Eugene Wigner's 60^{th} birthday, he showed that molecular binding is impossible in the Thomas-Fermi and Thomas-Fermi-Dirac approximations. Later, Elliot Lieb and his collaborators exploited Teller's reasoning in their study of the properties of matter under the Thomas-Fermi-Dirac and Thomas-Fermi-Weizsacker approximations.

In 1941, with Gregory Breit, Teller addressed the two-photon decay lifetimes of the metastable states of hydrogen and helium that occur in very dilute gases. Though an early, very influential analysis of two photon processes, the result was less important than originally thought, for in many practical plasmas there are small relativistic corrections to the states allowing single photon decay to compete with two-photon decay.

Later, after the war, while they were working together on the hydrogen bomb, Teller and Frederick de Hoffman worked out the generalization of the Rankine-Hugoniot relations for shocked gases to the case of relativistic magnetohydrodynamics. Soon thereafter, Enrico Fermi exploited these ideas in his theory of cosmic ray generation. With Richtmyer, at that time, Teller also worked on cosmic ray generation mechanisms.

Edward Teller's most influential collaboration aimed at practical equation of state computations resulted in the "Metropolis" or "MR^2T^2" method for Monte Carlo calculations in statistical mechanics. This was done in 1953 with Nick Metropolis, Marshall Rosenbluth (who had been Teller's student at Chicago), and Arianna Rosenbluth, and Mici Teller. Recently, in a paper written to celebrate the 50^{th} anniversary of their now famous algorithm, Rosenbluth gave a beautiful description of the path toward its discovery and the initial applications. During the crucial period developing Teller's concept for the hydrogen bomb, Teller created a theory group devoted to the necessary calculations. One of the tasks was to compute a wide variety of equations of state and, with Teller's encouragement, they began to investigate computational methods to accurately approximate the needed statistical ensembles in order to compute the required expectation values. The Monte Carlo method, recently invented by Stan Ulam and applied to neutron-matter interactions, seemed natural, but in this case, many of the possible configuration space points were of very low *a priori* probability because they were weighted by the Boltzmann factor $\exp(-E/kT)$. Their idea, which Rosenbluth says Teller invented, was to develop appropriate configurations by starting with a representative one at the temperature in question and testing trial "moves" with the following rule: accept the move if the energy decreases, and if it increases, accept it with the probability $\exp(-\Delta E/kT)$, with ΔE the difference in the energies of the two states. Seen from the viewpoint of computational compression, the MR^2T^2 algorithm is surely one of the most powerful in human history. As a point example, suppose one desired to compute expectation values of a quantity like magnetization in the 2 –D Ising model on a 100x100 lattice. The normal Boltzmann sum involves 2^{1000} terms, beyond the reach of any computer. However, application of MR^2T^2 produces a decent answer in perhaps 10^6 steps (depending on temperature).

Later, at Livermore, Teller continued to encourage the applications of large scale computing and in particular the computation of equations of state.

There, 1966, working with Stephen Brush and Harry Sahlin, he carried out the first Monte Carlo analysis of the liquid-solid phase transition in the one-component plasma.

In the late 1950's both the development of the mirror-machine concept for magnetically confined fusion and the discovery of the Van Allen belts stimulated Teller and Theodore Northrop to address the question of the stability of the motion of point charges in a dipole magnetic field. Having discovered a new, approximate, "third" adiabatic invariant for the Earth's imperfect dipole field, they conjectured that the problem might be in fact exactly soluble, like the Kepler problem, thereby giving an insight into the stability of the belts. Interestingly, about fifteen years later, Alex Dragt and John Finn showed that even the perfect dipole problem is not integrable, therefore leaving open the role of the Teller-Northrop invariant in such stability questions.

During the period after the war and before he moved to California, Teller divided his time between the University of Chicago and Los Alamos. At Chicago he had many of his old, close friends as colleagues, including Enrico Fermi, James Franck, and Maria Mayer. There, with Fermi and Victor Weisskopf, Teller, by carefully studying how a strongly interacting particle had to stop and decay in matter, showed definitively that the then newly discovered muon could not be Yukawa's hypothesized carrier of the nuclear force.

Maria Mayer collaborated with Teller though the 1940's. Their 1949 paper "The Origin of the Elements" was an early attempt to understand heavy element nucleosynthesis. Teller also frequently told an interesting story about how Maria Mayer began the field of complex radiation opacities. Early in the Manhattan project, Teller began to wonder if the fission device could fail because of losing too much energy by radiation. This question relied on radiative opacities but, because heavy elements were involved, of a much more complex nature than the opacities that had been considered in the astrophysical community. Teller obtained Oppenheimer's permission to ask Maria Mayer to consider the general question of such complex opacities. Her work, and subsequently that of her students Harris Mayer (no relation) and Boris Jacobson were the first significant steps in computing opacities with appreciable contributions from bound-bound absorption.

At Chicago, he also had many of his best students, including Chen Ning Yang (whose thesis was a beautiful generalization Teller and Emil Konopinski's paper on deuteron-deuteron reactions, and who later won the Nobel Prize for the co-discovery of parity violation, with T. D. Lee), Marshall N. Rosenbluth (the leading plasma physicist of the modern era), and Marvin Goldberger (a major figure in particle physics and later President of Caltech and Director of the Institute for Advanced Study), Walter Selove (a particle physicist and Professor at the University of Pennsylvania), and Lincoln Wolfenstein (a particle physicist and Professor at Carnegie Mellon who later co-invented the 'MSW' mechanism for neutrino oscillation).

Teller's characteristic drive to apply the leading results of basic science is illustrated by the following anecdote from late in his life.   To the end of his life, he often sought out colleagues to discuss the most exciting developments in all areas of science, from the most fundamental to the applied. Around 1998, when one of us (SBL), was telling him about quantum chromodynamics, it was initially difficult to convince him that this was indeed the correct underlying theory of the strong interactions. We tried many tacks. However, the moment I showed him the charmonium and bottomonium spectra, he got it right away, because we had been talking about asymptotic freedom and he saw the analogy of the bottomonium spectrum to positronium. After savoring this point for a few moments, he said: "You have finally convinced me! Now I have another question for you. I know from my own early work, that the moment quantum mechanics was elucidated, we could say many new things about molecules chemists didn't know because we knew the underlying mechanics. What can you now tell me about low energy nuclear physics that we didn't know before?"

(See also, *"Edward Teller's Scientific Life" by Libby and Weiss*)

Los Alamos

Work, in the US, on a nuclear weapon was initiated immediately after nuclear fission was discovered by Strassmann and Hahn and explained by Meitner and Frisch. Niels Bohr brought the news in January of 1939, to George Washington University, where George Gamow and Teller were running the fifth theoretical physics conference. As already mentioned, later that year, Teller drove Szilárd out on Long Island where Einstein signed his famous letter to President Roosevelt.

The idea of fission precipitated experimental work to develop a working reactor and obtain the needed materials through gaseous diffusion, electromagnetic separation and reactor generation of plutonium. There was, however very little theoretical work, and actual thinking about possible bomb designs prior to the summer study which Oppenheimer called in Berkeley in the summer of 1942. The small group (only 9) included some of the best theoretical physicists in the country, including Teller. Interestingly enough, the group focused not upon the A-bomb, but rather on a thermonuclear weapon (later to be called the H-Bomb).

Later in 1942, the Manhattan Project under Leslie Groves was formed and Oppenheimer was selected as leader of the effort. He selected the remote site of Los Alamos. Of course many books have been written about that work, perhaps the most comprehensive popular book the one by *Richard Rhodes* and the most extensive unclassified technical history by *Lillian Hoddeson et. al.* See also the very thorough "*Brotherhood of The Bomb*," by Gregg Herken. Here, we limit ourselves to only briefly discussing Teller's role in the effort.

After the initial organization of Los Alamos, Oppenheimer selected Bethe to be head of the theoretical group and this choice was a deep disappointment to Teller for he had worked longer on the atomic bomb project, had helped in recruiting, and helped Oppenheimer in getting Los Alamos launched. Perhaps that was instrumental in determining Teller's role at Los Alamos, for one would have to characterize him, during the war years, as somewhat outside the main effort. He declined, when asked by Bethe to lead the effort on detailed implosion calculations (crucial to a plutonium bomb). He did attend meetings and often made significant suggestions, contributed significantly to the lab's criticality test reactors, and was credited by Bethe for coming up with a crucial idea, but his main activity during that time was almost exclusively on the H-Bomb or "Super." With Oppenheimer's support, Teller assembled a small group of researchers who focused on this project. They included Emil (Kayski) Konopinski, Egon Bretscher, Cloyd Marvin Jr., Geoff Chew, Stan Ulam, Stan and Mary Frankel, Eldred Nelson, Nick Metropolis, Harold and Mary Argo, Henry Hurwitz, and Rolf Landshoff. One well known result of his group was the verifying calculation that the atmosphere would not be ignited by the atomic bomb. By the end of the war, Teller's group had produced a preliminary design for the "Super." Ironically this early work, which likely was secretly transmitted by Klaus Fuchs to the Soviets, would not have resulted in a weapon.

The Hydrogen Bomb

There is no question that the most important event in Teller's life was the concept, design, construction, and successful operation of the thermonuclear, or 'hydrogen' bomb. Teller was, with out question, the true "father of the hydrogen bomb", for Teller's interest in a fast fusion reactions, goes back at least to the summer study in Berkeley in 1942. And, of course, he spent the war years thinking about and directing a small effort on the

“Super”. Subsequently, he was relentless in his pursuit to construct a bomb far more powerful than the uranium or plutonium bombs of WWII.

There have been many books written on the genesis of the hydrogen bomb (see for example, “Dark Sun: The Making of the Hydrogen Bomb” by Rhodes) and we shall not go into those details that are described in these books. Suffice it to note that Teller spent vacations from the University of Chicago (where he had gone after spending the war years at Los Alamos) visiting at Los Alamos. Then in 1950 he went there to make the hydrogen bomb a reality. He recruited Emil Konopinski, Marshall Rosenbluth (just a few years after being a student of Teller), John Wheeler, Ken Ford, John Toll, and others. In addition, Conrad Longmire and Freddie de Hoffman worked with the group. Soon Johnny von Neumann, Stan Ulam, and Cornelius Everett had independently showed that the original Super would not work. Teller then had the crucial idea of radiation driven compression which, when coupled with Stan Ulam’s independent idea of ‘staging’, produced a practical design for a thermonuclear device. Together they wrote a report on this idea. It was this new idea for the hydrogen bomb that changed the view of the General Advisory Committee and the Atomic Energy Commission and led to the decision by President Truman to proceed with the development of the hydrogen bomb. Of course, the rapidly changing world political situation from 1948-1950, beginning with the Berlin crisis, the communist victory in the Chinese civil war, the successful Soviet atomic bomb test, and the communist invasion of South Korea also played a role in Truman’s decision.

There were tests of parts of the idea, a lot of theoretical work at Princeton when John Wheeler returned there in 1951 (bringing along with him a number of distinguished physicists and recruiting others), and finally the culminating test of Richard Garwin’s detailed design, at Bravo near Bikini atoll.

There are many details of the story, which are left out here. We have only presented the bare outlines of the story, but it should be clear that the hydrogen bomb was the result of many individuals' efforts, over several years. Teller acknowledged this in a 1955 article in Science entitled "The Work of Many People." However, the driving force was, without question, that of Teller, who had key ideas and was involved with the pure and applied science, sociology, administration and politics, all at the very highest level.

"In the Matter of J. Robert Oppenheimer"

There is no doubt that the single most important event in Teller's post war emotional life was the security hearing for J. Robert Oppenheimer. Though surely significant for Oppenheimer, it was perhaps even more so for Teller. One can readily see this in Teller's Memoirs, where relatively little space is devoted to scientific accomplishments, but the most space is devoted to political matters and the security hearings, and their consequences. In fact, the only Appendix in that book is devoted to a transcript of Teller's testimony.

It seems that Teller changed his view even during the interview. He was – he says – very much influenced by the evidence presented to him just before the testimony, that Oppenheimer (many years earlier) had not told the truth to security agents. Teller uttered the damning words, " I would like to see the vital interests of this country in hands which I understand better and therefore trust more". And later in the interview, "one would be wiser not to grant clearance". However, he did not question Oppenheimer's loyalty to the country, stating an earlier part of the testimony "Dr. Oppenheimer's character is such that he would not knowingly and willingly do anything that is designed to endanger the safety of this country". Most would have thought that this was the subject of the hearing, and if Teller had stopped there, his future world would have been very different. Perhaps Teller did not want to see, in a powerful position, a person whose views were different from his own and who had actively opposed the development of the Hydrogen Bomb, and he went on with those damning words.

The consequences – ostracism and insults from many of his friends (but not all) and general alienation by the community, came as a surprise to Teller. The effect was a change in his life. To be sure, he gathered, in the many years after 1954 many new friends (especially younger people), and some of his old friends – such as von Neumann, Szilárd, Wigner, Fermi, Maria Mayer, Luis Alvarez, John Wheeler, and Ernest Lawrence – remained friends, but many did not and Teller became quite isolated from most of the American scientific community.

Teller describes, in his memoir, his testimony as "stupid". In retrospect, probably everyone would agree, for it seems likely that Oppenheimer would have been stripped of his clearance even without Teller's testimony; whereas the testimony did great harm to Teller, probably more harm than it did to Oppenheimer.

Livermore

Immediately after the early promising results applying the Teller-Ulam concept to the creation of a workable hydrogen bomb, Lawrence and Teller advocated the founding of a second nuclear weapons lab to accelerate its development. In 1952, the Lawrence Radiation Lab branch at Livermore (later the Lawrence Livermore National Laboratory) was founded about 50 miles east of San Francisco on the site of a square mile Naval air station built during the war. The Livermore lab was established under the auspices of the University of California for the Atomic Energy Commission as part of the Lawrence Radiation Laboratory, which up until that time had exclusively been in Berkeley, except for some small activity at the very location selected for the Livermore site. Beyond Lawrence and Teller, the founding and early prominent figures included Herbert York (who was the first director), Harold

Brown (later Livermore Director, President of CalTech, and Secretary of Defense) John S. Foster Jr., (later Livermore Director and subsequently serving in several senior defense positions), Michael May (Later Lab Director and then Professor of Management Science and Engineering at Stanford), Roger Batzel (later Lab Director), John Nuckolls (later Lab director), Duane Sewell (who managed lab operations), and many other talented scientists and engineers, often with University of California pedigrees.

From the beginning the Livermore lab was characterized by an entrepreneurial, can-do stance. This approach reflected both Teller and Lawrence's personal philosophy that melded a deep interest in basic science and the desire to discover and push through important applications of that science. Probably also reflecting a kind of West Coast, 'frontier' egalitarianism in a manner similar to its 'cousin,' the Lawrence Berkeley Lab, the Livermore lab was quick to seize on the talents of its diversely educated population.

The Livermore lab was soon competing with Los Alamos in the development of thermonuclear devices. An important break point occurred in 1956 at the 'Nobska' meeting called by the Navy to explore concepts for submarine launched ballistic missiles. There, Teller famously shocked his new Livermore colleagues into action by forcefully arguing the feasibility of building lightweight thermonuclear weapons that could be carried by a practical submarine launched missile. The lab succeeded in developing the warhead for the Polaris missile system – the first of many innovative contributions to the US nuclear deterrent.

As was true of Los Alamos, the Livermore lab, under Teller's guidance was a trailblazer in the application of computers to scientific simulations. As the thermonuclear effort required the development of radiation hydrodynamics codes that could do useful calculations, an early spin-off in the 1950's was the application of computational physics to astrophysics and hydrodynamics. Early key papers were written at Livermore by May and Richard White, Jim Wilson, Chuck Leith, and Sterling Colgate. Likewise, in an outgrowth of their work on equations of state, Berni Alder and Tom Wainwright, doing molecular dynamics simulations in the early 1960's made major discoveries in phase transitions of 2-D systems and in the behaviors of fluids.

As has been noted above in our description of his scientific achievements, Teller had been fascinated by "high energy density physics" since his time at George Washington University. It was therefore natural that he strongly encouraged innovative, basic and applied work at Livermore in this area. Key examples are the development of the inertial fusion concept and x-ray lasers. The idea of inertial fusion driven by high-energy lasers or particle beams was an outgrowth of defense activities in the 1960's and quickly became a large program in its own right. Likewise, x-ray lasers were developed in innovative synergy between defense programs and the laser program. In 1971 there was a formal separation of the two branches of the Radiation Laboratory. The lab in Berkeley was to do no classified work and was re-named The Lawrence Berkeley Laboratory. The lab at Livermore was called the Lawrence Livermore Laboratory. Both labs now reported directly to the president of the University of California

The Plowshare Project

Many of those who were at Los Alamos were interested in three general areas in which nuclear energy might be applied. The first was nuclear weapons; the second generation of power and the third was in civil engineering. Teller was certainly interested in nuclear power, and made some interesting suggestions (such as putting nuclear power plants underground). However, his main interests in nuclear matters were in nuclear weapons and the possible peaceful applications of nuclear explosives such as civil engineering. That Teller was very interested in using nuclear explosives for peaceful purposes one could psychoanalyze, but it is also true that Teller had a great faith in technology and deeply believed that nuclear explosives could be used to make life better. With this motivation he created a program, in 1958, at the Lawrence Livermore National Laboratory, called "Plowshares". This program was rather controversial and aspects of the story is detailed in a critical book by O'Neill *("The Firecracker Boys" by O'Neill*).

After some successful tests in Nevada, Teller explored various possible sites for earthworks using Plowshare explosions. One possibility explored was a new canal to replace the Panama Canal, another was a harbor in Alaska. The latter idea was well received by the officials in Alaska, but certainly not by the ecologists, geologists, and biologists at the University of Alaska or by the local (Inuit) population. The fall-out, the ecological damage and the social disruption had been grossly underestimated, while the economic benefit of the harbor had been exaggerated.

Attention was given to various overseas uses, such as a project in Australia, one in Israel (bringing sea water to the Dead Sea), and others in Thailand, Singapore and Japan. However, Teller soon learned that no site in other countries was possible.

Attention then went in a very different direction; namely, using underground nuclear explosions to increase the production of gas and oil wells. Here there were a number of demonstrations and technically the results were very positive. One Utah test, in 1967, called Gasbuggy, increased gas production by a factor of six, another test, in Colorado, in 1969, called Rulison, increased well production by a factor between 10 and 15. Again, public concern about radiation (in this case quite unfounded) brought the activity to a halt.

Soon, the Plowshares Program, without ever having accomplished its original goal of moving nuclear explosions into a program that would directly benefit society (rather than, at best, protect it) was terminated. All in all, the very idea of using nuclear explosions in a peaceful way was not one of Teller's best initiatives. Perhaps the underground use will someday become a reality, but the effect of radioactive fall-out from the application of surface explosions was seriously – some would say even disingenuously – underestimated, while the inattention to public opinion eventually proved fatal to the overall program.

The Strategic Defense Initiative

While the President Reagan's "Strategic Defense Initiative" (SDI) of the 1980's grew from many sources and motivations, Teller certainly played a significant role in its advocacy. Teller's own motivations were consistent with the aspects of his philosophy already discussed: a desire to try new approaches to hard problems, certainty that organizations such as the Livermore lab needed new challenges in order to thrive, and his already mentioned desire to generate novel applications for nuclear explosives.

The basic problem of strategic defense against nuclear weapons had existed since the weapons themselves were invented, and quite a lot of work had been done over the decades by both the US and USSR, up to the fielding of anti-ballistic missile (ABM) systems. The rapidly developing Soviet nuclear arsenal and the general increase of tensions added urgency in the early 1980's. In the meantime, at Livermore, considerable innovative work was being done on the development of a nuclear pumped X-ray laser that offered the potential of rapidly striking targets at vast distances. Teller was very interested in this breakthrough, significantly because it represented a novel path forward in his quest to use nuclear devices not merely as explosives, but as 'engines.'

Very controversial from the start, the Strategic Defense Initiative was widely criticized by many defense experts as being technically unworkable, particularly in the face of the enormous numbers of Soviet weapons. Ironically, the work at Livermore on the X-ray laser, because its intrinsic use of nuclear explosives contradicted Reagan's desire for the defense to be non-nuclear, never commanded a significant portion of the SDI budget. The great bulk of the national program, under the auspices of the Department of Defense, (over 95 %) was devoted to other projects at other institutions (e.g. sensors, computer software, optical lasers, and so on).

Later, also with Teller's encouragement, Livermore scientists were also to contribute an innovative non-nuclear ballistic missile defense concept: "Brilliant Pebbles." This was based on the idea of fielding cheap, maneuverable spacecraft that could intercept ballistic missiles. Ultimately, with the end of the cold war, this project also ended but it did contribute several innovative technologies.

While it is difficult to objectively analyze the global role SDI may have played in the ultimate end of the cold war, one can certainly say that its challenges did invigorate the Livermore lab, engendering significant developments in computer codes, materials science, and fast experimental techniques and detectors in addition to engaging a new generation of highly talented scientists. On the other hand, for Teller personally, the advocacy of yet another unpopular position further increased his isolation from the broader scientific community.

(See, *"Edward Teller in the Public Arena by Brown and May*)

Teller as an Educator (1932 – 1975) and "Teller Tech" (1961-1975)

An aspect of Teller that is not widely appreciated, but most appropriate in this Memoir, was his devotion to education. Not only is this aspect not widely known, but his later impact upon the higher education of applied scientists and engineers, which was indeed very large, is not adequately recognized and appreciated.

Throughout his life, Teller had a deep interest in education. As has been mentioned above, during the primarily academic phase of his career, he mentored the early Ph.D. research of many young scientists in Germany, England, and in the US at George Washington, Columbia, Chicago, and Berkeley. Many of these young scientists went on to illustrious careers. Examples already mentioned in this narrative include Chen Ning Yang, Marshall Rosenbluth, Arthur Kantrowitz, Marvin Goldberger, Lincoln Wolfenstein, Walter Selove, Julius Ashkin, Charles Critchfield , and Bruno Renner. Other students included Harold and Mary Argo, Anne Bonney, Hans Peter Duerr, and Balazs Rosnyai.

Teller was also interested in basic scientific education, which he rightly regarded as a crucial part of the informed literacy of any civilization worthy of the name. For many years he taught, in the physics department in Berkeley, an elementary course on science appreciation. The course was highly regarded and although the lecture hall held only 600, often more than 1,000 signed up to take the course.

Starting in the early 1960's, Teller felt the growing need for applied scientists trained in an innovative way that would combine sophisticated awareness of the latest developments in basic science with the ability to carry out advanced engineering projects. He therefore worked to develop a Department of Applied Science at Livermore under the University of California. The initial plan was to have students do their research at Livermore, but obtain their degree in Berkeley. Despite the support of the university president, Clark Kerr, there was sufficient opposition from the Berkeley faculty that after two years of trying Teller gave up on Berkeley. He then turned to the Davis campus (60 miles from Livermore) and there he had success, for the Department was incorporated into the Davis College of Engineering. The Department had excellent staff from amongst the scientists at Livermore and soon was turning out fine graduates, many of who have, subsequently, had outstanding careers, both in staying at Livermore and going on to other things at other places. In fact, Teller Tech (as it was called by the students) has become a major source of highly trained applied scientists and engineers; to date the program has trained more than 200 PhDs and more than 200 Masters of Science.

Teller's second major activity, with its first awards in 1963, was the establishment of the Hertz Fellowship for study in applied science. This fellowship was founded with support from John Hertz, a fellow Hungarian and founder of *Yellow Cabs* and *Hertz Rent-a-Car*. Through the years over 1050 fellowships to very able students have been awarded. This is about half of all the fellowships in applied science ever given in the USA. Management of the original bequest has allowed the Hertz Foundation to spend over 40 million dollars through the years. Later, starting in 1966, Hertz prizes were also awarded.

Conclusion

Edward Teller was simultaneously one of the great physicists of the twentieth century and a major, but often controversial figure in the development and advocacy of American defense technologies. Courageously willing to push ideas persistently against the prevailing wisdom of the day, even at great personal cost, Teller was often very successful as with his development of the hydrogen bomb, the founding of the Livermore lab, and his role in the development of submarine launched missiles. However, in other cases he was less successful.

As was true of his fellow 'Martians,' Teller believed that much of the best, intellectually dynamic science grew synergistically with applications and acted accordingly. As is true of his peers' work from the heroic, early days of the development and application of quantum mechanics, his science continues to grow in influence, particularly in the deepening understanding of the microscopic properties of materials and their applications.

He was, also, interestingly enough – perhaps almost surprisingly -- a great advocate of openness in defense science and technology and frequently opposed secrecy, which he considered corrosive and damaging to America's interests.

Let us end this Memoir with a few selected quotations, by others, on Teller:

For Teller's memorial commemoration done in late 2003, his old friend Hans Bethe described their evolving relationship this way: describing Teller's early work in Munich (he was two years Bethe's junior under Sommerfeld in 1928) - "One student stood out – that was Edward Teller." Moving to their early collaboration on defense research in the early days of the Manhattan project: "We then began to map out the work needed at Los Alamos…Edward spent the remainder of the war primarily working on the 'Super,' but he made one very important contribution to the A-Bomb"…. Then, referring to the period from the end of the war through the 1980's and on to 2003: "Teller was a hawk and I was, and still am, a dove. Our once close relationship strained and then broke. When I read Edward's Memoirs, I was reminded of the good times. They were very good – among my most treasured memories. And that is how I prefer to remember my friend."

Andrei Sakharov, who has been compared to both Oppenheimer and Teller, gave the following interesting evaluation in his Memoirs: "I cannot help but feel deeply for and empathize with Oppenheimer whose personal tragedy has become a universal one. Some striking parallels between his fate and mine arose in the 1960's and later I was to go even further than Oppenheimer had. But in the 1940's and 1950's my position was much closer to Teller's, practically a mirror image…so that in defending his actions, I am also defending what I and my colleagues did at the time. Unlike Teller, I did not have to go against the current in those years, nor was I threatened by ostracism by my colleagues. I had to overcome some resistance on technical questions, but I was not without support; the struggle for the "Third Idea" arose for different reasons and was conducted in different circumstances than in Teller's case." ("*Memoirs" by Sakharov*, *p. 99-100)*

Finally George Schultz, Secretary of State in the Reagan Administration, and later a colleague of Teller's at the Hoover Institution at Stanford University, evaluating Teller's role in the 1980's said, at Teller's memorial commemoration: "…SDI, as it turned out, played a critical role in bringing that to pass the successful negotiations at Reykjavik and the end of the cold war. Edward Teller played a key role in strengthening Ronald Reagan's resolve. Edward Teller made quite a contribution to the end of the cold war…" Then describing Teller's characteristic manner of participation in his seminar at the Hoover institution at Stanford: "After all the obvious questions were asked, then Edward comes into play and he thinks of things that no one else thought of… So creative, so much fun, such a stimulating colleague. I'll miss him…. He didn't just make a difference, he made a gigantic difference."

* The work at LLNL was performed under the auspices of the U. S. Department of Energy both by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48, and Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.
**The work at LBNL was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. DE-AC02-05CH11231

References

Harold Brown and Michael May, *Edward Teller in the Public Arena*, Physics Today, 2004, 8, p. 51.

Istvan Hargittai, "*The Martians of Science, Five Physicists Who Changed the Twentieth Century*," Oxford University Press, New York, 2006.

Gregg Herken, *Brotherhood of the Bomb*, Henry Holt & Co., New York, 2002.

Lillian Hoddeson, Paul Henriksen, Roger A. Meade, and Catherine Westfall, *Critical Assembly, a Technical History of Los Alamos during the Oppenheimer Years 1943-1945*, Cambridge University Press, Cambridge, Great Britain, 1993.

Stephen B. Libby and Morton S. Weiss, *Edward Teller's Scientific Life*, Physics Today 2004, 8, p.45.

Dan O'Neill, *"The Firecracker Boys",* New York: St. Martin's Press, 1994.

Richard Rhodes, *The Making of The A-Bomb, Simon and Shuster, New York (1986).*

Richard Rhodes, *Dark Sun: The Making of the Hydrogen Bomb*, Simon and Schuster, New York (1995).

Andrei Sakharov, *Memoirs*, Knopf, New York, 1990.

Edward Teller and Judith Shoolery, *Memoirs*, Perseus Publishing, Cambridge, Massachusetts, 2001.

Appendix A: Significant Dates of Teller's Life

15 January 1908, Born in Budapest, Hungary
4 March 1941 Naturalized as a US citizen
9 September 2003, died in Palo Alto, California

1926-1928 Karlsruhe Institute of Technology, Germany
1928 University of Munich
1928-1930 University of Leipzig, Ph.D. under Werner Heisenberg
1929-1930 Research Associate, University of Leipzig
1930-1933 Research Associate, University of Göttingen
1934 Rockefeller Fellow, Institute for Theoretical Physics, Copenhagen, Denmark
1934-1935 Lecturer, City College of London, United Kingdom
1935-1946 Professor of Physics, George Washington University, Washington, D.C., USA
1941-1942 Professor Physics, Columbia University
1942-1943 Physicist, Manhattan Engineering District
1942-1943 Physicist, Metallurgical Laboratory, University of Chicago
1943-1946 Physicist, Los Alamos Scientific Laboratory

1946-1952 Professor of Physics, University of Chicago
1949-1952 Assistant Director, Los Alamos Scientific Laboratory
1952-1953 Consultant and Cofounder, Livermore Radiation Laboratory, University of California
1953-1960 Professor of Physics, University of California, Berkeley
1954-1958 Associate Director, Lawrence Livermore Laboratory
1958-1960 Director, Lawrence Livermore Laboratory
1960-1975 Associate Director, Lawrence Livermore Laboratory
1960-1970 Professor of Physics at Large, University of California
1963-1966 Chairman, Department of Applied Science at Livermore, University of California at Davis
1970-1975 University Professor, University of California
1975-2003 Director emeritus, Lawrence Livermore National Laboratory
1975-2003 Senior research fellow, Hoover Institution, Stanford University

Appendix B: Honors (selected)

1948: National Academy of Sciences - elected
1955: Harrison Medal, American Ordnance Association
1957: Joseph Priestly Memorial, Dickinson College
1958: Albert Einstein Award, Lewis and Rosa Strauss Memorial Fund
1962: Enrico Fermi Award, Atomic Energy Commission
1974: Leslie R. Groves Gold Medal
1975: Harvey Prize, Technion Institute of Israel
1977: Semmelweiss Medal
1977: Albert Einstein Award, Technion Institute of Israel
1978: Henry T. Heald Award, Illinois Institute of Technology
1980: American College of Nuclear Medicine Gold Medal ・Man of Science, Achievement Rewards for College Scientists ・Paul Harris Fellow, Rotary ・ A. C. Eringen Award, Society of Engineering Science, Inc
1981: Distinguished Scientist, National Science Development Board ・ Distinguished Scientist, Phil-American Academy of Science and Engineering
1982: American Academy of Achievement Gold Medal ・Jerusalem College of Technology
1983: National Medal of Science for 1982
1983: Joseph Handleman Prize, Jewish Academy of Arts and Sciences: Sylvanus Thayer Award, Association of Graduates, U.S. Military Academy, West Point
1988: Shelby Cullom Davis Award, Ethics and Public Policy
1988: Fannie and John Hertz Foundation Award
1989: Presidential Citizens Medal, President Reagan
1990: Ettore Majorana Erice Scienza Per La Pace, Science Peace Prize, Ettore Majorana Centre for Scientific Culture, Erice, Sicily

1990 Order of Banner with Rubies of the Republic of Hungary, President of the Republic of Hungary, Foreign Minister of the Republic of Hungary
1994: Middle Cross with the Star of the Order of Merit of the Republic of Hungary
1998: A Magyarsag Hirneveert Dij, (highest official Hungarian government award), Prime Minister of the Republic of Hungary
1999: Edward Teller Chair endowment, University of California at Davis's Department of Applied Science
2002: Department of Energy Gold Award, Energy Secretary Spencer Abraham
2003: Presidential Medal of Freedom, President George W. Bush

Honorary Degrees

Doctor of Science

1954: Yale University
1959: University of Alaska
1960: Fordham University
1960: George Washington University
1960: University of Southern California
1960: St. Louis University   Doctor of Natural Science
1962: Rochester Institute of Technology
1964: University of Detroit
1964:   Mount Mary College (Doctor of Humane Letters)
1966: Clemson University
1969: Clarkson College of Technology
1972:   Tel Aviv University (Doctor of Philosophy)
1981:   De La Salle University, Philippines
1983:   Medical University of South Carolina (Doctor of Medical Science, honoris causa)
1987: Adelphi University

Doctor of Law

1961: Boston College
1961: Seattle University
1962: University of Cincinnati
1963: University of Pittsburgh
1974: Pepperdine University
1977: University of Maryland, Heidelberg1987: Defense Intelligence College (Doctor of Strategic Intelligence)
1991: Eötvös University, Budapest (Honorary Professorship)

Appendix C: Publications

Scientific Papers (selected)

1. Über das Wasserstoffmolekülion (Hydrogen Molecular Ion). E. Teller. Zeits. f. ***Physik***, 61 7-8, pp 458-480 (1930) (Dissertation).

2. Bemerkung zur Theorie des Ferromagnetismus (Remarks on the Theory of Ferromagnetism). E. Teller. Zeits. f. ***Physik***, 62 1-2, pp 102-105 (1930).

3. Der Diamagnetismus von freien Elektronen (The Diamagnetism of Free Electrons). E. Teller. Zeits. f. ***Physik***, 67 5-6, pp 311-319 (January 31, 1931).

4. Zur Deutung des ultraroten Spektrums mehratomiger Moleküle (Infra-Red Spectra of Polyatomic Molecules). E. Teller and L. Tisza. Zeits. f. ***Physik***, 73 11-12, pp 791-812 (1932).

5. Bemerkungen über Prädissoziationsspektren dreiatomiger Moleküle (Remarks on the Predissociation Spectra of Triatomic Molecules). J. Franck, H. Sponer, and E. Teller. Zeits. f. ***Phys. Chem***. 18, Abt. B1, pp 88-101 (1932).

6. Eine für die Valenztheorie geeignete Basis der binären Vektorinvarianten (A Basis for Binary Vector Invariants Suitable for the Valence Theory). G. Rumer, E. Teller, and H. Weyl. Nachr. Ges. Wiss. Gottingen, ***Math-Physik Klasse***, 5, pp 499-504 (1932) (German).

7. Modellmässige Berechnung von Eigenschwingungen organischer Kettenmoleküle (Calculation of the Characteristic Vibrations of Organic Chain-Molecule Models). E. Bartholome and E. Teller. Zeits. f. ***Phys. Chem***. 19, Abt. B. 5, pp 366-388 (1932).

8. Die Rotationsstruktur der Ramanbanden mehratomiger Moleküle (Rotation Structure of the Raman Bands of Polyatomic Molecules). G. Placzek and E. Teller. Zeits. f. ***Physik*** 81 3-4, pp 209-258 (1932).

9. Die spezifische Wärme des gehemmten eindimensionalen Rotators (Specific Heat of the Restricted One-Dimensional Rotator). E. Teller and K. Weigert. Gottengen Nachrichten, ***Math. Phys. Klasse*** 2, pp 218-231 (1932).

10. Bemerkungen zur Quantenmechanik des anharmonischen Oszillators (Quantum Mechanics of the Anharmonic Oscillator). G. Poschl and E. Teller. ***Zeits. f. Physik*** 83 3-4, pp 143-151 (1933).

11. Schwingungsstruktur der Elektronenübergänge bei mehratomigen Molekülen (Oscillation Structure of Electron-Transfer in Polyatomic Molecules). G. Herzberg and E. Teller. Zeits. f. ***Phys. Chem.*** 21. Abt. B. 5-6, pp 410-446 (1933).

12. Molekül- und Kristallgitterspektren. Bd. IX, Abschnitt 2 of Hand- und Jahrbuch der ehemischen Physik. W.W. Finkelnburg, R. Mecke, O. Reinkober, and E. Teller. 2. Theorie der langwelligen Molekülspektren by E. Teller. Leipzig: ***Akad. Verlagsges.*** pp 43-160 (1934).

13. Molekül- und Kristallgitterspektren. Bd. IX, Abschnitt 2 of Hand- und Jahrbuch der ehemischen Physik. W. W. Finkelnburg, R. Mecke, O. Reinkober, and E. Teller. 3. Theorie der Kirstallgitterspektren by E. Teller. Leipzig: ***Akad. Verlagsges***. pp 161-188 (1934).

14. Theory of the Catalysis of the Ortho-para Transformation by Paramagnetic Gases. F. Kalckar and E. Teller. ***Roy. Soc. Proc.*** 150A. pp 520-533 (1935).

15. Vibration Frequencies of Ethylene and Ethane. E. Teller and B. Topley. ***Chem. Soc., J***. pp 885-889 (1935).

16. Time Effects in the Magnetic Cooling Method. Part I. W. Heitler and E. Teller. ***Roy. Soc. Proc.*** 155A. pp 629-639 (1936).

17. Zur Theorie Der Schalldispersion (Theory of Sound Dispersion). L. Landau and E. Teller. ***Phys. Zeits. d. Sowjetunion***, 10 1, pp 34-43 (1936)

18. Selection Rules for the Beta-Disintegration. G. Gamow and E. Teller. ***Phys. Rev.*** 49 12, pp 895-899 (1936).

19. Some Generalizations of the Beta-Transformation Theory. G. Gamow and E. Teller. ***Phys. Rev.*** 51. p 289 (1937) (Letter to Editor).

20. Heat of Sublimation of Graphite. G. Herzberg, K. F. Herzfeld, and E. Teller. ***J. Phys. Chem.*** 41. pp 325-331 (1937).

21. Stability of Polyatomic Molecules in Degenerate Electronic States. I. Orbital Degeneracy. H. A. Jahn and E. Teller. ***Proc. Roy. Soc.*** A161, pp 220-235 (1937).

22. The Scattering of Neutrons by Ortho- and Parahydrogen. Julian Schwinger and E. Teller. ***Phys. Rev.*** 51. p 775 (1937) (Letter to Editor).

23. The Scattering of Neutrons by Ortho- and Parahydrogen. Julian Schwinger and E. Teller. ***Phys. Rev***. 52. pp 286-295 (1937).

24. Crossing of Potential Surfaces. E. Teller. ***J. Phys. Chem.*** 41. pp 109-116 (1937).

25. Structure of Benzene. Pt. X. Intensities of Raman Lines in Benzene and Hexadeuterobenzene. R. C. Lord and E. Teller. ***Chem. Soc. J.*** pp 1728-1737 (1937).

26. Fluctuations of Composition in a System of Molecules in Chemical Equilibrium. F. G. Donnan. E. Teller, and B. Topley. ***Phil. Mag.*** 24. pp 981-1001 (1937).

27. The Rate of Selective Thermonuclear Reactions. G. Gamow and E. Teller. **Phys. Rev.** 53. pp 608-609 (1938) (Letter to Editor).

28. Adsorption of Gases in Multimolecular Layers. S. Brunauer, P. H. Emmett and E. Teller. **Am. Chem. Soc. J.** 60. pp 309-319 (1938).

29. Rotation of the Atomic Nucleus. E. Teller and J. A. Wheeler. **Phys. Rev.** 53. pp 778-789 (1938).

30. On the Saturation of Nuclear Forces. C. Critchfield and E. Teller. **Phys. Rev.** 53. pp 812-818 (1938).

31. Electrical Breakdown of Alkali Halides. R. J. Seeger and E. Teller. **Phys. Rev.** 54. pp 515-519 (1938).

32. Alpha-Particle Model of the Nucleus. L. R. Hafstad and E. Teller. **Phys. Rev.** 54. pp 681-692 (1938).

33. Role of Free Radicals in Elementary Organic Reactions. F. O. Rice and E. Teller. **J. Chem. Phys** 6, pp 489-96 (1938).

34. Migration and Photochemical Action of Excitation Energy in Crystals. J. Franck and E. Teller. **J. Chem. Phys.** 6, pp 861-872 (1938).

35. Vapor Pressure of Isotopes. Karl. F. Herzfeld and E. Teller. **Phys. Rev.** 54. pp 912-915 (1938).

36. Origin of Great Nebulae. G. Gamow and E. Teller. **Phys. Rev.** 55, pp 654-657 (1939).

37. Energy Production in Red Giants. G. Gamow and E. Teller. **Phys. Rev.** 55. p 791 (1939) (Letter to Editor).

38. Corrections to Paper "The Role of Free Radicals in Elementary Organic Reactions." F. O. Rice and E. Teller. **J. Chem. Phys.** 7, p 199 (1939).

39. On the Application of the Franck-Condon Principle to the Absorption Spectrum of $HgCl_2$. H. Sponer and E. Teller. **J. Chem. Phys.** 7, p 382 (1939) (Letter to the Editor).

40. Specific Heat and Double Minimum Problem of NH_3. R. F. Haupt and E. Teller. **J. Chem. Phys.** 7, pp 925-927 (1939).

41. Analysis of the Near Ultraviolet Electronic Transition of Benzene. H. Sponer, G. Nordheim, A. Sklar and E. Teller. **J. Chem. Phys.** 7. pp 207-220 (1939).

42. Remarks on the Dielectric Breakdown. R. J. Seeger and E. Teller. **Phys. Rev.** 56. pp 352-354 (1939).

43. Electron-Positron Field Theory of Nuclear Forces. E. P. Wigner, C. L. Critchfield and E. Teller. **Phys. Rev.** 56. pp 530-539 (1939).

44. Ionic Depression of Series Limits in One-Electron Spectra. D. R. Inglis and E. Teller. **Astrophys. J**. 90. pp 439-448 (1939).

45. Electric Breakdown of Alkali Halides. R. J. Seeger and E. Teller. **Phys. Rev**. 58. pp 279-280 (1940) (Letter to Editor).

46. Metastability of Hydrogen and Helium Levels. G. Breit and E. Teller. **Astrophys. J**. 91, pp 215-238 (1940).

47. Note on the Ultraviolet Absorption Systems of Benzene Vapor. G. Nordheim, H. Sponer and E. Teller. **J. Chem. Phys.** 8, pp 455-458 (1940).

48. On a Proposed Thermoelectric Origin of the Earth's Magnetism. D. R. Inglis and E. Teller. **Phys. Rev.** 57, pp 1154-1155 (1940).

49. Theory of the van der Waals Adsorption of Gases. S. Brunauer, L. S. Deming, W. E. Deming and E. Teller. **Am. Chem. Soc. J.** 62, pp 1723-1732 (1940).

50. Scattering of Fast Electrons in Helium. J. B. H. Kuper and E. Teller. **Phys. Rev.** 58, pp 602-603 (1940).

51. The Role of Ions in Surface Catalysis. P. H. Emmett and E. Teller. Twelfth Report of the Committee on Catalysis, National Research Council, John Wiley & Sons, Inc., pp 68-81 (1940).

52. Energy Loss of Heavy Ions. J. Knipp and E. Teller. **Phys. Rev**. 59. pp 659-669 (1941.)

53. Polar Vibrations of Alkali Halides. R. H. Lyddane, R. G. Sachs and E. Teller. **Phys. Rev**. 59. pp 673-676 (1941).

54. Electronic Spectra of Polyatomic Molecules. H. Sponer and E. Teller. **Rev. Mod. Phys.** 13, pp 75-170 (1941).

55. Angular Distribution of Alpha-Particles Produced in the Li^7-Proton Reaction. C. L. Critchfield and E. Teller. **Phys. Rev**. 60, pp 10-17, (1941).

56. Scattering of Slow Neutrons by Molecular Gases. R. G. Sachs and E. Teller. **Phys. Rev**. 60, pp 18-27 (July 1, 1941).

57. On the Momentum Loss of Heavy Ions. J. H. M. Brunings, J. K. Knipp and E. Teller. **Phys. Rev.** 60, pp 657-660 (1941).

58. Asymmetric Vibrations Excited by an Electronic Transition. E. Teller. **Annls. of NY Acad. of Sci.** XLI, Art. 3, pp 173-186 (1941).

59. Deviations from Thermal Equilibrium in Shock Waves. H. A. Bethe and E. Teller. (Undated Memorandum) Distributed by Defense Technical Information Center; Rept. No. ATI-18278; NP-4898; BRL-X-117.

60. The Inelastic Scattering of Neutrons by Crystal Lattices. R. J. Seeger and E. Teller. **Phys. Rev.** 62, pp 37-40 (1942).

61. X-ray Interference in Partially Ordered Layer Lattices. S. Hendricks and E. Teller. **J. Chem. Phys**. 10, pp 147-167 (March 1942).

62. Interpretation of the Methyl Iodide Absorption Bands Near λ2000. R. S. Mulliken and E. Teller. **Phys Rev**. 61, pp 283-296 (1942).

63. Interaction of the van der Waals Type Between Three Atoms. B. M. Axilrod and E. Teller. **J. Chem. Phys**. 11, pp 299-300 (June 1943).

64. Statistics of Two-Dimensional Lattices with Four Components. J. Ashkin and E. Teller. **Phys. Rev.** 64, pp 178-184 (1943).

65. Neutron Emission by Polonium Oxide Layers. M. Argo and E. Teller. Los Alamos Scientific Laboratory Rept. LAMS-121. (August 8, 1944) (Declassified 1956).

66. Critical Amounts of Uranium Compounds. E. Konopinski, N. Metropolis, E. Teller, and L. Woods. Los Alamos Scientific Laboratory Rept. CF-548. (March 19, 1943) (Declassified 1956).

67. Theory of Water-Tamped Water Boiler. Work done by E. Teller, et al.; report written by E. Greuling. Los Alamos Scientific Laboratory Rept. LA-399. (September 27, 1945) (Declassified 1958).

68. Critical Dimensions of Water-Tamped Slabs and Spheres of Active Material. Work done by E. Teller, et al.; report written by E. Greuling. Los Alamos Scientific Laboratory Rept. LA-609. (August 6, 1946) (Declassified 1956).

69. Ignition of the Atmosphere with Nuclear Bombs. E. Konopinski, C. Marvin and E. Teller. Los Alamos Scientific Laboratory Rept. LA-602 (August 14, 1946) (Declassified 1974).

70. Neutron Spectrum from a Cold Parahydrogen Radiator. Work done by T. Hall, F. de Hoffman, and E. Teller; report written by T. Hall and F. de Hoffman. Los Alamos Scientific Laboratory Rept. LADC-111 (February 11, 1946) (edited to conform to security regulations).

71. The Decay of Negative Mesotrons in Matter. E. Fermi, E. Teller and V. Weisskopf. **Phys. Rev.** 71, pp 314-315 (March 1, 1947).

72. On the Production of Mesotrons by Nuclear Bombardment. W. G. McMillan and E. Teller. **Phys. Rev.** 72, pp 1-6 (1947).

73. The Capture of Negative Mesotrons in Matter. E. Fermi and E. Teller. **Phys. Rev.** 72, pp 399-408 (1947).

74. On the Change of Physical Constants. E. Teller. **Phys. Rev**. 73. pp 801-802 (1948).

75. Theoretical Considerations Concerning the D + D Reactions. E. J. Konopinski and E. Teller. **Phys. Rev**. 73, pp 822-830 (1948).

76. On Nuclear Dipole Vibrations. M. Goldhaber and E. Teller. **Phys. Rev.** 74, pp 1046-1049 (1948).

77. Equations of State of Elements Based on the Generalized Fermi-Thomas Theory. R. P. Feynman, N. Metropolis and E. Teller. **Phys. Rev**. 75, pp 1561-1573 (1949).

78. On the Origin of Cosmic Rays. R. D. Richtmyer and E. Teller. **Phys. Rev**. 75, pp 1729-1731 (1949).

79. The Origin of Cosmic Radiation. E. Teller. **Phys. Today** 2, pp 6-13 (1949).

80. On the Origin of Elements. M. G. Mayer and E. Teller. **Phys. Rev**. 75, pp 1226-1231 (1949).

81. On the Abundance and Origin of Elements. M. G. Mayer and E. Teller. **Particules Elementaires**, Institut International de Chimie Solvay, Burxelles (1950).

82. Magneto-Hydrodynamic Shocks. F. de Hoffman and E. Teller. **Phys. Rev.** 80, pp 692-703 (1950).

83. The Assumptions of the B.E.T. Theory. W. G. McMillan and E. Teller. **J. Phys. Chem.** 55, pp 17-20 (1951).

84. The Role of Surface Tension in Multilayer Gas Adsorption. W. G. McMillan and E. Teller. **J. Chem. Phys**. 19, pp 25-32 (1951).

85. Equation of State Calculations by Fast Computing Machines. N. Metropolis, A. Rosenbluth, M. Rosenbluth, A. H. Teller and E. Teller. **J. Chem. Phys**. 21, No. 6, pp 1087-1092 (1953).

86. Theory of Origin of Cosmic Rays. E. Teller. **Rep. Progr. Phys**. 17, pp 154-172 (1954).

87. Proton Distribution in Heavy Nuclei. M. H. Johnson and E. Teller. Letter in **Phys. Rev.** 93, No. 2, pp 357-358 (1954).

88. Comments on Plasma Stability and on a Constant-pressure Thermonuclear Reactor. E. Teller. Paper submitted to Conference on Thermonuclear Reactions, Princeton University, October 1954 (Declassified January 23, 1959).

89. Opening Remarks - Symposium on Plasma Instabilities. E. Teller. Paper submitted to Conference on Thermonuclear Reactions, University of California Radiation Laboratory, February 1955 (Declassified January 23, 1959).

90. The Work of Many People, Edward Teller; ***Science***, pp. 267-275, (1955).

91. Classical Field Theory of Nuclear Forces. M. H. Johnson and E. Teller. **Phys. Rev**. 98, No. 3, pp 783-787 (1955).

92. Interaction of Antiprotons with Nuclear Fields. H. P. Duerr and E. Teller. **Phys. Rev.** 101, p 494-495 (1956).

93. Deep Underground Test Shots. D. Griggs and E. Teller. University of California, Lawrence Radiation Laboratory Rept. UCRL-4659 (1956).

94. General Problems of the Controlled Thermonuclear Process. E. Teller. **Nucl. Sci. Engng**. 1, pp 313-324 (1956).

95. General Problems of the Controlled Thermonuclear Process. E. Teller. Paper submitted to Conference on Controlled Thermonuclear Reactions, June 1956 (Declassified January 23, 1959).

96. Peaceful Uses of Fusion. E. Teller. Reprinted from "Progress in Nuclear Energy, Series XI, Volume 1 -- Plasma Physics and Thermonuclear Research," pp 56-65 (1958).

97. Seismic Scaling Law for Underground Explosions. A. L. Latter, E. A. Martinelli and E. Teller. **Phys. Fluids** 2, No. 3, pp 280-282 (1959).

98. Peaceful Uses of Atomic Explosives. E. Teller. Fifth World Petroleum Congress Proceedings, Symposium on the Applications of Atomic Energy to the Petroleum Industry, New York, pp 11-20 (1959).

99. Stability of the Adiabatic Motion of Charged Particles in the Earth's Field. T. G. Northrop and E. Teller. **Phys. Rev.** 117, pp 215-225 (1960).

100. Nuclear Power Potential for Space Vehicles. E. Teller. Proceedings of the Bureau of Naval Weapons Missiles and Rockets Symposium, Concord, CA., pp 15-17 (April 1961).

101. Der quantenmechanische Mebprozeb und die Entropie. E. Teller. **Werner Heisenberg und die Physik unserer Zeit**, pp 90-92 (1961).

102. On the Speed of Reactions at High Pressures. E. Teller. **J. Chem. Phys.** 36, No. 4, pp 901-903 (1962).

103. On the Stability of Molecules in the Thomas-Fermi Theory. E. Teller. **Rev. Mod. Phys**. 34, No. 4, pp 627-631 (1962).

104. The Hazards of Radiation. E. Teller. **J. Nuclear Med.** 3, No. 5, pp 1-9 (1962).

105. Plowshare. E. Teller. **Nucl. News** 6, pp 1-13 (March 1963).

106. Proposal of Experiments on Electromagnetic Radiation from a Distant Nuclear Explosion. W. K. Talley and E. Teller. Proceedings of the Third Plowshare Symposium, Engineering with Nuclear Explosives, University of California/Davis, pp 31-35 (April 1964).

107. Energy from Oil and from the Nucleus. E. Teller. **J. Pet. Tech**., pp 505-508 (May 1965).

108. On a Theory of Quasars. E. Teller. From **Perspectives in Modern Physics, Essays in Honor of Hans A. Bethe**, R. E. Marshak (Ed.), Interscience Publishers, pp 449-462 (1966).

109. Monte Carlo Study of a One-Component Plasma. I. S. G. Brush, H. L. Sahlin and E. Teller. **J. Chem. Phys.** 45, No. 6, pp 2102-2118 (1966).

110. On the Adiabatic Compression of a Light Packet. E. Teller. **Sci of Light** (Japan), Vol. 16 No. 1, pp 22-25 (May 1967).

111. Some Remarks on Time Reversal. E. Teller. Proceedings of Symmetry Principles at High Energy, Fifth Coral Gables Conference, University of Miami, pp 1-6 (1968).

112. Prehistoric Safety Studies. E. Teller. Proceedings of the Livermore Array Symposium, Livermore, CA, pp 1-5 (1968).

113. Atomic Explosives: Solved and Unsolved Problems. E. Teller. **The Physics Teacher**, Vol. 6, #5 (May 1968).

114. Internal Conversion in Polyatomic Molecules. E. Teller. Twentieth Farkas Memorial Symposium. **Israel Journal of Chemistry**, Vol. 7, No. 2, pp 227-235 (1969).

115. Thermonuclear Energy. E. Teller. Center for Theoretical Studies, University of Miami Rept. CTS-HS-69-2 (1969).

116. Absorption of K^- Mesons in Nuclear Surfaces. E. Teller, M. H. Johnson and S. D. Bloom. **Phys. Rev. Letters**, 23, 1, pp. 28-30 (1969).

117. General Remarks on Electronic Structure. E. Teller and H. L. Sahlin from **Physical Chemistry, An Advanced Treatise**, Vol. V, Henry Eyring (Ed.), Academic Press, pp 1-34 (1970).

118. The Hydrogen Molecular Ion and the General Theory of Electron Structure. E. Teller and H. L. Sahlin. From **Physical Chemistry, An Advanced Treatise,** Vol. V, Henry Eyring (Ed.), Academic Press, pp 35-124 (1970).

119. Some Thoughts About High Energy Densities. E. Teller. **Physics of High Energy Density**, Academic Press, Inc., pp 1-6 (1971).

120. Relativistic Hydrodynamics in Supernovae. E. Teller. **Physics of High Energy Density**, Academic Press, Inc., pp 402-418 (1971).

121. Die Verantwortlichkeit des Wissenschaftlers in der Gesellschaft. E. Teller. **Quanten und Felder**, Physikalische und philosophische Betrachtungen zum 70. Geburtstag von Werner Heisenberg, pp 93-100 (1971) .

122. An Effective Potential Calculation for the Ground State of Excited States of H^2. H. Sahlin, R. Speed and E. Teller. University of California, Lawrence Radiation Laboratory Rept. UCRL-73338 (April 1971) for submission to the Journal of Chemical Physics.

123. General Shock Conditions. E. Teller and M. H. Johnson. **Geophysical Monograph Series**, Vol. 16, pp 313-318 (1972).

124. A Future Internal Combustion Engine. E. Teller. University of California, Lawrence Livermore Laboratory Rept. UCRL-74487. For presentation at the 7th International Quantum Electronics Conference, Montreal, Canada (May 1972).

125. Concerning Strong Convergent Compression of Thermonuclear Fuel in Laser-Fusion CTR Schemes. E. Teller. University of California, Lawrence Livermore Laboratory Rept. UCRL-74117. 1972 Annual Meeting of the Division of Plasma Physics of the American Physical Society (1972).

126. Lasers in Chemistry. E. Teller. Proceedings of **The Robert A. Welch Foundation Conferences on Chemical Research**, XVI. Theoretical Chemistry, Houston, TX (November 1972).

127. The Dirac Hypothesis. E. Teller. **Fundamental Interactions in Physics and Astrophysics**, A Volume Dedicated to P. A. M. Dirac on the Occasion of his Seventieth Birthday, pp 351-352, Plenum Press, New York (1972).

128. K^--Mesic Atoms and Capture in the Nuclear Surface. S. D. Bloom, M. H. Johnson and E. Teller. W. H. Freeman & Co., pp 89-111 (1972).

129. Are the Constants Constant? E. Teller. **Cosmology, Fusion & Other Matters**, George Gamow Memorial Volume, Colorado Associated University Press, pp 60-66 (1972).

130. Thermonuclear Energy. E. Teller. **Impact of Basic Research on Technology**, Plenum Publishing Corp., New York, pp 181-192 (1973).

131. A Future ICE (thermonuclear, that is!). E. Teller. **IEEE Spectrum,** 10, pp 60-64 (1973).

132. Introductory Remarks to International Conference on Photonuclear Reactions and Applications. E. Teller and M. S. Weiss. Asilomar Conference Grounds, Pacific Grove, CA, March 26-30, 1973. Lawrence Livermore Laboratory Rept. CONF-730301 (1973).

133. Highly Excited Nuclear Matter. G. F. Chapline, M. H. Johnson, E. Teller and M. S. Weiss. **Phys. Rev. D**, 8, No. 12, pp 4302-4308 (1973).

134. Die grundsätzliche Antwort. E. Teller. **Einheit und Vielheit, Festschrift für Carl Friedrich v. Weizsäcker**, Vandenhoeck & Ruprecht in Göttingen, (1973).

135. Futurology of High Intensity Lasers. E. Teller. **Laser Interactions and Related Plasma Phenomena**, Vol. 3, pp 3-10, Plenum Press (1974).

136. Isotope Separation by Resonance Scattering. A. F. Bernhardt and E. Teller. **Appl. Phys. Lett**. 30, pp 550-552 (1977).

137. Electromagnetism and Gravitation. E. Teller. **Proc. Nat. Acad. Sci.** 74, 7, pp 2664-2666 (1977).

138. Technical Initiatives on Early Sufficiency in Energy. E. Teller. **Energy Research** 2, pp 3-7 (1978).

139. Remarks on the Thorium Cycle. E. Teller. Thorium and Gas Cooled Reactors. A seminar for the 65th birthday of Dr. Peter Fortescue. **Annals of Nuclear Energy**, 5, pp 287-296 (1978).

140. Is the Muon a Multipole Meter? E. Teller and M. S. Weiss. **A Festschrift for Maurice Goldhaber**, Transactions of the New York Academy of Sciences, Series II, Vol. 40, pp 222-229 (1980).

141. Introduction. E. Teller. **Fusion**, Volume 1, Part A, pp 1-29. Academic Press. (1981).

142. The Jahn-Teller Effect -- Its History and Applicability. E. Teller. **Physica 114A**, pp 14-18, North-Holland Publishing Co., (1982).

143. Intensity Changes in the Doppler Effect. M. H. Johnson and E. Teller. **Proc. Natl. Acad. Sci.**, Vol. 79, p 1340 (1982).

144. The Fusion Breeder--An Early Application of Nuclear Fusion. J. A. Maniscalco, D. H. Berwald, R. W. Moir, J. D. Lee and Edward Teller. University of California, Lawrence Livermore Laboratory Rept. UCRL-87801. For submission to **Science**, (June 1983).

145. On the Extragalactic Origin of Gamma-Ray Bursts. M. H. Johnson and E. Teller. University of California, Lawrence Livermore Laboratory Report UCRL-91744, Rev. 1. Presented at the Quantum

Theory and the Structures of Time and Space, 6th Symposium, Tutzing, Germany, July 2-5, 1984.

146. Remarks on Stellar Clusters, E. Teller, contribution to a Festschrift volume in honor of Yuval Ne'eman's 60th birthday. Festschrift entitled, ***From SU (3) To Gravity***. (January 16, 1985).

147. Some Generalizations of the Virial Theorem. E. Teller. submitted to **Foundations of Physics** in honor of John A. Wheeler's 75th birthday (1986).

148. The Lunar Laboratory by Edward Teller published in the volume ***New Directions in Physics: The Los Alamos 40th Anniversary Volume.*** Academic Press, Inc., 1986

149. ***An Introduction To Equations of State: Theory and Applications*** (Foreward) by Edward Teller. ***Equations of State*** authored by Shalom Eliezer, A. K. Ghatak and Heinrich Hora, Cambridge University Press, 1986.

150. Remarks About Fields of High Intensity. E. Teller. For submission to **Nuclear Instruments and Methods in Physics Research** (Netherlands). (April 1987).

151. On The Chemistry of Superconductivity. R. More and E. Teller. University of California, Lawrence Livermore National Laboratory Report UCRL-98684. Presented at the International Conference on Lasers '87, December 1987.

152. Explosive Fusion Devices by Edward Teller published in **Encyclopedia of Physical Science and Technology**, Academic Press, Vol. 5, 1987, pp. 723 - 726.

153. Adaptation of the Theory of Superconductivity to the Behavior of Oxides, E. Teller. To appear in Proceedings of the NATO Advanced Study Institute on *The Nuclear Equation of State*, Peniscola, Spain, May 1989.

154. Theory of Superconductivity at High Temperatures by A. A. Broyles, E. Teller and B. G. Wilson published in the ***Journal of Superconductivity***, Vol. 3, No. 2, pp. 161 - 169, 1990.

155. Lecture in connection with *The Edward Teller Medal Award*, published in ***Laser Interaction and Related Plasma Phenomena***, Plenum

Press, Vol. 10, pp. 1-4, 1992. Proceedings of the Tenth International Workshop on Laser Interaction and Related Plasma Phenomena held November 11-15, 1991 at the Naval Postgraduate School, Monterey, California.

156. Space Propulsion By Fusion in a Magnetic Dipole, Edward Teller, Alexander J. Glass and T. Kenneth Fowler. Published in ***Fusion Technology***, V. 22, August 1992, pp. 82-97 (a publication of the American Nuclear Society). Also presented at the 1st International A. D. Sakharov Conference on Physics, Moscow, USSR; May 27-31, 1991.

157. Fusion Devices, Explosive, Edward Teller. Published in ***Encyclopedia of Physical Science and Technology***, Vol. 7, 1992 by Academic Press, Inc.

158. Introduction by Edward Teller, published in ***Advances in Spectroscopy in Hungary (Spectrochimica Acta)*** by Pergamon Press, Vol. 48A, No. 1, p. 1, 1992.

159. The Miracle of Superconductivity; **Materials Science Forum** Vols. 105-110 (1992) pp. 161-170.

160. Foreword by Edward Teller, published in the ***Textbook of Hyperbaric Medicine*** by Dr. K. K. Jain, American College of Hyperbaric Medicine, 1993; pp. XI-XII.

161. Yang, A Great Physicist. E. Teller, contribution to a Festschrift volume in honor of Professor C. N. Yang's 70th birthday. (1995)

162. Cosmic Bombardment V: Threat Object-Dispersing Approaches To Active Planetary Defense by Lowell Wood, Rod Hyde, Muriel Ishikawa and Edward Teller. Paper prepared for submittal to the Planetary Defense Workshop, May 22-26, 1995, Livermore, CA; Report UCRL-JC-Draft; (May 1995).

163. Completely Automated Nuclear Reactors for Long-Term Operation II: Toward A Concept-Level Point-Design Of A High-Temperature, Gas-Cooled Central Power Station System by Edward Teller, Muriel Ishikawa, Lowell Wood, Roderick Hyde and John Nuckolls. Prepared for submittal to 1996 International Conference on Emerging Nuclear Energy Systems (ICENES '96), Obninsk, Russian Federation; 24-28 June 1996. UCRL-JC-122708 Pt. 2, June 20, 1996.

164. High Energy-Density Physics: From Nuclear Testing to the Superlasers. E. M. Campbell, N. C. Holmes, S. B. Libby, B. A. Remington, and E. Teller. 1996 American Institute of Physics No. 370; pp. 21-26.

165. The Evolution of High Energy-Density Physics: From Nuclear Testing to the Superlasers; E. M. Campbell, N. C. Holmes, S. B. Libby, B. A. Remington and E. Teller. **Lasers and Particle Beams,** 4, pp. 607-626, (1997).

166. Nuclear Energy for the Third Millennium; Edward Teller. UCRL-JC-129547, prepared for submittal to the International Conference on Environment and Nuclear Energy, Washington, D.C., 27-29 October 1997.

167. Global Warming and Ice Ages: I. Prospects for Physics-Based Modulation of Global Change; Edward Teller, Lowell Wood, Roderick Hyde. UCRL-JC-128715, prepared for submittal to the 22nd International Seminar on Planetary Emergencies, Erice (Sicily), Italy, 20-23 August 1997.

168. Three Problems: Nuclear Energy, National Defense and International Cooperation by Edward Teller; UCRL-JC-135608 prepared for submittal to the Second International Symposium on the "History of Atomic Projects—The 1950s: Sociopolitical, Environmental and Engineering Lessons Learned" (HISAP '99), Laxenburg,, Austria, October 4-8, 1999.

169. Long Range Weather Prediction III: Miniaturized Distributed Sensors for Global Atmospheric Measurements by Edward Teller, Cecil Leith, Gregory Canavan and Lowell Wood; UCRL-JC-146204, Part 3 prepared for presentation at the 26th International Symposium on Planetary Emergencies, Majorana Centre for Scientific Culture, Erice, Italy, 20-23 August 2001.

170. Five Issues by Edward Teller and Dr. Behram N. Kursunoglu, Global Foundation, Inc.; UCRL-JC-142054 submitted to Global Warming and Energy Policy Conference, Fort Lauderdale, Florida, November 26-28, 2000.

171. Thorium Fueled Underground Plant Based on Molten Salt Technology, E. Teller and R. Moir, **Nuclear Technology** 151, (3), pp.334-340, (2005).

Other Articles in Newspapers and Magazines

1. The Evolution and Prospects for Applied Physical Science in the United States. E. Teller. Reprinted from Applied Science and Technological Progress, A Report to the Committee on Science and Astronautics, U. S. House of Representatives, by the National Academy of Sciences (1967).

2. Can a Progressive be a Conservationist? E. Teller. **New Scientist**, February 19, 1970, pp 346-349.

3. University Role in Nuclear Explosives Engineering Research. E. Teller. **Education for Peaceful Uses of Nuclear Explosives,** University of Arizona Press, pp 293-298 (1970).

4. The Necessity of Strategic Defense by Edward Teller as presented to The New York Academy of Sciences Conference on the High Technologies and Reducing the Risk of War. Published in ***High Technologies***, Vol. 489, pp. 146 - 151, 1986.

5. Why I Am in America by Edward Teller published in ***The San Jose Mercury News***, July 4, 1986.

6. Defense and the NATO Alliance by Edward Teller. Published in ***The National Interest,*** spring 1986.

7. ***Die Waffenabwehr*** (The Anti-Weapons) by Dr. Edward Teller published in ***Physikalische Blätter (Physikalische und technische Aspekte von Teilchenstrahl- und Laserwaffen)***, Vol. 42, No. 8, pp. 289-292, 1986.

8. Scientists and National Defense, An Open Letter to Hans Bethe by Edward Teller published in ***Policy Review***, No. 39, pp. 18-23, Winter 1987.

9. In the Worst Event . . . by Edward Teller published as a book review on ***The Medical Implications of Nuclear War*** & ***A World Beyond Healing: The Prologue and Aftermath of Nuclear War***.. Book review published in ***Nature*** magazine, Vol. 328, pp. 23-24, July 1987.

10.. Defense Is The Best Defense by Edward Teller published in **The New York Times Magazine**, April 5, 1987, pp. 47-48.

11. The Question of Strategic Defense by Edward Teller published in **Information Week**, September 28, 1987, Issue 136, pp. 72.

12. Deterrence? Defense? Disarmament? The Many Roads Toward Stability by Edward Teller published in ***Thinking About America: the United States in the 1990s*** by Annelise Anderson and Dennis L. Bark, editors, pp. 21-32, September 1988 .

13. Widespread After-Effects of Nuclear War. E. Teller, **Nature** (London), Vol. 310, No. 5979, pp 621-624 (August 23, 1984).

14. Science, Technology and Policy in the 1980's; **Harvard International Review 10th Anniversary Issue**; 1989; pp. 114-118

15. Survivability and Effectiveness of Near-term Strategic Defense by Gregory Canavan and Edward Teller. Published in Los Alamos as a technical paper: LA-11345-MS, UC-700, issued January 1990.

16. The Role of LLNL in the Education Process by Edward Teller published in ***The Quarterly*** at Lawrence Livermore National Laboratory: *Looking Toward the 21st Century: Laboratory Leaders Share Their Vision of the Future.* Vol. 21, No. 2, pp. 15-17, November 1990.

17. Strategic Defence for the 1990s by Gregory Canavan and Edward Teller published in ***Nature*** magazine, Vol. 344, No. 6268, pp. 699-704, April 19, 1990.

18. The Future of Defense and Technology by Edward Teller. Formal paper presented at the Lawrence Livermore National Laboratory workshop: ***The Role of Nuclear Weapons in the Year 2000*** sponsored by the Center for Technical Studies on Security, Energy and Arms Control. UCRL-JC-105925, CTS-11-90, January 10, 1991.

19. Nuclear Glasnost by Edward Teller published in ***The Bulletin of the Atomic Scientists***, Vol. 47, No. 9, pp. 34-35, November, 1991.

20. Low-Level Satellites Expand Distributed Remote Sensing; Dr. Gregory Canavan and Dr. Edward Teller; **SIGNAL Magazine**; Vol. 45, No. 12, August 1991; pp. 99-103

21. The Laboratory of the Atomic Age by Edward Teller, published in ***Los Alamos Science***, Number 21, pp. 32-37, 1993. Published for the Laboratory's 50th Anniversary.

22. U.S. Needs Fresh Approach to Nuclear Energy; **The Christian Science Monitor**, 1994; pp. 66-67.

23. Who's Afraid of Science? And Why? **National Review,** October 10, 1994; pp. 72.

Books (selected)

The Structure of Matter, Francis Owen Rice and Edward Teller, John Wiley and Sons, NY, 1949.

Our Nuclear Future, Edward Teller and Albert L. Latter, Criterion Books, NY, 1958.

The Legacy of Hiroshima, Edward Teller with Allen Brown, Doubleday and Co., Garden City, NY, 1962.

The Reluctant Revolutionary, Edward Teller, University of Missouri Press, Columbia, MO, 1964.

The Constructive Uses of Nuclear Explosives, Edward Teller, Wilson K. Talley, and Gary H. Higgins, McGraw Hill, NY, 1968.

Great Men of Physics, Emilio G. Segrè, Joseph Kaplan, Leonard I. Schiff, and Edward Teller, Tinnon-Brown, Los Angeles, CA, 1969.

Energy: A Plan for Action, Edward Teller, available from the Commission on Critical Choices for Americans, NY, 1975.

Critical Choices for Americans: Power and Security, Edward Teller, Hans Mark, and John S. Foster, Lexington Books, Lexington, MA, 1976.

Nuclear Energy in the Developing World, Edward Teller, Mitre Corporation, Metrek Division, McLean, VA, 1977.

Energy from Heaven and Earth, Edward Teller, W. H. Freeman and Co., San Francisco, CA, 1979.

Better a Shield Than a Sword, Edward Teller, Free Press/MacMillan, New York, NY, 1987.

Conversations on the Dark Secrets of Physics, Edward Teller, Wendy Teller, and Wilson Talley, Plenum Press, NY, 1991.

Memoirs: A Twentieth-Century Journey in Science and Politics, Edward Teller and Judith Shoolery, Perseus Publishing, Cambridge, MA, 2001.