Probing Deep into the Nucleus

Teller's Contributions to Nuclear and Particle Physics

January 15, 2008, marks the 100th anniversary of Edward Teller's birth. This highlight is the eighth in a series of 10 honoring his life and contributions to science.

As researcher, theoretician, colleague, educator, and mentor, Edward Teller influenced every field of physics. His contributions to the fast-growing fields of nuclear physics and particle physics were part of the Golden Age of Physics, in which discovery after discovery produced an increasingly clearer picture of the nucleus and the fundamental interactions of the subatomic particles contained within the nucleus.

The Teller–Gamow theory on beta decay appeared in 1936 and was immensely influential in the growing field of particle physics.

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Selection Rules for the β-Disintegration

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§1. The selection rules for β-transformations are stated on the basis of the neutrino theory outlined by Fermi. If it is assumed that the spins of the heavy particles have a direct effect on the disintegration these rules are modified. §2. It is shown that whereas the original selection rules of Fermi lead to difficulties if one tries to assign spins to the members of the thorium family the modified selection rules are in agreement with the available experimental evidence.

§1.

According to the theory of β-disintegration given by Fermi[1] no change of the total nuclear spin should occur in the most probable transformations, i.e., in transformations located on the first Sargent curve.[2] The transformations corresponding to the second Sargent curve approximately 100 times less probable should correspond to changes ±1 or 0 of the angular momentum of the nucleus. One may expect the existence of still lower curves for higher changes in the nuclear spin. This selection principle is based on the assumption that the spin of the heavy particles does not enter in the part of the Hamiltonian which is responsible for the β-disintegration. The same assumption was made in the modified theory of Konopinski and Uhlenbeck[3] who introduced the derivative of the neutrino wave function in the Hamiltonian in order to get a better fit with the experimental curves of the energy distribution in β-spectra. We should like to note here that this selection rule will be changed if the spins of the heavy particles are introduced into the Hamiltonian, a possibility proposed in many discussions about this subject.

We shall first give the derivation of Fermi's selection rule in a somewhat generalized form. The probability of β-disintegration is proportional to the square of the matrix element.

$$M_1 = \sum_l \int (\Omega_l^{N,P}\psi_i)\psi_f^* \delta q_l \{0(\psi_e^*\psi_\nu^*)\}. \quad (1)$$

Here ψ_i and ψ_f are the proper functions of the heavy particles, protons and neutrons, for the initial and final state, respectively. These functions depend on the positions of the heavy particles, on their spins, and on a third variable[4] which corresponds to the charge of the heavy particles and which is capable of two values, in a manner similar to the spin variable, the value 1 corresponding to a proton and the value 0 to a neutron. The operator $\Omega_l^{N,P}$ acts on this last variable converting the lth particle in ψ_i into a proton if it was a neutron and giving $\Omega_l^{N,P}\psi_i = 0$ if the lth particles is already a proton. The integration in (1) includes summation over the spin and charge coordinates of the heavy par

[1] Fermi, Zeits. f. Physik **88**, 161 (1934).
[2] Sargent, Proc. Roy. Soc. **A139**, 659 (1933).
[3] Konopinski and Uhlenbeck, Phys. Rev. **48**, 7 (1935).
[4] Introduced by Heisenberg, Zeits. f. Physik **77**, 1 (1932).

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Teller's contributions often were made in collaboration with some of the greatest luminaries of 20th-century physics such as Enrico Fermi, George Gamow, and Hans Bethe. Even in his earliest papers on nuclear physics, Teller's style is readily apparent: a complete command of mathematics, an intuitive understanding of physics, and elegant arguments.

As a student of Werner Heisenberg in the late 1920s and early 1930s, Teller's early work in theoretical physics focused on applying the new theory of quantum mechanics to understanding phenomena in molecular and condensed-matter physics. However, the rapidly developing field of nuclear physics soon caught his attention. Fermi, James Chadwick, Hideki Yukawa, and others made the first important steps in understanding that the atomic nucleus is composed of protons and neutrons held together by a strong nuclear force, now considered as one of the four fundamental interactions of nature. Further clues to the fundamental interactions came from studying the decays of unstable nuclei. These nuclei may undergo alpha decay, in which they emit a helium nucleus, or beta decay (controlled by the weak force of nature), in which nuclei eject an electron (or positron) and a neutrino.

Teller fled Nazi Germany in 1934, going first to the Niels Bohr Institute in Copenhagen and then to University College in London. In 1935, Gamow invited him to join the faculty at George Washington University. Soon, the two were collaborating on a

This photo, taken in 1982, shows Edward Teller with Chen Ning Yang, who was Teller's student in the late 1940s. (Courtesy of Brookhaven National Laboratory.)

paper that eventually proved to be a crucial leap in understanding fundamental physics.

In 1934, Teller's lifelong friend Fermi proposed a significant beta-decay theory, in which Fermi stipulated that the spin of nucleons (protons and neutrons) tended to remain constant. In a 1936 paper published in *Physical Review*, Teller and Gamow focused on the experimental evidence presented by the complicated beta-decay scheme of thorium. They wrote that several observed nuclear spin assignments and beta- and gamma-decay rates contradicted Fermi's theory. They proposed modifications that allowed a nucleon to flip its spin during transition when emitting an electron and antineutrino, which became known as the Gamow–Teller transition.

The Teller–Gamow paper unexpectedly and quickly led to a better understanding of the generation of nuclear energy in the Sun. Bethe had just proposed the carbon–nitrogen–oxygen cycle as a mechanism for catalyzing the transformation of hydrogen into helium, which works for heavier, hotter stars than the Sun. Bethe, along with Gamow and Charles Critchfield, realized that another mechanism must be required for the Sun. Together, they proposed the proton–proton chain reaction, which relies on the Gamow–Teller spin-flip transformation of two protons into deuterium, releasing a positron and a neutrino as one proton changes into a neutron.

Both the original Fermi and Gamow–Teller theories of beta decay obeyed the symmetry of parity (or mirror symmetry). In the 1950s, Chen Ning Yang, a student of Teller's, and Tsung-Dao Lee explored the conservation of parity in beta decays. They discovered that, unlike gravitation and electromagnetism, parity was not conserved in some weak decays described by a novel mixture of the Gamow–Teller and Fermi theories. Yang and Lee were awarded the Nobel Prize in Physics in 1957 for this work. Later, the unification of weak and electromagnetic interactions grew out of these and other insights. Thus, the Gamow–Teller transitions, originally proposed to explain nuclear phenomena, proved to be a key step toward the standard model of fundamental interactions.

Teller also worked on other aspects of nuclear physics. In 1937, he wrote a set of papers with Julian Schwinger, who shared the Nobel Prize in Physics with Sin-Itiro Tomonaga and Richard Feynman in 1965. These papers focused on the coherent behavior of neutrons scattering off hydrogen molecules—similar to x rays scattering off crystals. The scattering of slow neutrons provided a new tool for understanding the behavior of molecular and condensed-matter systems and explained the basic binding of neutrons and protons into deuterons. During this era, Teller also worked with John Wheeler analyzing nuclei rotations.

A decade later, Teller and Maurice Goldhaber—another refugee from Germany—proposed that the giant dipole nuclear resonance observed in high-energy, gamma-ray reactions with nuclei was the result of a collective vibration of the neutrons and protons. Realizing that the resonance was analogous to the oscillating behavior of sodium and chlorine ions within a crystal of salt in the presence of light, Goldhaber sought out Teller because he had understood and proposed important general laws governing the interaction of light and salts. Together, they went on to invent their giant dipole resonance model.

Edward Teller and Enrico Fermi converse on the University of Chicago campus in 1951. (Courtesy of American Institute of Physics Emilio Segré Visual Archives.)

During the late 1940s and early 1950s, many nuclear physicists shifted their focus to probing the properties of newly discovered fundamental particles. In the 1930s, Yukawa hypothesized a new particle called pi meson (or pion) as the intermediary of the strong nuclear force that binds protons and neutrons. In 1947, scientists debated whether the newly discovered mu meson (or muon) was the long-sought pion. Teller, together with Fermi and Victor Weisskopf, showed that the muon could not be the pion. Several months after their paper appeared, other researchers discovered the real pion.

After the founding of Lawrence Livermore in 1952, Teller focused on developing the hydrogen bomb and related areas of science at the new laboratory. In the 1960s, he worked with Livermore physicists, including Mort Weiss and Stewart Bloom, on the interactions of K mesons with matter. Teller also worked with George Chapline, Montgomery Johnson, and Weiss on one of the earliest papers regarding the collisions of heavy ions.

For more than four decades, Teller made key contributions to nuclear and particle physics, including a major step toward the unification of fundamental interactions.

—Arnie Heller

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