Enrico Fermi’s impact on science

BY JOHN H. MARBURGER III

Fermi’s work with slow neutrons prepared the way for the discovery of nuclear fission, the key to extracting energy from nuclear reactions.

ENRICO FERMI IS the father of modern nuclear physics and a physicist’s physicist, whose legacy was one of style as well of substance—a style so attractive and so productive for science that it became substantive in itself. In his 1938 Nobel Prize speech, Fermi acknowledged the grandfather of this field, Lord Rutherford, who a generation earlier had begun bombarding substances with alpha particles, the positively charged nuclei of helium atoms that shoot out from uranium, radium, and other heavy elements. Those early experiments bore much fruit for physics, including today’s atomic model of a tiny massive nucleus orbited by electrically bound lightweight electrons. But while they elucidated the overall structure of the atom, Rutherford’s experiments did not penetrate the mysteries of the nucleus itself.

Fermi realized that the electrostatic repulsion on the positive charge of Rutherford’s bombarding alpha particles prevented them from entering the positively charged nucleus. He perceived that the neutron, discovered by James Chadwick in 1932, having no charge at all, would be the ideal probe for nuclear studies. Starting in 1933, Fermi and his students conducted systematic studies of the effect of neutron irradiation of the chemical elements. This was the beginning of our knowledge of nuclear matter.

Neutrons were produced for these studies by the collisions between alpha particles from a radioactive source (an alpha emitter) and a light element such as beryllium. The two elements were mixed together in pellets to form compact “neutron guns.” Later beryllium targets were bombarded by deuterium ions energized in an accelerator. The most modern sources produce neutrons in a similar way, by directing a high-energy proton beam onto a target, dislodging a spray of neutrons in what is called a spallation reaction. The Department of Energy’s huge Spallation Neutron Source, now under construction at Oak Ridge, Tenn., is designed to provide neutrons for thousands of scientists whose work follows in a direct line from that of Fermi and his many students.

Fundamental discoveries

In these early experiments, Fermi made two fundamental discoveries cited by the Nobel Committee. The first was the discovery of new elements created from targets whose nuclei trapped the bombarding neutrons in a fashion that is easy to visualize but hard to calculate. Fermi’s laboratory was the first to create and identify elements with atomic numbers greater than 92 (uranium), the highest naturally occurring element. In honor of this work, the artificial element number 100 is named “Fermium,” abbreviated Fm. Its longest lived isotope (257) has, coincidentally, a half-life of 100 days.

Fermi: A lifetime of achievement

The second important discovery was a more subtle effect, in which the trapping process was found to depend on the energy or speed of the incoming neutrons. To perform these experiments, Fermi exploited the slowing effect of “moderating” substances like paraffin and water that contain hydrogen nuclei of nearly the same mass as the neutrons. As you are probably aware from your own experience with colliding things, energy transfer is maximized in collisions among particles of equal mass. By interposing various thicknesses of moderators between the neutron source and the target, Fermi and his students could map out a spectrum of the neutron speeds required to activate the target, with well-defined peaks of activation energy. This was the beginning of nuclear spectroscopy, an essential tool for the production and application of isotopes in chemistry, medicine, and materials science—a field that remains important today.

Fermi was an ingenious experimenter who obviously took pride in the details of his apparatus. The following excerpt from his Nobel speech reveals his enthusiasm, as well as his talent for clever experiments:

> In order to measure, directly at least, the order of magnitude [of the time neutrons remained free to diffuse in a moderator], an experiment was attempted by myself and my collaborators. The source of neutrons was fastened at the edge of a rotating wheel, and two identical detectors were placed on the same edge, at equal distances from the source, one in front and one behind with respect to the sense of rotation. The wheel was then spun at a very high speed inside a fissure in a large paraffin block. We found that, while, with the wheel at rest, the two detectors became equally active, when the wheel was in motion during the activation, the detector that was behind the source became considerably more active than the one in front. From a discussion of this experiment was deduced, that the neutrons remain inside the paraffin for a time of the order of 10^{-4}seconds.

Years before these famous experiments, Fermi had already proven himself to be a powerful theorist. He was the first to apply the Pauli exclusion principle to systems of multiple electrons not attached to atoms.

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The Pauli principle states that for a certain class of particle known collectively today as "fermions," no two can be in exactly the same quantum state. Crudely speaking, two such particles cannot be found in the same place. By contrast, another class of particle exists, known as "bosons," which rather prefer to be in the same state. The 2001 Nobel Prizes in physics were awarded to scientists who demonstrated "Bose-Einstein Condensation" of bosonic atoms. Similar experiments on fermionic atoms are also being conducted, but of course they behave completely differently because they prefer to be in different states, even at low temperatures.

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Electrons are fermions, and when metallic atoms condense to form electrical conductors or semiconductors, their electrons fill the lowest unoccupied energy states up to a surface called the Fermi surface, whose location and shape determine many important properties of the material. The surface does not appear in real space, but rather in the space of labels that define the quantum states that are filled or unfilled. It is most convenient to label states of electrons that can move freely about by their momenta, so the Fermi surface is a surface of constant energy in momentum space. I do not mean to imply that Fermi was responsible for the electronics industry, but every electrical engineer today knows what a Fermi surface is.

In this same category of work appears Fermi's treatment of the properties of atoms with many electrons. Every physics student learns how to apply the equations of quantum theory to derive the spectrum of hydrogen, which with one electron is the simplest atom. But a similarly direct approach for heavier atoms is hopelessly complicated. Fermi regarded the many electrons surrounding such atoms as forming a gas that moves in an effective potential whose form could be derived in a self-consistent way. A similar result was obtained independently by L. H. Thomas, so the approach is called the Thomas-Fermi method. Fermi performed many calculations using this method, laboriously executing the necessary repeated arithmetical operations that today are done so effortlessly by computers.

These theoretical manipulations occurred at the time when quantum theory itself was still being invented by the great frontiersmen of the early 20th century. Fermi contributed important technical ideas to the theory of quantum electrodynamics, notably in the quantization of the electromagnetic field. His 1930 paper on this subject is a model of lucid exposition wherein deep results appear almost effortlessly. His treatment remains to this day a standard way of introducing the subject.

Weak interactions

Of greater importance has been Fermi's theory of weak interactions, a topic of profound interest even decades after his death in 1954. Some historical context is necessary to appreciate its importance. Until the discovery of the neutron in 1932, progress in the understanding of matter was toward simplification. By the end of the 19th century, chemists had nearly exhausted the search for different kinds of elementary atoms. The result, summarized in Mendeleev's periodic table, included 92 varieties, from hydrogen, the lightest, to uranium, the heaviest. After Rutherford demonstrated the general shape of the atom in 1911, there was reason to believe that all of the 92 varieties could be made up of only two particles, electrons and protons. Some electrons were assumed to be bound within the nucleus by a mysterious force, others orbited far away from the nucleus. This extraordinary reduction of all nature to only two components was a great triumph for science, but it created a psychological prejudice against the introduction of additional particles to explain new phenomena.

When Chadwick discovered the neutron, it was only natural to think of it as a combination of a proton and an electron, especially since it was found to decay—in about 10 minutes, when outside a nucleus—into an electron and another particle that we now call the "electron neutrino." It was difficult to understand, however, why an electron should be bound so tightly in the neutron, which except for its charge closely resembles the tiny massive proton, when the electron circling the proton in a hydrogen atom keeps its distance at 100 000 times the proton radius. By what process is the electron held within the neutron, and how do we describe its release during neutron decay?

Fermi's theory of weak interactions remains an accurate and useful approximation.

Fermi answered this question with a theory of neutron decay that became the model for all future theories of particle interaction. He did not assume that the decay products were present in the neutron before the decay, but rather compared the situation with the emission of light from an electron within an atom. A photon is created "on the spot" out of the energy available when the electron passes to a lower state. Fermi postulated that the proton, electron, and neutrino were similarly created on the spot, and wrote down a mathematical expression for the interaction that was similar to the basic interaction in quantum electrodynamics, but more complicated. This theory was the first to apply quantum fields to particles other than the electron, and has guided the development of our understanding of weak interactions to the present day. We now understand more about what is happening, of course, and the complicated interaction Fermi postulated is now known to involve two simpler interactions, both very similar to the electromagnetic interaction. In place of the photon, a new kind of particle is involved (one of the "massive vector bosons" of the weak gauge field), unknown to science before the 1970s. But Fermi's theory of weak interactions remains an accurate and useful approximation. Moreover, the entire subsequent development of what is now called the Standard Model employs quantum fields and interactions in much the way Fermi first introduced them into physical theory.

Fermi's work with slow neutrons prepared the way for the discovery of nuclear fission, the key to extracting energy from nuclear reactions. He might well have made this discovery himself, but others did it first, in Germany. When he came to the United States directly after the 1938 Nobel ceremony, the clouds of war were gathering in Europe. In the following year, Hitler's troops overran Poland. The intellectual community in America that Laura Fermi later described in her famous book *Illustrious Immigrants* included physicists who pondered with foreboding the unfortunate coincidence of Hitler's rise to power and the discovery of nature's most awesome source of energy. It was natural that Fermi should join the effort first to understand, and then to enlist, nuclear power in the cause of war. Within two years, Fermi was building the world's first nuclear reactor under the University of Chicago's Stagg Field.

Nuclear reactors

Fermi's talents were well-suited to this task. No one understood the interaction of neutrons with matter as well as he, and no one else had the wide range of skills and knowledge that would lead as quickly to a working reactor. Fermi's team did build a successful reactor that first went critical on December 2, 1942. The reactor was a "pile" of graphite moderator and uranium fuel, with cadmium control elements. Fermi had found cadmium to be a strong neutron absorber, and the combination of components was designed to produce neutrons with just the right energy to be captured by the uranium nuclei, which subsequently break apart, or fission, creating additional neutrons to keep the reaction going. Many new elements are created in this process, not only in the direct incorporation of neutrons in the uranium nuclei, but also among the fission fragments.

Nuclear reactors can produce three things: new chemical isotopes, heat, and neutrons. For the war effort, reactors could produce the new element plutonium, useful for nuclear weapons, from an old chemical, natural uranium, which is not (a rare isotope of uranium is useful for weapons, but that is another story). For practical applications, the production of heat is most important, because it can drive steam generators to produce electricity. For science, the most important applications are the production of isotopes for medical and materials studies, and the production of neutrons to use as probes to image the atomic structure of matter. Reactors optimized for one application will not in general be optimized for another. Research reactors, for example, are optimized for neutron or isotope production, and not for heat, so they "run cool" and tend to be much smaller than power reactors.

Over the next few years, Fermi came to be viewed as an oracle by people working on the Manhattan Project. His long experience with neutrons and remarkable mastery of physics gave him what seemed an intuitive knowledge of neutron behavior. In his biography of Fermi, Emilio Segrè remarked that when an engineer needed a piece of information, the regular procedure was to ignore Fermi's protests that that quantity had not been measured and could not be predicted. The engineer would just recite slowly a series of numbers while watching Fermi's eyes closely, and "the correct number would produce an involuntary twinkle in his eyes."

In 1943, Fermi provided both scientific and engineering guidance for the development of a new nuclear reactor at Argonne, in Illinois. This work ultimately led to the construction of large plutonium production reactors at Hanford, Wash., by the DuPont Company. In 1943 and 1944, and again after the war, Fermi also used the Argonne reactor for pure research, and showed how neutrons could be useful for solid-state physics.

By that time, X-ray diffraction had become an established technique for examining crystal structures. When any wave with a well-defined wavelength falls upon a structure that has a pattern that repeats itself on the scale of the wavelength, the incoming wave is strongly redirected at a definite angle related to the spacing of the structure. Since, according to quantum theory, particles like neutrons have wave properties, they can be used in diffraction experiments just like X rays. Unlike X rays, however, which interact with the clouds of electrons within a crystal structure, neutrons interact directly with the nuclear cores of the crystal lattice, which possess nearly all the mass of the structure. Neutrons are also microscopic magnets, and therefore they can be used to probe the magnetic properties of materials. This is why we go to so much trouble to produce neutrons in facilities like research reactors, or the upcoming Spallation Neutron Source at Oak Ridge. These facilities are complementary to the fabulously productive synchrotron light sources, which produce intense X rays.

Variety of problems

Back to the Manhattan Project: Everyone knows the story of the secret laboratory established at Los Alamos, N.M., under the direction of J. Robert Oppenheimer. Here the atomic bomb itself was to be designed and built. The laboratory got under way in mid-1943 and Fermi went occasionally as a consultant until August 1944, when he moved there full-time. Throughout these years, he helped the scientists and engineers to solve a wide variety of physical problems, ranging from hydrodynamics to electronic circuit design. As an associate director, Fermi had responsibility for a new division, which included theory, and later the hydrogen bomb, and a homogeneous reactor in which Fermi took an active interest. In this reactor, uranium salts were dissolved in water, which served as moderator. It was made to operate at 5 kilowatts.

In the preparations for testing the bomb, Fermi's help was invaluable. As Segrè says, "This was one of those occasions when Fermi's dominion over all physics, one of his most startling characteristics, came into its own. The problems involved in the Trinity test ranged from hydrodynamics to nuclear physics, from optics to thermodynamics, from geophysics to nuclear chemistry. Often they were closely interrelated, and to solve one it was necessary to understand all the others. Even though the purpose was grim and terrifying, it was one of the greatest physics experiments of all time. Fermi completely immersed himself in the task. At the time of the test, he was one of the very few persons (or perhaps the only one) who understood all the technical ramifications of the activities at Alamogordo."

The Trinity test—the actual ignition of the device—occurred on July 15, 1945, and Fermi observed it from a distance of nine miles. Soon after the bomb exploded, he released small pieces of paper from his hand. In still air they would fall at his feet, but when the shock wave arrived (many seconds after the brilliant flash of light), the bits of paper were blown some distance away from him. Using a table of numbers he had prepared in advance, he was able to estimate the energy released by the bomb from the displacement of air and the known distance from the source. As usual for Fermi, his answer closely approximated that of the elaborate official measurements, which took several days to analyze. The bomb's energy proved to be near the high end of the range of estimates that had been made by scientists at Los Alamos.

Fermi's work with reactors makes him the father of nuclear energy, and it is for this reason, as well as for his important contribution to the war effort, that the United States Congress gave him a special award just prior to his death in November 1954. Two years later an award was established in his honor, given annually by the Department of Energy and the President of the United States.

I have mentioned only the high points of Fermi's contribution to science. Those who worked with him held him in the greatest esteem. C. N. Yang, another great physicists' physicist, wrote this in his autobiography:

> . . . my taste in physics was largely formed . . . when I was a student in Kunming. It was in those years that I learned to admire the work of Einstein, Dirac, and Fermi. They have, of course, very different styles. Nonetheless, they share the ability to extract the fundamentals of a physical concept, a theoretical structure, or a physical phenomenon and to zero in on the essentials. Later, when I came to know Fermi and Dirac, I realized that they spoke and thought about physics very much in the way that I had imagined them to do from studying their papers.

Yang's scope of accomplishment in physics is also broad and brilliant, his style elegant and more austere than Fermi's, and his words testify to the power of Fermi's approach to science. Even through the dry language of technical reports, dense with mathematical equations, Fermi's spirit reaches across oceans of time and space to inspire us still to zero in on the essentials. NN