ture at the base of the envelope.†† On the other hand, the β-particle emitted from the practically flat surface of the nuclear core always had the *same energy* determined by the inner properties of the nuclear fluid. Thus, there must have existed a dynamical equilibrium between the nuclear core and the surrounding ionized gas (plasma) similar to the equilibrium between the water and the saturated vapor above it. The number of β-particles emitted by the radioactive core was equal to the number of free electrons from the envelope absorbed by it. But, whereas the energy of the absorbed free electrons from the envelope was determined by its temperature T, the energy of β-particles emitted by the core was always the same, corresponding to a certain universal nuclear temperature, T_0. Therefore, for $T < T_0$ there was a constant energy flow from the nuclear core into the envelope, and this flow, rising to the star's surface, maintained its high temperature. By virtue of non-conservation of energy in β-emission processes nothing changed in the nuclear core and the stars could shine eternally. Bohr spoke about this theory of his in a slightly critical fashion, but it looked as if he would not be greatly surprised if it were true.

THE NEUTRINO

Pauli, who could not be called conservative in any sense of the word, was nevertheless strongly opposed to Bohr's view. He preferred to assume that the bal-

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†† According to the mechanical theory of heat developed by Boltzmann and Maxwell in the middle of the last century, "Heat is nothing but the motion of molecules forming material bodies." They found that the energy of thermal motion (per molecule) is proportional to its absolute temperature—that is, the temperature counted from "absolute zero" at −273°C. The empirically determined coefficient of proportionality (or rather two-thirds of it) was called the Boltzmann constant.

ance of energy violated by the continuity of β-ray spectra was re-established by the emission of some other kinds of yet unknown particles which he called "neutrons." The name of this "Pauli neutron" was later changed to "neutrino" after Chadwick's discovery of what today we call the neutron. Neutrinos were supposed to be particles carrying no electric charge and having no mass (or, at least, no mass to speak of). They were supposed to be emitted, being paired with β-particles in such a way that the sum of their and the β-particles' energies was always the same, which would of course re-establish the good old law of Conservation of Energy. But, due to their zero-charge and zero-mass, they were practically undetectable, slipping between the fingers of the most skillful experimentalists. Besides Bohr, another neutrinophobe was P. Ehrenfest, and heated verbal discussions and voluminous but never-published correspondence on the subject were exchanged among the three of them.

As the years passed, more and more evidence was accumulated in favor of Pauli's neutrinos even though this evidence was circumstantial. It was not until 1955 that two Los Alamos physicists, F. Reines and C. Cowan, established beyond any doubt the existence of neutrinos by trapping them when they were escaping from the atomic piles of the Savannah River Atomic Energy Commission project. They found that the interaction between neutrinos and matter was so small that an iron shield several light years thick would be needed to reduce the intensity of the neutrino's beam by one-half. Today neutrinos have a larger and larger place in the study of elementary particles and astrophysical phenomena; they may become the most important elementary particles in physics. Like electrons, neutrinos were found to behave as little spinning tops, and their angular momenta are exactly equal to an

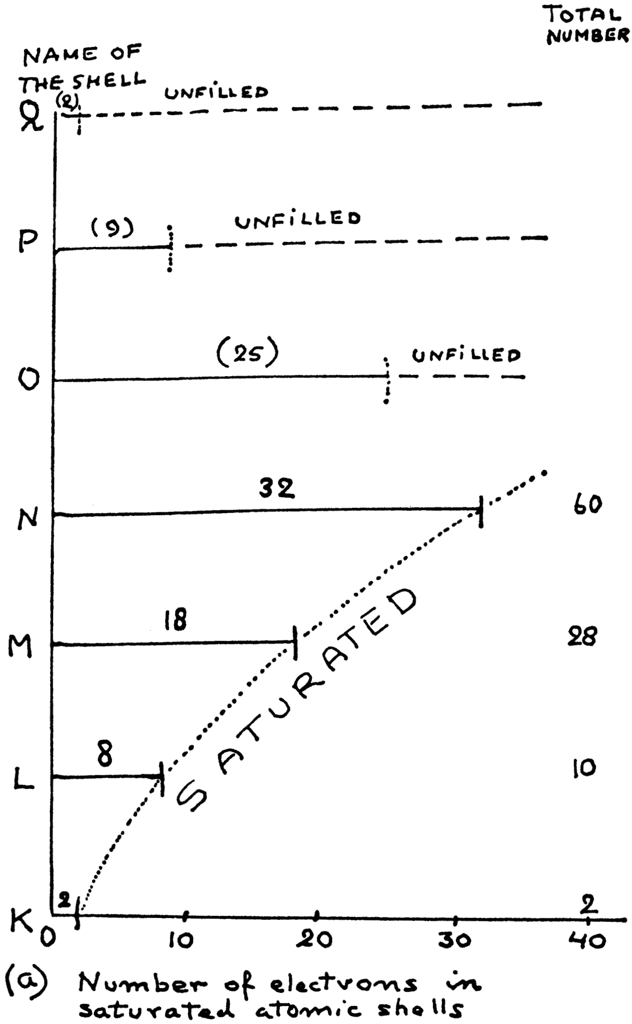
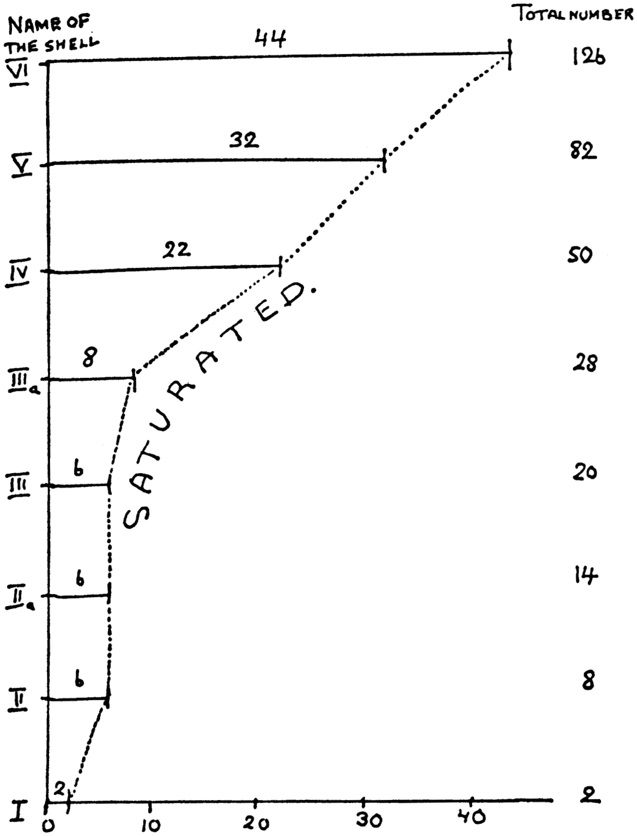


Fig. 18. A comparison between (a) the saturation of electron shells in Bohr-Coster diagram of the sequence of atoms and (b) Mayer-Jensen's diagram of the saturation of proton and neutron shells in the sequence of atomic nuclei.



(8) Number of protons or neutrons in saturated nuclear shells

electron's. But since neutrinos carry no electric charge, their magnetic moment is equal to zero.

It was later found experimentally that protons and neutrons also have the same spin as electrons and also obey the Pauli Principle. The latter fact is of great importance in the problem of internal structure of atomic nuclei, which are formed by an agglomeration of various numbers of protons and neutrons tightly bound together by nuclear forces. As was first shown by G.

Gamow in 1934, the natural sequence of atomic nuclei from hydrogen to uranium isotopes shows periodic changes in their various properties, similar to but much smaller than the changes of chemical properties of atoms in Mendeleev's periodic system of elements. This periodicity indicated that atomic nuclei must have a shell structure similar to but probably more complicated than the shell structure of the atomic electron envelopes. The situation here is complicated by the fact that, whereas atomic envelopes are formed by only one kind of particle, namely electrons, the nuclei are formed by two kinds of particles, neutrons and protons, and that Pauli's Exclusion Principle applies to each kind separately. Thus, any given energy state characterized by three quantum numbers can accommodate two protons (with opposite spin) along with two neutrons (also with opposite spin), and we actually have two systems of shells, one for protons and one for neutrons, overlapping on one another. There is another difficulty. Because of the close packing of protons and neutrons in the nucleus, the calculations of energy levels become considerably more complicated. The problem was finally solved in 1949 by M. Goeppert Mayer and H. Jensen et al., who were able to prove that the neutron as well as the proton shells inside the nuclei have capacities of 2, 8, 14, 20, 28, 50, 82, and 126 particles each, as is shown schematically in Fig. 18. These numbers, known as "Magic Numbers," permitted physicists to understand completely the observed periodicity in nuclear structure.

Another important application of Pauli's Principle can be found in the work of P. A. M. Dirac, who used it for the explanation of the stability of matter, as will be described in Chapter VI. On the basis of his theory, Dirac was led to the conclusion that to each "normal particle," such as an electron, proton, neutron, and the hordes of other particles discovered during the last decade, there must exist an "anti-particle" with exactly the same physical properties but the opposite electric charge. This will be discussed in more detail in Chapters VI and VIII.

To finish this present chapter, it is enough to say that it is just as difficult to find the branch of modern physics in which the Pauli Principle is not used as to find a man as gifted, amiable, and amusing as Wolfgang Pauli was.

more complicated, too much for any one man to handle. The physics profession split into two branches, "experimentalists" and "theoreticians." The great theoretician Albert Einstein never did an experiment with his own hands (to the author's knowledge, at least), while the great experimentalist Lord Rutherford was so poor in mathematics that the famous Rutherford formula for α-particle scattering was derived for him by a young mathematician, R. H. Fowler. Today, as a rule, a theoretical physicist never dares touch experimental equipment for fear of breaking it (see the Pauli Effect in Chapter III), while experimentalists are lost in the turbulent flow of mathematical computations.

Enrico Fermi, born in Rome in 1901, represented a rare example of an excellent theoretical as well as experimental physicist. One of his important contributions to theoretical physics was the study of degenerated electron gas, which had important consequences in the electron theory of metals as well as in the understanding of the super-dense stars known as white dwarfs. Another important work was the formulation of the mathematical theory of particle transformation, involving the emission of mysterious chargeless and massless particles proposed earlier by Pauli.

Fermi was a sturdy Roman boy with a great sense of humor. While he was still a professor in the University of Rome, Mussolini awarded him a title: "Eccellenza" (His Excellency). Once he had to attend a meeting of the Academy of Sciences at the Palazzo di Venezia, which was strongly guarded because Mussolini himself was to address it. All other members arrived in large foreign-made limousines driven by uniformed chauffeurs, while Fermi drew up in his little Fiat. At the gate of the Palazzo he was stopped by two *carabinieri* who crossed their weapons in front of his little car and asked his business there. According to the story he told to the author of this book, he hesitated to say to the guards: "I am His Excellency Enrico Fermi," for fear that they would not believe him. Thus, to avoid embarrassment, he said: "I am the driver of His Excellency, Signore Enrico Fermi." *"Ebbene,"* said the guards, "drive in, park, and wait for your master."

Although the idea of chargeless and massless particles accompanying electrons emitted in β-transformations was originally conceived by Pauli, Fermi was the first to develop the strict mathematical theory of β-emission coupled with the emission of Pauli's pet particles, and to show that it fits perfectly with the observed facts. He was also responsible for its present name, *neutrino.* The point is that Pauli called his protégé the *neutron,* which was all right since the particle called "neutron" today (the chargeless proton) had not then been discovered. However, that name was not "copyrighted" since it was used only in private conversations and correspondence but never in print. When, in 1932, James Chadwick proved the existence of a chargeless particle with a mass closely equal to that of a proton, he called it the *neutron* in his paper published in the *Proceedings of the Royal Society of London.* When Fermi, still being a professor in Rome, reported Chadwick's discovery at the weekly physics seminar, somebody from the audience asked whether "Chadwick's neutron" is the same as "Pauli's neutron." "No," answered Fermi (naturally speaking in Italian), *"i neutroni di Chadwick sono grandi e pesanti. I neutroni di Pauli sono piccoli e leggieri; essi debbono essere chiamati neutrino."*†

Having made this philological contribution, Fermi

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† In Italian *neutrino* is the diminutive of *neutrone;* in other words, "the little neutron." Fermi's reply is translated: "No, the neutrons of Chadwick are large and heavy. Pauli's neutrons are small and light; they have to be called neutrinos."

set forth to develop a mathematical theory of β-transformation in which an electron (positive or negative) and a neutrino are emitted simultaneously by unstable atomic nuclei, sharing the available energy at random among themselves. He shaped his theory along lines similar to the theory of light emission by atoms, where an excited electron makes the transition to a state of lower energy, in the process liberating the excess energy in the form of a single light quantum. The motion of the electron before the discontinuous transition was described by the wave function spreading over a comparatively large area. After the transition the electron's wave function shrank to a smaller size, and the liberated energy formed a divergent electromagnetic wave spreading through the surrounding space. The forces responsible for that transformation were the familiar forces acting between the electromagnetic field and the point charge. Thus, their effect could easily be computed on the basis of the existing theory. It was found that the computed probabilities of electron transitions stood in perfect agreement with the observed intensities of spectral lines.

In his theory of β-decay Fermi faced a much more complicated situation. In this case, a neutron occupying a certain energy state within the nucleus turned into a proton, thus changing its electric charge. Also, instead of a single light quantum, two particles (an electron and a neutrino) were emitted simultaneously.

THE FORCES BEHIND β-TRANSFORMATION

The main difficulty, however, was that, whereas in the case of light emission the forces governing the process were the familiar electromagnetic forces, the forces responsible for β-transformation were absolutely unknown and Fermi had to make a guess as to what they were. Characteristically for a genius, he decided to make the simplest possible assumption–that the probability of the transformation of a neutron into a proton (or vice versa), resulting in the formation of an electron (negative or positive) and a neutrino,‡ is simply proportional to the product of the intensities of four corresponding wave functions at any given point within the nucleus. The coefficient of proportionality, which Fermi designated by the letter g, had to be determined by comparison with the experimental data. Using rather complicated mathematics, Fermi was able to compute what the shape of the β-energy spectrum should be, and how the rate of β-decay should depend on the amount of energy involved if his simple interaction hypothesis was correct. The result was in brilliant agreement with the observed curves.

The only flaw in Fermi's theory of β-decay was that the numerical value of the constant g (3×10^{-14} in dimensionless units§) could not be derived from the theory and had to be taken directly from observation. The extreme smallness of the numerical value of g is responsible for the fact that, whereas emission of a γ-quantum by a nucleus occurs within 10^{-11} seconds, the emission of an electron-neutrino pair may take hours, months, or even years. This is why all particle transformations are known in modern physics as *weak interactions*. It is the task of physics of the future to explain these extremely weak interactions in all processes involving the neutrino emission absorption.

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‡ We will not go here into the distinction between a neutrino and an anti-neutrino.

§ $|g| \cdot \frac{|mc^2|}{|\sqrt{2\pi h^3}|}$, where m is the electron mass, c the velocity of light, and h the quantum constant.

USING FERMI INTERACTION LAWS

Analogous to the β-decay processes[¶]

$$n \longrightarrow p + \bar{e} + \nu + \text{energy}$$

and

$$p + \text{energy} \longrightarrow n + \overset{+}{e} + \nu$$

are other processes which are also subject to Fermi interaction laws. One is the absorption of the atomic electron by a nucleus which is unstable in respect to positive β-decay. Instead of emitting a positive electron and a neutrino, a nucleus may absorb a negative electron from its own electron shell, emitting a neutrino according to the formula:

$${}_{z}(\text{nucl.})^{A} + \bar{e} \longrightarrow {}_{z-1}(\text{Nucl.})^{A} + \nu + \text{energy}$$

Since the atomic electron absorbed by the nucleus in such a process is one of the electrons from the K-shell (nearest to the nucleus), it is usually known as "K-capture." The simplest example of such a process is the unstable isotope of beryllium, Be^7, which may transform either according to formula[††]

$${}_{4}Be^{7} \longrightarrow {}_{3}Li^{7} + \overset{+}{e} + \nu + \text{energy}$$

or

$${}_{4}Be^{7} + (\bar{e})_{K-\text{shell}} \longrightarrow {}_{3}Li^{7} + \nu + \text{energy}$$

In the latter case, cloud chamber photographs show just a single track (that of ${}_{3}Li^{7}$), and the situation is similar to an incident described by H. G. Wells in his

[¶] According to energy considerations, the first process occurs in the case of the free neutron, as well as in the case of neutrons bound inside the nucleus, whereas the second occurs only within the complex nuclei where the additional energy supply can be obtained from other nucleons.

[††] The lower index on the left gives the atomic number whereas the upper index on the right gives atomic weight.

well-known story *The Invisible Man,* where a London constable was kicked in the pants from behind and, turning around, could not see anybody who could have kicked him. Observational studies of the K-capture processes showed that the frequency of their occurrence agrees exactly with that predicted by Fermi's theory.

Another interesting process belonging to the same category is the H-H (Hydrogen-Hydrogen) reaction, first proposed by Charles Critchfield, which is responsible for the energy production in our Sun and other fainter stars.‡‡ During the short interval of time while two colliding protons are in close contact, one of them turns into a neutron through emission of a positive electron and a neutrino, forming the nucleus of deuterium (heavy hydrogen) according to the equation:

$$ {}_1p^1 + {}_1p^1 \longrightarrow {}_1d^2 + \overset{+}{e} + \nu + \text{energy} $$

The probability of this process can be predicted exactly on the basis of Fermi's theory.

The last but not the least example of the Fermi interaction is the process by means of which F. Reines and C. Cowan directly proved the existence of neutrinos. It is:

$$ {}_1p^1 + \nu + \text{energy} \longrightarrow {}_0n^1 + \overset{+}{e} $$

Reines and Cowan observed it in a chamber placed close to an "atomic pile," at the Savannah River Atomic Energy Project. The number of observed neutrons and positive electrons formed simultaneously in the chamber subjected to extensive neutrino bombardment turned out to be exactly equal to that predicted by the Fermi theory. The interaction is so weak that,

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‡‡ In the case of brighter stars, Sirius for example, the main energy-producing reaction is the so-called carbon cycle, proposed independently by C. von Weizsacker and H. Bethe.

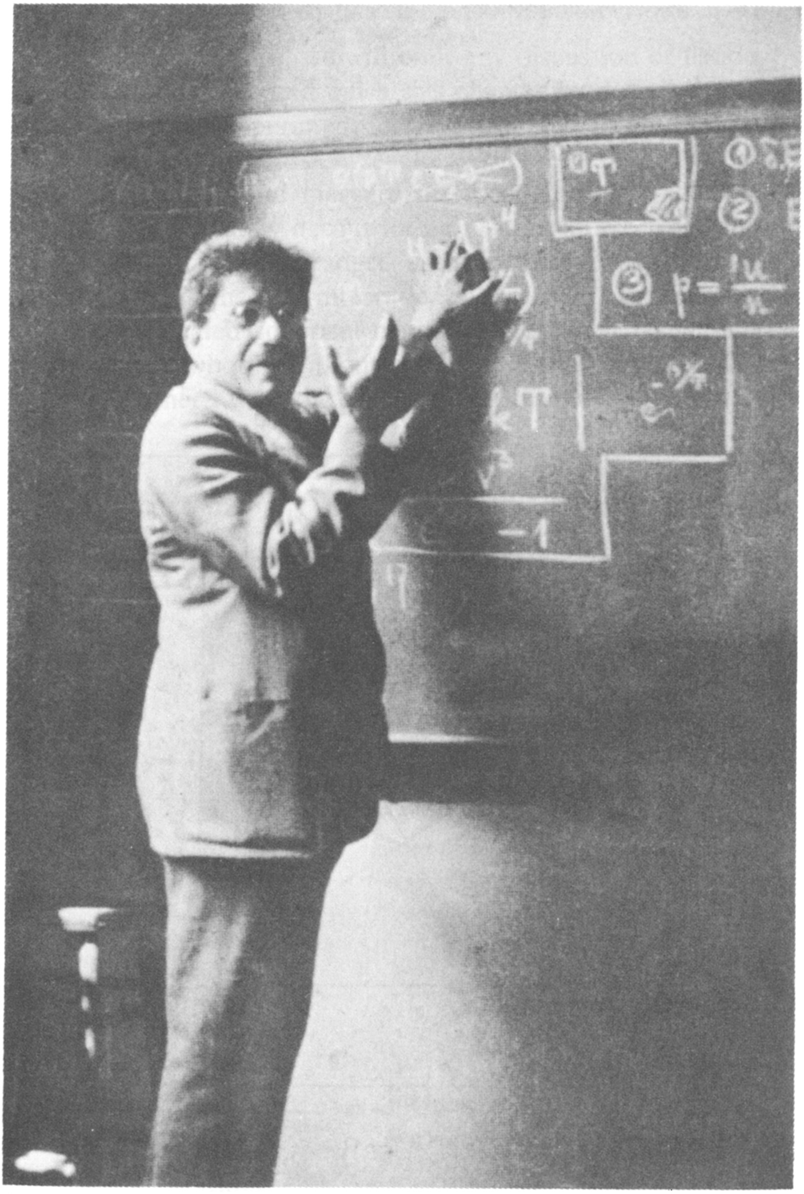
in order to absorb one-half of the emitted neutrinos, one should use a liquid hydrogen shield several light years thick! Fermi's theory of the processes involving neutrinos also applies to many cases of decay of new elementary particles discovered during more recent years, and one speaks today about the "Generalized Fermi Interaction."

FERMI'S RESEARCH IN NUCLEAR REACTIONS

Along with his theoretical studies, Fermi was involved in extensive experimental research on nuclear reactions in heavy elements bombarded by slow neutrons, and the formation of trans-uranium elements ($z > 92$), and for this work he received the Nobel Prize for 1938. Soon thereafter he came to the United States to live and was present at the 1939 conference at George Washington University at which Niels Bohr read a telegram from Lise Meitner, a noted German physicist, (who by that time was living in Stockholm) containing very exciting news. She told him that her former collaborators, Otto Hahn and Fritz Strassman, at Berlin University had found that a uranium nucleus hit by a neutron splits into two about equal parts, liberating vast amounts of energy. This announcement started a series of events which culminated, not too many years later, in nuclear bombs, nuclear power plants, etc., heralding the beginning of what one often calls the Atomic (Nuclear would be more correct) Age.

Fermi took the leadership in the top-secret laboratory at the University of Chicago, and on December 2, 1942 announced that on that afternoon the first chain reaction in uranium was achieved, thus initiating the first controlled release of nuclear energy by man.

Since this book is devoted to the progress of the understanding of the nature of things, and not to the prac-



Professor Paul Ehrenfest explaining a difficult point to his audience. (Photographed, probably, by Dr. S. Goudsmit)