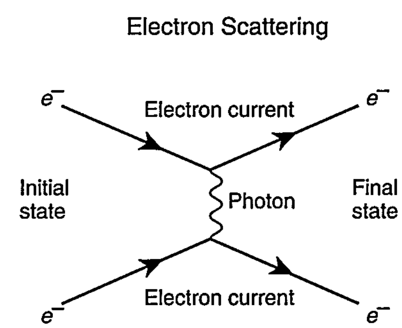
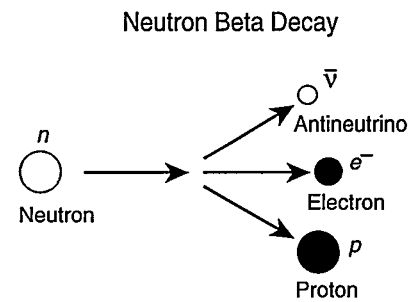
Fermi's Theory of Beta Decay and Neutrino Processes

In 1934, long before the neutrino was detected in an experiment, Fermi gave the neutrino a reality by writing down his simple and brilliant model for the beta decay process. This model has inspired the modern description of all weak-interaction processes. Fermi based his model on Dirac's quantum field theory of electromagnetism in which two electron currents, or moving electrons, exert force on each other through the exchange of photons (particles of light). The upper diagram represents the interaction between two electrons. The initial state of the system is on the left, and the final state is on the right. The straight arrows represent currents, or moving electrons, and the wiggly line between the currents represents the emission of a photon by one current and its absorption by another. This exchange of a photon causes the electrons to repel each other. Note that the photon has no mass, a fact related to the unlimited range of the electromagnetic force.



The fundamental process that takes place in beta decay (see lower diagram) is the change of a neutron into a proton, an electron, and an antineutrino. The neutron may be a free particle, or it may be bound inside the nucleus.

In analogy with quantum electrodynamics, Fermi represented beta decay as an interaction between two currents, each carrying the weak charge. The weak charge is related to the electric charge. Unlike the electromagnetic force, however, the weak force has a very short range. In Fermi's theory, the range of the force is zero, and the currents interact directly at a single point. The interaction causes a transfer of electric (weak) charge between the currents so that, for example, the neutron current gains one unit of charge and transforms into a proton current, while the electron current loses one unit of charge and transforms into a neutrino current.*



Because Fermi's theory is a relativistic quantum field theory, a single current-current interaction describes all weak-interaction processes involving the neutron, proton, electron, and neutrino or their antiparticles. As a result, we can represent all these weak-interaction processes with one basic diagram (on facing page, upper left corner).

*In the modern theory, the currents interact through the exchange of the *W*, a very heavy particle analogous to the photon. The *W* carries one unit of electric charge and one unit of weak isotopic charge between the weak currents.

a new subatomic particle that shares the available energy with the electron. To produce the observed energy spectrum, this new particle, later named the neutrino ("little neutral one"), could have a mass no larger than that of the electron. It had to have no electric charge. And like electrons and protons, the only subatomic particles known at that time, it had to be a fermion, a particle having half-integer spin (or intrinsic angular momentum). It would therefore obey the Pauli exclusion principle according to which no two identical neutrinos can be in the same state at the same time. Once created, the neutrino would speed away from the site at, or close to, the speed of light. But Pauli was concerned that the neutrinos he had postulated should have been already detected.

Shortly thereafter, in a brilliant burst of insight, Enrico Fermi formulated a mathematical theory that involved the neutrino and that has endured with little modification into the present. This theory postulates a force for beta decay and incorporates several brand-new concepts: Pauli's neutrino hypothesis, Dirac's ideas about the creation of particles, and Heisenberg's idea that the neutron and the proton were related to each other. In Fermi's theory of beta decay, this weak force, so called because it was manifestly much weaker than the electromagnetic force, turns a neutron into a proton and simultane-