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Weak Interactions and Nonconservation of Parity

T. D. Lee

In the previous lecture C. N. Yang (*1*) has outlined the position of our understandings concerning the various symmetry principles in physics prior to the end of 1956. Since then, in the short period of one year, the proper roles of these principles in various physical processes have been greatly clarified. This remarkably rapid development was made possible only through the efforts and ingenuities of many physicists in various laboratories all over the world. To have a proper perspective and understanding of these new experimental results, it may be desirable to review very briefly our knowledge about elementary particles and their interactions.

Elementary Particles and Their Interactions

The family of elementary particles that we know today consists of numerous members. Each member is characterized, among other properties, by its mass, charge, and spin. These members are separated into two main groups, the "heavy-particle" group and the "light-particle" group. The well-known examples of heavy particles are protons and neutrons, of light particles, photons and electrons. Apart from the obvious implication that a heavy particle is heavier than a light particle, this classification stems from the observation that a single heavy particle cannot disintegrate into light particles even if such disintegration should be compatible with the conservation laws of charge, energy, momentum, and angular momentum. This fact is more precisely formulated as the "law of conservation of heavy particles," which states that if to each heavy particle we assign a heavy particle number +1, to each antiheavy particle a heavy particle number −1, and to each light particle a corresponding number 0, then in all known physical processes the algebraic sum of the heavy particle numbers is absolutely conserved. One of the simplest evidences of the validity of this law is the fact that we, or our galaxy, have not disintegrated into radiation and other light particles.

Figure 1 shows all the known heavy particles (and antiheavy particles). All heavy particles except the nucleons are called hyperons and are labeled by capital Greek letters. The solid lines represent particles that have already been observed, while the dotted lines represent particles that are expected to exist from general theoretical arguments. All known heavy particles have half-integral spins. Figure 2 shows all the known light particles. Among these, the $e^{\pm}$, $\mu^{\pm}$ and ν, $\bar{\nu}$ have half-integral spins. They are called leptons. The rest—photons, pions, and K-mesons—have integral spins.

The interactions (not including the gravitational forces) between these particles can be classified into three distinct groups.

1) *Strong interactions.* This group is responsible for the production and the scattering of nucleons, pions, hyperons (that is, Λ°, Σ^{-}, and so forth), and K-mesons. It is characterized by a coupling constant $f^2/\hbar c \cong 1$.

2) *Electromagnetic interactions.* The electromagnetic coupling constant is $e^2/\hbar c = 1/137$.

3) *Weak interactions.* This group includes all known nonelectromagnetic decay interactions of these elementary particles and the recently observed absorption process of neutrinos by nucleons (*2*). These interactions are characterized by coupling constants $g^2/\hbar c \cong 10^{-14}$.

The law of conservation of parity is valid for both the strong and the electromagnetic interactions but is not valid for the weak interactions. This discussion will be mainly concerned with the recently observed effects of nonconservation of parity in the various weak interactions.

Noninvariance under Mirror Reflection and Charge Conjugation

The weak interactions cover a large variety of reactions. At present there are about twenty known phenomenologically independent reactions ranging from the decay of various hyperons to the decay of light particles. Within the last year, many critical experiments have been performed to test the validity of the law of conservation of parity in these reactions. We shall first summarize the experimental results together with their direct theoretical implications. Next, we shall discuss some further possible consequences and theoretical considerations.

β-Decay. The first experiment that conclusively established the nonconservation of parity was that on β-angular distribution from polarized cobalt-60 nuclei (*3*) (Fig. 3). The cobalt-60 nuclei are polarized by a magnetic field at very low temperatures. Indeed, in this experi-

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ment, the circular direction of the electric current in the solenoid that produces the polarizing magnetic field, together with the preferential direction of the β-ray emitted, differentiates in a very direct way a right-handed system from a left-handed system. Thus the nonconservation of parity or the noninvariance under a mirror reflection can be established without reference to any theory.

Furthermore, from the large amount of angular asymmetry observed, it can also be established (*4*) that the β-decay interaction is not invariant under a charge conjugation operation. That this can be concluded without performing the extremely difficult (in fact, almost impossible) experiment using anticobalt-60 is based on certain theoretical deductions under the general framework of local field theory. In the following we shall try to sketch this type of reasoning (*5*).

Let us consider the β-decay process, say,

$$n \rightarrow p + e^- + \nu, \qquad (1)$$

in which each particle is described by a quantized wave equation. In particular the neutrino is described by the Dirac equation (*6*)

$$\sum_{\mu=1}^{4} \gamma_\mu \frac{\partial}{\partial x_\mu} \psi_\nu = 0, \qquad (2)$$

where γ_1, γ_2, γ_3, γ_4 are the four (4×4) anticommuting Dirac matrices and x_1, x_2, x_3, $x_4 = ict$ are the four space-time coordinates. For each given momentum there exist two spin states for the neutrino and two spin states for the antineutrino. These may be denoted by ν_R, ν_L, $\bar{\nu}_R$, $\bar{\nu}_L$. If we define the helicity $\mathcal{H}$ to be

$$\mathcal{H} \equiv \vec{\sigma} \cdot \hat{p}, \qquad (3)$$

with $\vec{\sigma}$ as the spin operator and $\hat{p}$ the unit vector along the momentum direction, then these four states have, respectively, helicities equal to $+1$, -1, -1 and $+1$ (Fig. 4). Mathematically, this decomposition of states corresponds to a separation of ψ_ν into a right-handed part ψ_R and a left-handed part ψ_L with

$$\psi_\nu = \psi_R + \psi_L, \qquad (4)$$

where

$$\psi_R = \tfrac{1}{2}(1 - \gamma_5)\psi_\nu, \qquad (5)$$

$$\psi_L = \tfrac{1}{2}(1 + \gamma_5)\psi_\nu, \qquad (6)$$

and

$$\gamma_5 = \gamma_1\gamma_2\gamma_3\gamma_4$$

It is easy to see that both ψ_R and ψ_L separately satisfy the Dirac equation (Eq. 2). With this decomposition the β process of a nucleus A can be represented schematically as

$$A \rightarrow B + e^- + \begin{cases} C_i^R \nu_R & (\mathcal{H} = +1) \quad (7) \\ C_i^L \nu_L & (\mathcal{H} = -1) \quad (8) \end{cases}$$

with C_i^R and C_i^L as the various probability amplitudes for emission of ν_R and ν_L, respectively. The suffix i represents the various possible channels for such emissions. If the theory is invariant under proper Lorentz transformation, then there are five such channels: namely scalar S, tensor T, vector V, pseudoscalar P and axial-vector term A. According to the general rules of quantum field theory with any interaction term representing the decay of a particle, there exists a corresponding hermitian conjugate term which represents the decay of the antiparticle. Thus, the decay of the antinucleus $\bar{A}$ can be schematically represented by

$$\bar{A} \rightarrow \bar{B} + e^+ + \begin{cases} C_i^{R*} \bar{\nu}_R & (\mathcal{H} = -1) \quad (7') \\ C_i^{L*} \bar{\nu}_L & (\mathcal{H} = +1) \quad (8') \end{cases}$$

with C_i^{R*} and C_i^{L*} as the corresponding amplitudes for emission of $\bar{\nu}_R$ and $\bar{\nu}_L$. Under the charge conjugation operator we change a particle to its antiparticle but we do not change its spatial or spin wave functions. Consequently, it must have the same helicity. Thus, if the β-decay process is invariant under the charge conjugation operator, then we should expect process 7 to proceed with the same amplitude as process 8′. The condition for invariance under charge conjugation is, then,

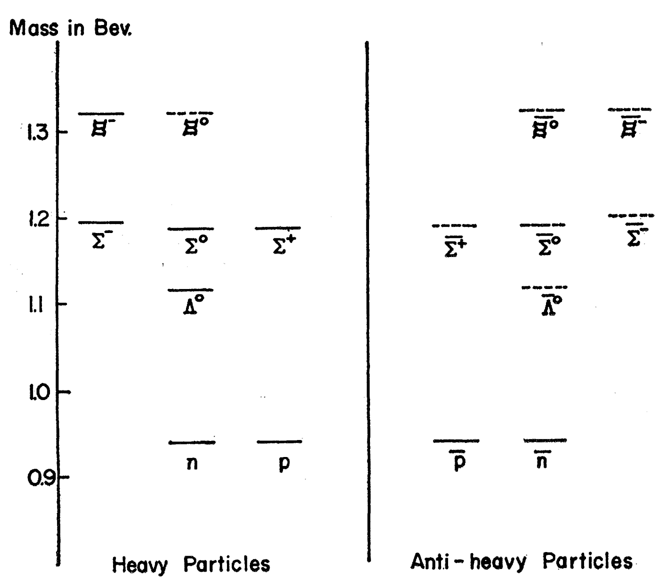
$$C_i^R = C_i^{L*} \qquad (9)$$

for all $i =$ S, T, V, P, A.

In the decay of cobalt-60, because there is a difference of spin values between cobalt-60 and nickel-60, only the terms $i =$ T and $i =$ A contribute. From the large angular asymmetry observed it can be safely concluded that for both $i =$ T, A

$$|C_i^R| \neq |C_i^L|$$

which contradicts Eq. 9 and proves the noninvariance of β-interaction under charge conjugation. In the above, for illustration purposes, we assume the neu-



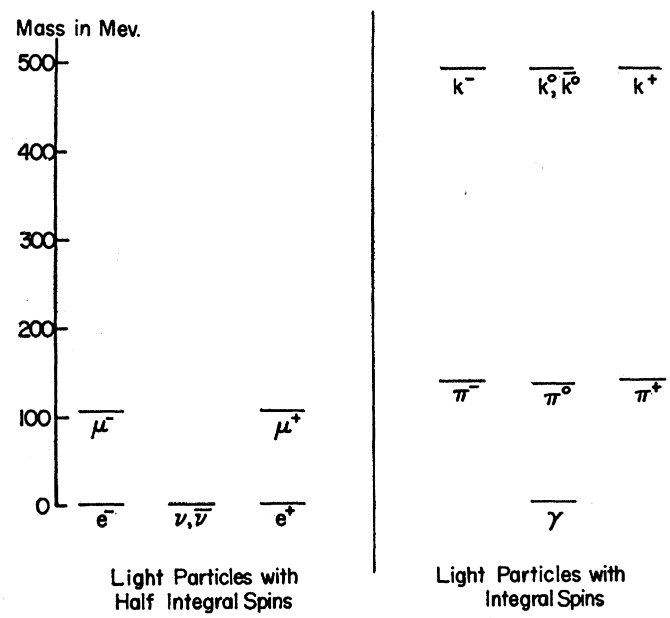


Fig. 1 (Left). Masses and charges of heavy particles and antiheavy particles. Fig. 2 (Right). Masses and charges of light particles.

trino to be described by a four-component theory and, further, we assume that in the β-decay process only a neutrino is emitted. Actually, the same conclusion concerning the noninvariance property under charge conjugation can be obtained even if the neutrino should be described by a, say, eight-component theory, or, if in addition to the β-process that a neutrino is produced an antineutrino may also be emitted.

Recently many more experiments (*7*) have been performed on the longitudinal polarization of electrons and positrons, the β-γ correlation together with the circular polarization of the γ radiation and the β-angular distribution with various polarized nuclei other than cobalt-60. The results of all these experiments confirm the main conclusions of the first cobalt-60 experiment, that neither the parity operator nor the charge conjugation operator is conserved in β-decay processes.

Another interesting question is whether the β-decay interaction is invariant under the product operation of (charge conjugation × mirror reflection). Under such an operation we should compare the decay of A with that of $\overline{A}$ but with opposite helicities. Thus, if β-decay is invariant under the joint operation of (charge conjugation × mirror reflection) we should expect process 7 to proceed with the same amplitude as process 7′ and similarly for processes 8 and 8′. The corresponding conditions are then

$$C_i^{R} = C_i^{R*},$$

and

$$C_i^{L} = C_i^{L*}. \qquad (10)$$

Although experiments have been performed to test the validity of these conditions, at present these experiments have not reached a conclusive stage and we still do not know the answer to this important question.

π-μ-e Decay. The $\pi^{\pm}$-meson decays into a $\mu^{\pm}$-meson and a neutrino. The $\mu^{\pm}$-meson, in turn, decays into an $e^{\pm}$ and two neutrinos (or antineutrinos). If parity is not conserved in π-decay, the μ-meson emitted could be longitudinally polarized. If in the subsequent μ-decay parity is also not conserved, the electron (or positron) emitted from such a μ-meson at rest would in general exhibit a forward and backward angular asymmetry with respect to the polarization of the μ-meson (Fig. 5). Consequently, in the π-μ-e decay sequence we may observe an angular correlation between the momentum of a $\mu^{\pm}$-meson measured in the rest system of a π-meson and the momentum of $e^{\pm}$ measured in the rest system of $\mu^{\pm}$. If this angular correlation shows a forward-backward asymmetry, then parity must be nonconserved in both π-decay and μ-decay. The experimental results (*8*) on these angular correlations appeared within a few days after the results on β-decay were known. These results showed conclusively that not only is parity not conserved but that the charge conjugation operator is also not conserved in π-decay as well as in μ-decay.

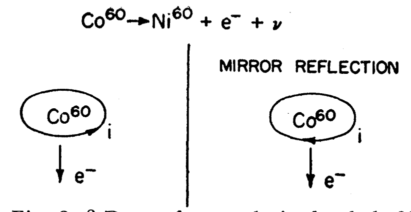


Fig. 3. β-Decay from polarized cobalt-60 nucleus.

Later, direct measurements (*9*) on the longitudinal polarization of the positron from μ^+-decay were made and established the same conclusion concerning μ-decay.

K-μ-e Decay. In this case we have instead of the π-meson the heavier K-meson which decays into a μ-meson and a neutrino (Fig. 6). An experiment (*10*) on the angular correlation between the μ^+ momentum from the decay of a K^+-meson and the positron momentum from the μ^+-decay established that in K-decay the parity as well as the charge conjugation operator is not conserved.

Λ° Decay. The Λ° particle can be produced by colliding an energetic π^- on a proton. The Λ° subsequently decays into a proton plus a π^- (Fig. 7). The observation of an asymmetrical distribution with respect to the sign of the product $\vec{p}_{out} \cdot (\vec{p}_{in} \times \vec{p}_{\Lambda})$ formed from the momentum of the incoming pion $\vec{p}_{in}$, the momentum of the lambda particle, $\vec{p}_{\Lambda}$, and that of the decay pion $\vec{p}_{out}$ would constitute an unequivocal proof that parity is not conserved in this decay. Recent experiments (*11*) on these reactions demonstrate that in these reactions there is indeed such an angular correlation between $\vec{p}_{out}$ and $(\vec{p}_{in} \times \vec{p}_{\Lambda})$. Furthermore, from the amount of the large up-down asymmetry, it can be concluded that the Λ°-decay interaction is also not invariant under the charge conjugation operation.

From all these results it appears that the property of nonconservation of parity in the various weak interactions and that the noninvariance property of these interactions under charge conjugation are well established. In connection with these properties we find an entirely new and rich domain of natural phenomena which, in turn, give us new tools to probe further into the structure of our physical world. These weak interactions offer us natural ways to polarize and to analyze the spins of various elementary particles. Thus, for example, the magnetic moment of the μ-meson can now be measured to an extremely high degree of accuracy (*12*) which, otherwise, would be unattainable; the spins of some hyperons now may perhaps be determined (*13*) unambiguously through the observed angular asymmetries in their decays; new aspects of the electromagnetic fields of various gas, liquid, and solid materials can now be studied by using these unstable, polarized particles. However, perhaps the most significant consequences are the openings of new possibilities and the reexamination of our old concepts concerning the structure of elementary particles. We shall next discuss two such considerations—the two-component theory of the neutrino and the possible existence of a law of conservation of leptons.

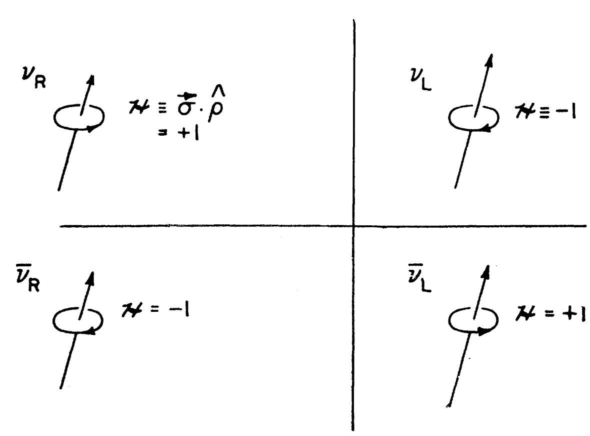


Fig. 4. Helicities of a four-component neutrino.

Two-Component Theory of Neutrino and Law of Conservation of Leptons

Before the recent developments on nonconservation of parity, it was customary to describe the neutrino by a four-component theory in which, as mentioned before, to each definite momentum there are the two spin states of the neutrino ν_R and ν_L, plus the two spin states of the antineutrino $\bar{\nu}_R$ and $\bar{\nu}_L$. In the two-component theory, however, we assume that two of these states, say ν_L and $\bar{\nu}_L$, simply do not exist in nature. The spin of the neutrino is then always parallel to its momentum, while the spin of the antineutrino is always antiparallel to its momentum. Thus, in the two-component theory we have only half of the degrees of freedom that we have in the four-component theory. Graphically, we may represent the spin and the velocity of the neutrino by the spiral motion of a right-handed screw and that of the antineutrino by the motion of a left-handed screw (Fig. 8).

The possibility of a two-component relativistic theory of a spin ½ particle was first discussed by H. Weyl (*14*) as early as 1929. However, in the past, because parity is not manifestly conserved in the Weyl formalism, it has always been rejected (*15*). With the recent discoveries such an objection becomes completely invalid (*16*).

To appreciate the simplicity of this two-component theory in the present situation, it is best if we assume further the existence of a conservation law for leptons (*17*). This law is in close analogy with the corresponding conservation law for the heavy particles. We assign to each lepton a leptonic number l equal to $+1$ or -1 and to any other particle the leptonic number zero. The leptonic number for a lepton must be the negative of that for its antiparticle. The law of conservation of leptons then states that, "in all physical processes the algebraic sum of leptonic numbers must be conserved."

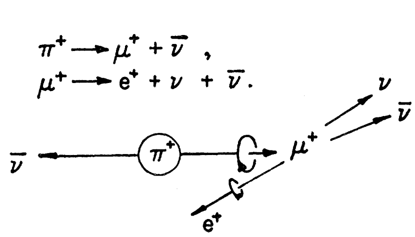


Fig. 5. π-μ-e Decay.

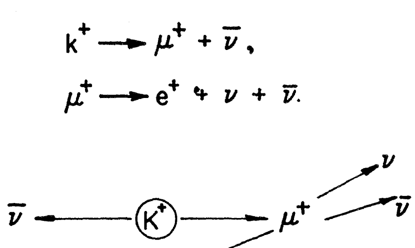


Fig. 6. K-μ-e Decay.

Some simple consequences follow immediately if we assume that this law is valid and that the neutrino is described by the two-component theory.

1) The mass of the neutrino and the antineutrino must be zero. This is true for the physical mass even with the inclusion of all interactions. To see this let us consider a neutrino moving with a finite momentum. From the two-component theory the spin of this neutrino must be parallel to its momentum. Suppose now it has a nonvanishing physical mass. Then, we can always send an observer traveling along the same direction as the neutrino but with a velocity faster than that of the neutrino. From this observer's point of view this "neutrino" now becomes a particle with the spin along its original direction but the direction of momentum reversed—that is, it becomes an "antineutrino." However, since the leptonic number for the neutrino is different from that of the antineutrino, these two particles cannot be transformed into each other by a Lorentz transformation. Consequently, the physical mass of a neutrino must be zero.

2) The theory is not invariant under the parity operator P which by definition inverts all spatial coordinates but does not change a particle into its antiparticle state. Under such an operation one inverts the momentum of a particle but not its spin direction. Since in this theory these two are always parallel for a neutrino, the parity operator P, when it is applied to a neutrino state, leads the neutrino to a nonexisting state. Consequently, the theory is not invariant under the parity operation.

3) Similarly, one can show that the theory is not invariant under the charge conjugation operation which changes a particle into its antiparticle but not its spin direction or its momentum.

To test the complete validity of the conservation law of leptons and the two-component theory, we have to investigate in detail all the neutrino processes. For example, in β-decay we must have either

$$n \to p + e^- + \nu \qquad (\mathcal{H}_\nu = +1),$$

or

$$n \to p + e^- + \bar{\nu} \qquad (\mathcal{H}_{\bar{\nu}} = -1).$$

This can be determined by measuring the spin and the momentum of the neutral lepton—to see whether it is a neutrino (right-handed helicity) or an antineutrino (left-handed helicity). Through the law of conservation of angular momentum, measurements on polarizations and angular distributions of the nucleus and the electrons can lead to determination of the spin states of the neutrino. Similarly, through recoil momentum measurements, we can find out information about the linear momentum of the neutrino. In the same way we can use not only β-decay but π-decay, μ-decay and K-decay to test the validity of either the two-component theory or the law of conservation of leptons. At present, these measurements have not yet reached a definitive stage (*18*). Much of our future theory may depend on the results of these experiments.

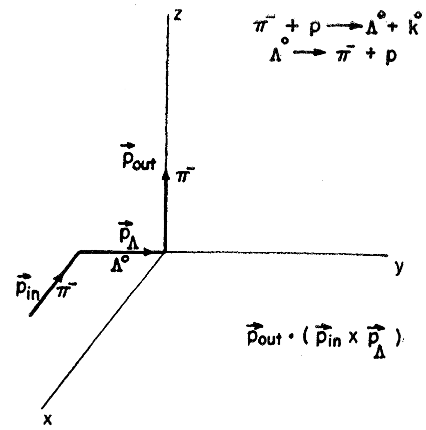


Fig. 7. Production and decay of Λ^0.

Remarks

The progress of science has always been the result of a close interplay between our concepts of the universe and our observations of nature. The former can only evolve out of the latter, and yet the latter is also conditioned greatly by the former. Thus, in our exploration of nature, the interplay between our concepts and our observations may sometimes lead to totally unexpected aspects among already familiar phenomena. As in the present case, these hidden properties are usually revealed only through a fundamental change in our basic con-

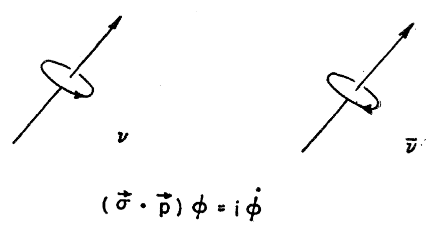


Fig. 8. Two-component neutrino.

cept concerning the principles that underlie natural phenomena. While all this is well known, it is nevertheless an extremely rich and memorable experience to be able to watch at a close distance in a single instance the mutual influence and the subsequent growth of these two factors—the concept and the observation. It is, indeed, a privilege that I have this opportunity to tell you part of this experience in the recent developments concerning the nonconservation of parity and the weak interactions.

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5. If the neutrino is described by a two-component theory (see section on the two-component theory) then the result of the large angular asymmetry in Co^{60} decay establishes in a trivial way the noninvariance property of β-decay under the charge conjugation operation. However, this noninvariance property can also be proved under a much wider framework. In this section we take as an example the case of a four-component theory of the neutrino to illustrate such a proof.
6. For notations and definitions of γ matrices see, for example, W. Pauli, *Handbuch der Physik* (Springer, Berlin, 1933), vol. 24.
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14. H. Weyl, *Z. Physik* 56, 330 (1929).
15. See W. Pauli, *Handbuch der Physik* (Springer, Berlin, 1933), vol. 24, pp. 226–227.
16. The possible use of a two-component theory for expressing the nonconservation property of parity in neutrino processes was independently proposed and discussed by T. D. Lee and C. N. Yang [*Phys. Rev.* 105, 1671 (1957)], A. Salam [*Nuovo Cimento* 5, 299 (1957)], and L. Landau [*Nuclear Phys.* 3, 127 (1957)].
17. The possible existence of a conservation law for leptons was discussed before the discovery of nonconservation of parity. See for example E. Konopinski and H. M. Mahmond, *Phys. Rev.* 92, 1045 (1953).
18. *Note added in proof*: Recent experiments by M. Goldhaber, L. Grodzins, and A. W. Sunyar (*Phys. Rev.*, in press) showed that in a β^- decay the neutrino emitted is of right-handed helicity.

Science, Industry, and the Abuse of Rights of Way

Frank E. Egler

The problem of improving the present unsatisfactory methods of controlling brush and other vegetation on our national rights-of-way is a fine illustration of the more general problem of getting industry to accept and act upon established scientific principles. The right-of-way domains are those narrow threads of land which serve for transportation and communication of men and materials. They include highways, railroads, electric power and telephone lines, and pipelines for gas, oil, and coal. The rights-of-way of the utility corporations alone comprise an acreage greater than all six New England states combined.

The fundamental scientist traditionally has observed, recorded, and interpreted the facts of the world about him and in doing so has usually remained aloof from society. He has been unconcerned about the discoveries of his science and indifferent about whether they are used for good or evil. In recent years, however, these discoveries have been of enormous import. More and more do we hear of a "Scientific Revolution" that may prove more challenging to the development of the human race than the Industrial Revolution from which we are just emerging. There are three significant recent events which, though differing greatly in magnitude, emphasize the contemporary trend of science toward integrating itself into society.

The first of these events was seen during the last political campaign for the Presidency of the United States. For the first time in our history, a scientific issue became a major feature. I refer to the problems of radiation hazard and of continuing H-bomb tests. Unfortunately the issue became a political football and then was left in the field, deflated. The second event occurred at the annual meetings of the American Association for the Advancement of Science. This august and distinguished body, representing organized science in America, broke with its traditional aloofness relative to the social effects of scientific discoveries. For the previous year, an Interim Committee under the chairmanship of Ward Pigman had been studying the subject, and the report has been distributed as evidence of the committee's interests and activities. The AAAS Council has voted to continue the existence of this committee. In a measure, therefore, science has begun to show a sense of responsibility to provide professional guidance on how to manage and control the revolutionary potentials that it is creating. The third event directly involves our present discussion. For the first time in the 10-year history of commercial herbicidal brush control, a utility corporation presented a system-wide policy that drew upon the common pool of biologic data. At the meetings of the Northeast Section of the Wildlife Society, a leading New England power corporation offered a paper which—in its statements—was scientifically sound. Furthermore, the opinions are in accord with a joint policy statement released at the same time by the Connecticut State Board of Fisheries and Game and the Connecticut Botanical Society.

Following a general review of the problem, I shall consider four of its aspects. The first is a definition of terms. The second is the question of "brush control—for whose benefit?" The third involves the authority of the scientific statements here made. The fourth and last is a short survey of specific factors that have become critical in the actual programming of brush control.

The author is a consulting vegetationist in Norfolk, Conn. This article is based on an invited paper presented at a panel discussion on "Programming Brush Control on Utility Rightofways," Northeastern Weed Control Conference, 11 Jan. 1957.