Cell Systems and Their Control, D. Rudnick, Ed. (Ronald Press, New York, 1960), p. 45.
33. A. Levan and J. J. Biesele, *Ann. N.Y. Acad. Sci.* **71**, 1022 (1958).
34. E. H. Y. Chu, *J. Cellular Comp. Physiol.* **60**, suppl. 1, 77 (1962).
35. L. Hayflick and P. S. Moorhead, *Exptl. Cell Res.* **25**, 585 (1961).
36. H. B. Fell, *J. Natl. Cancer Inst.* **19**, 601 (1957).
37. J. Paul, *Cell and Tissue Culture* (Williams and Wilkins, Baltimore, 1961), chap. 4.
38. C. Grobstein, in *The Cell*, J. Brachet and A. E. Mirsky, Eds. (Academic Press, New York, 1959), vol. 1.
39. B. Ephrussi and H. M. Temin, *Virology* **11**, 547 (1960).
40. S. R. Hilfer, *Develop. Biol.* **4**, 1 (1962).
41. K. E. Ebner, E. C. Hageman, B. L. Larson, *Exptl. Cell Res.* **25**, 555 (1961).
42. E. Weiler, *Exptl. Cell Res. Suppl.* **7**, 244 (1959).
43. A. A. Moscona, *J. Cellular Comp. Physiol.* **60**, suppl. 1, 65 (1962).
44. P. Weiss, *ibid.*, p. 45.
45. V. Buonassisi, G. Sato, A. I. Cohen, *Proc. Natl. Acad. Sci. U.S.* **48**, 1184 (1962).
46. E. Bell and M. Schuler, "Abstracts of Papers, 13th Annual Meeting, Tissue Culture Association, Washington, D.C." (1962), p. 39.
47. I. Lieberman and P. Ove, *J. Biol. Chem.* **233**, 634 (1958); H. Burlington, *Am. J. Physiol.* **197**, 68 (1959).
48. I. R. Konigsberg, N. McElvain, M. Tootle, H. Herrmann, *J. Biophys. Biochem. Cytol.* **8**, 333 (1960).
49. I. R. Konigsberg, *Exptl. Cell Res.* **21**, 414 (1960).
50. ———, *Circulation* **24**, 447 (1961).
51. J. W. Lash, H. Holtzer, H. Swift, *Anat. Record* **128**, 679 (1957).
52. H. Holtzer, in *Regeneration in Vertebrates*, C. Thornton, Ed. (Univ. of Chicago Press, Chicago, 1958); in *Cytodifferentiation*, D. Rudnick, Ed. (Univ. of Chicago Press, Chicago, 1958); H. Firket, *Arch. Biol. Liége* **69**, 1 (1958); S. Bintliff and B. E. Walker, *Am. J. Anat.* **106**, 233 (1960); F. E. Stockdale and H. Holtzer, *Exptl. Cell Res.* **24**, 508 (1961); H. Holtzer, in *Synthesis of Molecular and Cellular Structure*, D. Rudnick, Ed. (Ronald Press, New York, 1961), p. 35.
53. C. E. Wilde, in *Cell, Organism and Milieu*, D. Rudnick, Ed. (Ronald Press, New York, 1959); C. R. Capers, *J. Biophys. Biochem. Cytol.* **7**, 559 (1960).
54. W. G. Cooper and I. R. Konigsberg, *Anat. Record* **140**, 195 (1961).
55. A. Kitiyakara, *ibid.* **133**, 35 (1959).
56. M. R. Murray, in *The Structure and Function of Muscle*, G. H. Bourne, Ed. (Academic Press, New York, 1960), p. 111.
57. W. G. Cooper and I. R. Konigsberg, *Exptl. Cell Res.* **23**, 576 (1961).
58. M. C. Reporter, I. R. Konigsberg, B. L. Strehler, *ibid.* **30**, 410 (1963).
59. I. R. Konigsberg, *Carnegie Inst. Wash. Yearbook No. 61* (1962).
60. The technique finally adopted for preparing conditioned medium is as follows. Growth medium (10 cm^3) in petri plates 150 mm in diameter is inoculated with 6×10^6 cells [prepared as described in I. R. Konigsberg *et al.* (*48*)]. The medium is replaced with 15 cm^3 of fresh medium on the 2nd and 5th day of culture, and the old medium is discarded. On day 11 the medium is removed, under conditions of sterility, and passed through a Millipore filter (type HA) to insure removal of any possible cellular or microbial contamination. This medium is our standard conditioned medium. It is prepared each week; unused portions are stored at 5°C and discarded after 2 weeks. The growth medium used is that described in I. R. Konigsberg *et al.* (*48*), modified as described in I. R. Konigsberg (*24*), except for the following changes. (i) The inorganic salt and glucose concentrations of both the Hanks solution and the amino acid-vitamin supplement have been altered and are now the same for the two solutions (the concentrations, in millimoles per liter, are as follows: NaCl, 128.6; KCl, 4.1; $CaCl_2$, 1.12; $MgCl_2$, 0.49; Na_2HPO_4, 0.93; KH_2PO_4, 0.45; $NaHCO_3$, 15.3; $MgSO_4$, 0.21; and glucose, 6.10). (ii) The growth medium now contains 50-percent embryo extract to a concentration of 10 percent. The only other innovation in our recent techniques is the use of polystyrene petri plates (obtained from Falcon Plastics).
61. P. Weiss and B. Garber, *Proc. Natl. Acad. Sci. U.S.* **38**, 264 (1952); P. Weiss, *Intern. Rev. Cytol.* **7**, 39 (1958).
62. I. Lieberman and P. Ove, *Biochim. Biophys. Acta* **25**, 449 (1957); H. W. Fischer, T. T. Puck, G. Sato, *Proc. Natl. Acad. Sci. U.S.* **44**, 4 (1958); A. C. Taylor, *Exptl. Cell Res. Suppl.* **8**, 154 (1961).
63. W. H. Lewis and M. R. Lewis, *Am. J. Anat.* **22**, 169 (1917).
64. I. R. Konigsberg and H. Herrmann, *Arch. Biochem. Biophys.* **55**, 534 (1955).
65. M. Abercrombie, *Exptl. Cell Res. Suppl.* **8**, 188 (1961); P. Weiss, *ibid.*, p. 260.
66. I acknowledge my indebtedness to Mrs. Wilma Gabbay and Mr. Francis J. Kupres for their invaluable and unstinting assistance during the progress of the original work reported. I wish to thank Drs. D. W. Bishop, D. D. Brown, J. D. Ebert, M. S. Steinberg, and J. P. Trinkaus for their valuable criticisms during the preparation of the manuscript.

Can the Direction of Flow of Time Be Determined?

No method has been found, but properties of strange particles offer a new chance to explore the question.

Robert G. Sachs

The notion that the direction of flow of time cannot be determined by any physical experiment has been deeply ingrained in the thought and theories of physicists until very recent years. In all cases in which they have been adequately tested, the laws of physics satisfy this condition and, in unexplored areas, the condition is usually taken as a starting principle for formulating a theory. Violation of this principle would affect the results obtained from laboratory experiments, thereby making it subject to direct experimental verification. It may appear that the notable distinction between past and future from the cosmological, biological, and psychological points of view settles the issue without further experimentation, but even if the laws of physics are assumed to underlie these phenomena, we shall find that they do not stand in contradiction to the principle of the reversibility of time.

"Time reversal" is the term used in physics to describe the procedure of going from one direction of time flow to the other in writing equations describing the physical behavior of a system; the principle responsible for the belief that there is no distinction between the two directions of flow is known as "invariance [of physical laws] under time reversal" or "*T*-invariance." Although recent discussion of *T*-invariance has been associated with quantum phenomena, application of the principle to classical physics is not without interest. The most important application in classical physics was made by Loschmidt (*1*) to show that Boltzmann's proof of the H-theorem contained a fallacy; Loschmidt's work raised a question concerning the connection between the second law of thermodynamics and the mechanical theories of physics. Resolution of this very compelling question, which goes to the very foundations of statistical mechanics, is not my particular concern and is not discussed in this article. I refer the interested reader to the basic exposition of the subject by the Ehrenfests (*2*). I shall consider the application of the principle to a very simple classical mechanical system which provides an insight into the nature of the question being raised here.

The important role of time-reversal invariance in quantum mechanics was

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first brought out in a classic paper by Wigner (*3*), although it was not widely recognized until some years later. The significance of this and related invariances for relativistic quantum field theories was delineated by Pauli (*4*) when he presented his proof of the Luders-Pauli *CPT*-theorem (*5*). Here, *T* stands for the time-reversal transformation—that is, the interchange of past and future; *P*, for the interchange of left and right (handedness); and *C*, for the interchange of matter and antimatter (*6*). The term *transformation* is used here to mean that the equations of physics are transformed by changing the quantities that appear in them. For example, *P* may be accomplished by expressing the coordinates that occur in the equations in terms of a left-hand rather than a right-hand coordinate system.

The *CPT*-theorem states that the equations do not change their form when all three substitutions are made simultaneously. This remarkable result, which follows from very general assumptions concerning physical theories (*7*), is discussed later.

Recent impetus for an intense interest in transformations of types *T* and *C*, as well as *P*, arose from the discovery by Wu *et al.* (*8*), on the basis of a beta-decay experiment suggested by Lee and Yang (*9*), that there exists an absolute distinction between left and right; certain physical laws appear to be modified by the transformation denoted by *P*. The distinguishing of right from left has so far been found to be possible only by means of an experiment in which use is made of the "weak interactions" of physics, the interactions responsible for radioactive beta decay and for the rather slow disintegration of the various particles produced in high-energy collisions between atomic nuclei.

Lee and Yang proposed to seek for the effect in beta decay, after discovery of the peculiar disintegration properties of certain of the strange particles of high-energy physics, the K-mesons. We show later that K-mesons, as a consequence of some recently discovered properties, may also provide us with a unique opportunity to test the interchangeability of past and future. In the domain in which such tests have been carried out—and this includes ordinary beta decay—there has been no indication that past and future are not interchangeable, but no information is yet available on this question for the beta decay of strange particles.

Time Reversal Invariance in Classical Mechanics

The question being raised here can be understood in terms of the simplest classical system, a mass point moving in one dimension under the influence of conservative forces. An example might be an electrically charged bead sliding on a straight horizontal wire under the influence of an electric field which is constant in time. If we denote the position of the bead, measured along the wire, by x, then the motion of the bead may be described by a curve such as is shown in Fig. 1*a*, where x is plotted as the ordinate and the time t is plotted as the abscissa. The indicated curve begins in the distant past ($t = -\infty$) and proceeds to the distant future ($t = +\infty$).

The time scale in Fig 1*a* is based on comparison with a clock which is arbitrarily assumed to be moving "forward" in time, and we are concerned here with establishing the arbitrariness of this choice, so clocks moving backward as well as forward must be considered. To illustrate the distinction between such clocks, let us suppose that two non-aging observers, A and B, measure time on different clocks, the time measured by observer A being denoted by t and that measured by B, by t'. Each now determines the motion of the same bead in terms of his own clock. If A's delineation of the motion is the curve shown in Fig. 1*a* and B's is the mirror image, as shown in Fig. 1*b*, they conclude that their clocks are running in opposite directions; that is,

$$t' = -t \qquad (1)$$

Nevertheless, B would indicate the direction of motion to be as shown by the solid arrows in Fig. 1*b*, since, to him, increasing values of t' would point toward the future.

The question is, Are the laws governing the motion of the bead different when they are expressed in terms of the two opposing time scales? If they are, they could be used to establish an absolute standard of "forward"-moving time which would discriminate between the two time scales without requiring a direct comparison of the clocks, such as that made above. To show that *T*-invariance of the physical laws precludes any such discrimination, the direct comparison of the clocks to a common physical system must be avoided, so we consider an experiment similar to the one described but with observers A and B isolated from one another, each carrying out his own experiment, the two using identical beads moving under identical conditions.

The motion of the bead observed by A is governed by the Newtonian equation of motion

$$ma = F(x,t) \qquad (2)$$

where m is the mass of the bead, a is its acceleration, and $F(x,t)$ is the force along the wire on the bead at position x and time t. On the other hand, the equation of motion that applies to B's observations is

$$ma' = F'(x,t') \qquad (3)$$

where the primes indicate that all time measurements are made on the t' scale —that is, on B's clock. The force $F'(x,t')$ is obtained from $F(x,t)$ by writing t in terms of t'—that is, $F'(x,t') = F(x,t[t'])$. The question of interest involves a comparison of the two equations if, unbeknownst to the observers, the clocks are running in opposite directions so that $t(t') = -t'$; henceforth, this is assumed to be the case.

The connection between $F(x,t)$ and $F'(x,t')$ depends in general on the detailed nature of the forces, but in the present case of a constant electric field, F does not actually depend on t and

$$F'(x,t') = F(x,t') \qquad (4)$$

Equation 4 is in fact a general statement of the invariance of the dynamics under time reversal, and from this equation it is evident that the equations of motion, Eqs. 2 and 3, are identical in form. Therefore, the motion observed by B will be exactly the same as that observed by A if the initial conditions are the same.

The initial conditions—for example, the position and velocity at some given initial time—are required in order to determine the path of the bead from the equations of motion. As long as the initial conditions seen by B in his system are the same as those seen by A, the motion in the two systems is identical. Note, however, that when the two observers look at the *same* system, the initial conditions are necessarily different; this is the reason for the difference in their observations, as indicated in Fig. 1, *a* and *b*. The difference is evident if $t = 0$ is taken to be the initial time. Although the initial position is $x = 0$ in both Fig. 1*a* and Fig. 1*b*, the initial velocities are opposite in sign, since they are given by the slopes of the two curves at $t = 0$. This difference in the initial conditions leads to the difference in the paths shown in the two figures, a difference that exists in spite of the fact that the paths are solutions of the same equations of motion.

The reversal of sign between the velocities measured by the two observers is quite general. Since a velocity has the form $v = (x_2 - x_1)/(t_2 - t_1)$, the transformation of t_1 to t_1' and of t_2 to t_2' given by Eq. 1 leads to the relationship (*10*)

$$v' = -v \qquad (5)$$

between the velocity (v) of any object observed by A and the velocity (v') of the same object observed by B.

The result illustrated by the motion of the bead may now be generalized. As long as the basic forces or interactions are invariant under time reversal, as they are for the well-established laws of physics, observers A and B can find no physical experiment, to be performed by each within his own isolated system, that will distinguish the different directions of time flow.

This general conclusion may appear to contradict our biological experience, at least if we presume that the laws of physics govern biological processes. We do, of course, have a unique definition of "past" and "future," based on our observation of the direction in which biological processes evolve. To show that this is not contrary to the principle of T-invariance, we consider a greatly oversimplified biological universe composed of a small number of particles whose physical history may be traced. Two alternative time sequences may be considered for this universe, one associated with the time scale t as observed by A and the other, with time scale $t' = -t$ as observed by B.

To establish the direction of evolution from physical principles, initial conditions must be established for each of the alternatives. Thus, A's universe may, at $t = 0$, consist of a collection of isolated particles moving toward a common center in such a way that, through nuclear and chemical reactions, it ultimately develops into an evolving biological system. The direction of evolution is then toward increasing t, as it should be. On the other hand, if at $t' = 0$, B's alternative form of the universe satisfies the *same* initial conditions (that is, the velocities v' point toward the common center) and the physical laws take the same form (T-invariance), the evolution will move toward increasing t'. Thus, under the assumption of T-invariance, the two alternatives are internally indistinguishable, in each case the positive sense of time is the same as the direction of evolution.

Failure of Time-Reversal Invariance

Our strong inclination to believe in the isotropy of space and time makes any simple, dynamical scheme that violates time reversal appear awkward to us. Nevertheless, one can invent forces or interactions which violate the invariance principle while still being in accord with all other general requirements usually imposed on physical theories. To illustrate the point, let us imagine that the force acting on the classical system described does not satisfy the critical condition expressed by Eq. 4. For example, the force may be imagined to depend on the velocity with which the *wire* is moving, and in such a way that it is greater when the wire is moving upward with a uniform velocity and smaller when the wire is moving downward.

A quantitative description of the force determined by observer A in this situation might be

$$F(x,V) = F_1(x) + VF_2(x) \qquad (6)$$

where V is the vertical velocity of the wire. To determine the force F' observed by B, we must write V in terms of V'. According to the transformation law for velocities (Eq. 5),

$$F'(x,V') = F_1(x) - V'F_2(x) \qquad (7)$$

a result clearly contradicting the invariance condition

$$F'(x,V') = F(x,V') \qquad (8)$$

which is equivalent to Eq. 4. In fact, Eq. 7 shows that observer B will find that the force on his own bead is greater when his wire is moving *downward* rather than upward. When A and B compare notes on this score they will have clearly established that their clocks are running in opposite directions.

We see, then, that by merely establishing the existence of the second term in Eq. 6 or Eq. 7 for the force, an observer is able to conclude that there is a distinct physical difference between the two directions of time flow.

However, there is an alternative to this interpretation which most physicists would be inclined to invoke because of their strong prejudice in favor of T-invariance—namely, the view that there is an external, time-dependent influence common to the two experiments which was not taken into account in writing Eq. 7. For example, if A and B performed the experiment in separated isolation booths, both of which were on the surface of the earth, they would indeed find a small term of the type F_2 in the force. The external agency responsible for this term is the rotation of the earth, which produces a Coriolis force on the bead, the Coriolis force being proportional to the velocity of the bead relative to the earth and to the velocity of rotation of the earth.

This example serves to illustrate how careful one must be to isolate each system. If each observer were indeed relegated to his own isolated planet, the Coriolis force would no longer provide a basis for comparing clocks because A would assign a velocity of rotation to his planet which would have the opposite sign from the rotational velocity ascribed to it by B. The two changes in sign, that of the bead and that of the rotational velocity, would compensate one another.

Weak Interaction Effects

The direction of time flow might be fixed in an entirely different way—namely, on the microscopic, nuclear scale rather than on the macroscopic scale. Microscopic violations of time-reversal invariance might be expected to occur in beta-decay and related weak interaction phenomena. Invariance under one transformation, the interchange of left and right, *is* violated in these processes and, although the failure of P-invariance does not imply a corresponding failure of T-invariance, it does suggest the need for a closer examination of the time-reversal problem in connection with the weak interactions.

Weak interactions are so weak that we are not in a position to measure the forces they produce; instead, measurements must be made on the decay processes themselves—for example, on the beta decay of the neutron. The observed products of decay of the neutron are a proton and an electron (the neutrino need not be considered here), and the number of disintegrations observed per unit of time may depend on the polarization of the neutron. *Polarization* is the term used to indicate what fraction of the neutrons have their intrinsic spin oriented one way or

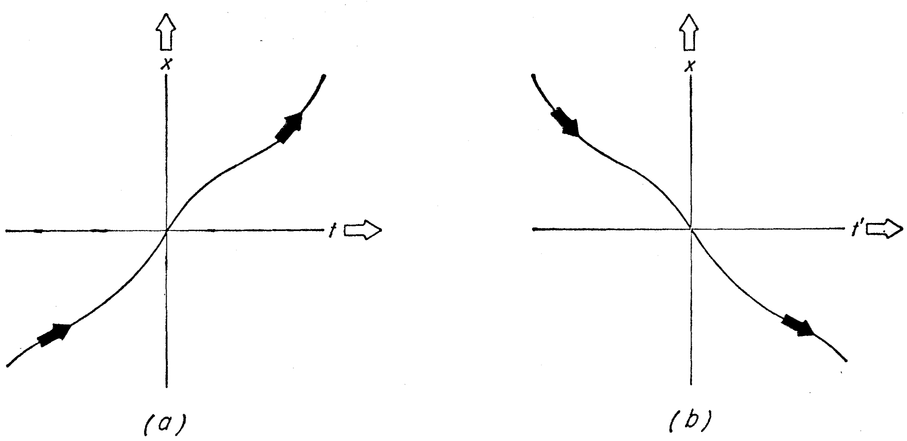

Fig. 1. Motion of a bead on a straight wire. The position of the bead on the wire is denoted by x; the time, by t in diagram a and by $t'(=-t)$ in diagram b.

the other. A quantitative measure of the polarization may be taken to be the difference, P, between the fraction spinning clockwise and the fraction spinning counterclockwise, these being the only two possibilities for the neutron. Then the rate of disintegration of a neutron with polarization P into an electron and proton with certain definite velocities may be denoted by $n(P)$. Although $n(P)$ also depends on the velocities of the products, this dependence need not be made explicit here.

T-invariance implies that the decay rates measured by the two observers are indistinguishable. That is,

$$n'(P') = n(P') \qquad (9)$$

where P is measured by A and P', by B. The rate $n'(P')$ is obtained from $n(P)$ by expressing P in terms of P'; to accomplish this one need only remember that the sign of the polarization is determined by the direction of a spin or an angular velocity. Angular velocity changes sign when time is reversed, for the same reason that linear velocity does, so the connection is

$$P' = -P \qquad (10)$$

Now let us suppose that measurement of the decay rate by observer A reveals that it depends on P in the following way:

$$n = n_1 + Pn_2 \qquad (11)$$

where n_1 and n_2 satisfy Eq. 9. By expressing this in terms of the primed quantities we find that the partial rate observed by B would be

$$n' = n_1 - P'n_2 \qquad (12)$$

This does not satisfy the time reversal condition, Eq. 9. Thus, through comparison of their results, A and B would conclude that their clocks are running in opposite directions.

A single observer need only establish the existence of the term proportional to n_2 in beta decay to show that time-reversal invariance is violated (*11*). From this he could establish an absolute standard for time direction—for example, forward-moving time might be defined to correspond to the plus sign in Eq. 11, and each observer could decide which way his clock was going by measuring n and determining the sign of the second term. Aside from its implications for the basic theory, such a discovery would have cosmological significance. Beta decay plays an important role in the evolution of the universe. The role would be different in A's universe and in B's universe, even if the two were initiated in the same way. Therefore, one universe might be "favored" over another insofar as its evolution is concerned, and this could lead to the conclusion that there is a preferred direction of time.

Measurements on the partial decay rate of polarized neutrons have led to the conclusion that the term n_2 is quite small. Burgy *et al.* (*12*) have found that the contribution of n_2 to the rate of decay is probably less than 4 percent, hence it seems unlikely that neutron, or the closely related nuclear, beta decay would be of use for ascertaining the direction of time flow.

Before a firm conclusion is drawn from this experiment, a modification of the foregoing arguments is needed, to take account of the essential wave-mechanical nature of the process. Physical properties of atomic particles are properly described in terms of waves. These waves are scattered when two particles interact with one another, and the magnitude of the scattering may be measured in terms of the amplitude of the scattered wave. The rate of decay of a system may also be measured in terms of a similar amplitude, which is closely related to the amplitude for scattering of the decay products by one another, if the underlying physical laws are invariant under time reversal (see *13*).

Electrons are scattered by protons because of their Coulomb interaction, and the existence of this scattering amplitude implies through T-invariance that the decay rate of the neutron actually has the form of Eq. 11. However, the function n_2 that appears there does *not* satisfy Eq. 9 (as it was assumed to in obtaining Eq. 12) but restores the T-invariance by changing sign under the transformation as a consequence of the time-reversal properties of the scattering amplitude. The calculated value of n_2 turns out to be very small in this case, much smaller than the limits of sensitivity of the experiment of Burgy *et al.* If the experiment had established the existence of an n_2 term large enough to be detected, and therefore larger than the calculated value, it would have been a clear demonstration of the failure of T-invariance. On the other hand, the ultimate experiment will be a careful enough measurement of n_2 to determine whether n_2 bears exactly the relationship to the scattering amplitude which is expected from T-invariance. For the present, we can be confident that there is not a large violation of the invariance principle, and the chances are that there is no violation, in nuclear beta decay.

Strange-Particle Decays

A particle of physics is called "strange" to distinguish it from the "ordinary" particles, such as the proton, neutron and π-meson (pion), only if it is an unstable particle able to be produced only by the absorption of another strange particle or in association with the production of another strange particle. Examples are the Λ-hyperon and the K-meson. The Λ and K particles can be produced together in a sufficiently energetic collision of two ordinary particles, or the Λ-particle can be produced by absorption of the $\bar{\text{K}}$, which is the antiparticle of the K-meson.

The instability of the strange particles may occur in a variety of ways,

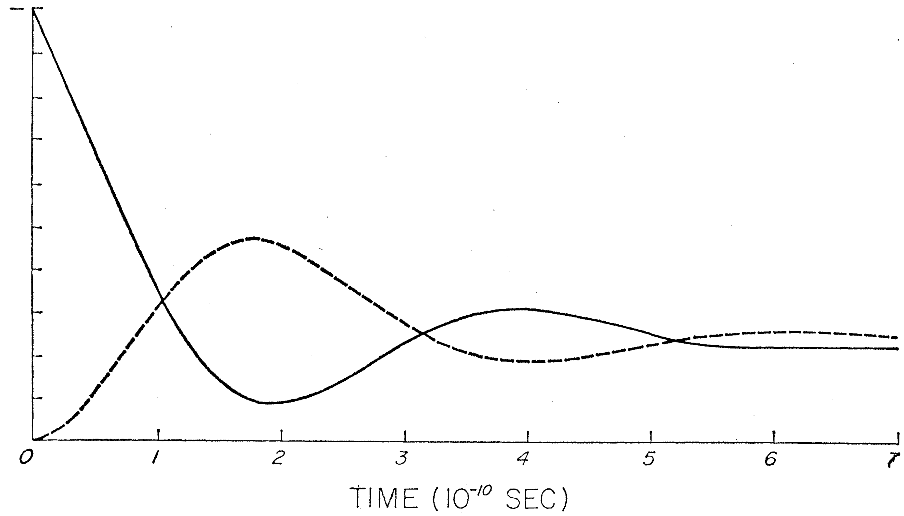

Fig. 2. Number of K^0-mesons (solid curve) and $\bar{K}^0$-mesons (broken curve) as a function of time if the source is composed of K^0-mesons at $t = 0$.

but all fall into two general classes—particles whose modes of decay are leptonic and nonleptonic, respectively. A "lepton" is a particle that is light in mass: the electron, the neutrino, the μ meson. Leptonic decay is a decay process in which leptons are produced; ordinary beta decay is an example. Nonleptonic decay is a decay process in which no leptons are produced. An example is the dominant decay mode of the Λ-hyperon

$$\Lambda \rightarrow p + \pi^-$$

where π^- is a negatively charged pion.

This decay mode provides an opportunity to test the reversibility of time in a manner analogous to the test used in the case of neutron decay. Again, use may be made of the spin of Λ-hyperon to define a Λ polarization P_Λ, and the decay rate w, may be expressed in a form similar to Eq. 11:

$$w = w_1 + P_\Lambda w_2 \qquad (13)$$

Here w_1 and w_2 depend on the velocity and polarization of the outgoing proton, but this dependence may be suppressed. As before, the second term provides the desired test, since T-invariance leads to a specific relationship between w_2 and the amplitude for scattering of the decay products by one another, the products being the proton and the pion. Direct measurements of the pion-proton scattering yield the required scattering amplitude, which cannot be calculated reliably on purely theoretical grounds. The test of time reversal is whether or not the measured value of w_2 appearing in Eq. 13 bears the proper relationship to the measured scattering.

This test has recently been performed by Cronin and Overseth (*14*), with results that favor the time-reversal principle, although again the result is a negative one: The w_2 term is not observed, but the errors are comparable to the rather small value of w_2 calculated from data on pion-nucleon scattering under the assumption of T-invariance. On this basis, there is no reason to suspect a failure of the principle insofar as the *nonleptonic* decay modes of strange particles are concerned.

A violation of T-invariance may still occur in the leptonic decay modes of the strange particles, for either K-mesons or hyperons. Tests of the invariance may, in principle, be made by using the beta decay of the Λ-hyperon in exactly the same way that the decay of the neutron was used. Unfortunately, the beta mode of the Λ-hyperon does not compete very well with the nonleptonic modes, and data have been accumulated very slowly. It may be a long time before enough information is available to settle this question in this way.

The CPT-Theorem

Another opportunity to test T-invariance follows from recently discovered properties of the neutral K-mesons. The connection between T-invariance and the experiment in question rests on the aforementioned CPT-theorem of Luders and Pauli. For our purpose the essential point of the theorem is that the physical laws must be unchanged under the simultaneous transformation of matter into antimatter (C), right-handedness into left-handedness (P), and past into future (T). The validity of the theorem does not depend on invariance under any one of the transformations. For example, although the laws of beta decay are not invariant under P, it follows from the theorem that they must be invariant under CPT.

Since the neutron experiment suggests that the laws of nuclear beta decay are invariant under T, it follows from the theorem that they must also be invariant under C and P together. From the failure under P it can be concluded, then, that there must be a counterbalancing failure of the laws of nuclear beta decay under C, a conclusion that has been verified by compar-

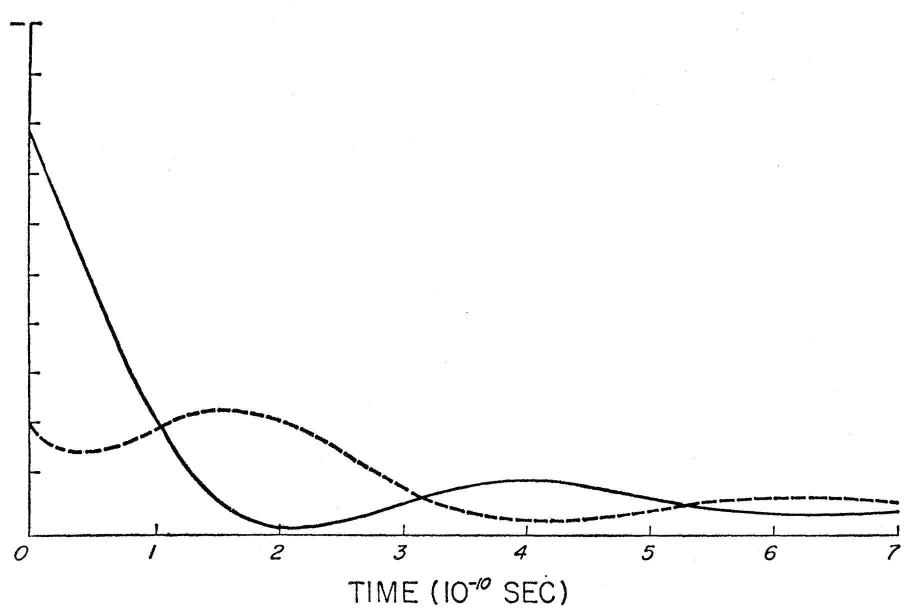

Fig. 3. Rate of decay of a K^0-meson source into $\pi^- e^+ \nu$ (solid curve) and $\pi^+ e^- \bar{\nu}$ (broken curve) as a function of time.

ing beta decay into positrons with beta decay into electrons.

By the same argument, a failure of time-reversal invariance means that the physical laws must change under *CP*—that is, under the transformation consisting of simultaneous interchange of matter and antimatter and of left and right. Conversely, a demonstrated failure of *CP* means, according to the *CPT*-theorem, that the principle of *T*-invariance is violated. This is the basis for the test with neutral K-mesons; it is a direct test of *CP*-invariance.

The K-mesons and their associated antiparticles, the $\overline{\mathrm{K}}$-mesons, have quite distinct physical properties. For example, absorption of a $\overline{\mathrm{K}}$-meson by a nucleus may lead to the production of a hyperon, but, except at very much higher energy, this is not possible for a K-meson. Such properties as this may be used to distinguish the two types of particle in an experiment.

Both electrically charged and neutral K-mesons occur in nature, but our interest centers on the neutral ones, denoted by K^0 and $\overline{\mathrm{K}}^0$. K^0-mesons have many decay modes, including, among others

$$\mathrm{K}^0 \rightarrow \pi^+ + \pi^- \qquad (14a)$$

and

$$\mathrm{K}^0 \rightarrow \pi^- + e^+ + \nu \qquad (14b)$$

where e^+ denotes the positron and ν denotes the neutrino. The dominant process is the nonleptonic 2π mode, which occurs about 100 times more frequently than all the others. The half-life for decay is about 10^{-10} second; this is consistent with the magnitude expected from interactions comparable to the weak interactions responsible for beta decay.

Decay of the antiparticle, $\overline{\mathrm{K}}^0$, is also dominated by the 2π mode. Gell-Mann and Pais (*15*) were the first to notice that the possible decay of both particle and antiparticle into the same mode has the remarkable consequence that the K^0 will convert itself slowly into a $\overline{\mathrm{K}}^0$ and vice versa. This has the result that neither the K^0 nor the $\overline{\mathrm{K}}^0$ has the simple decay properties expected of a radioactive system. The time dependence of a normally radioactive decay is exponential, hence the number of decaying particles decreases in a monotone fashion. Because of the mixing up of the K^0- and the $\overline{\mathrm{K}}^0$-mesons there is an interference between them, with the result that the time dependence of the number of particles has the damped oscillatory form shown

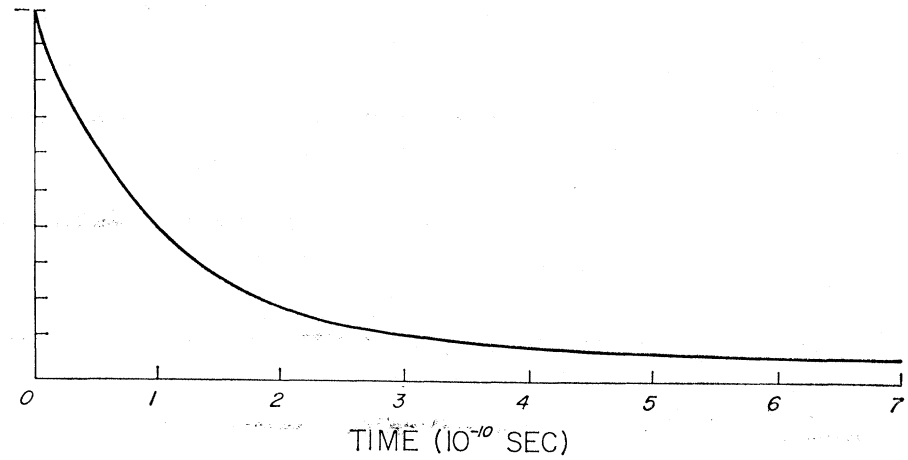

Fig. 4. Total rate of beta decay of a K^0-meson source as a function of time under the assumption of *CP*-invariance.

in Fig. 2. The solid curve shows the fraction of K^0-mesons as a function of the time in a source initially made up entirely of K^0-mesons, while the broken curve shows the relative number of $\overline{\mathrm{K}}^0$-mesons as a function of time in the same source (*16*).

The K^0- and $\overline{\mathrm{K}}^0$-mesons decay into leptonic modes such as the $\pi^- e^+ \nu$ mode indicated in Eq. 14b. The intensity of the leptonic mode as a function of time is shown in Fig. 3 (*17, 18*). The solid line gives the intensity of $\pi^- e^+ \nu$; the broken line, the intensity of $\pi^+ e^- \bar{\nu}$, where e^- denotes the electron and $\bar{\nu}$, the antineutrino. The fact that these curves do not have the same form as those in Fig. 2 is a most significant

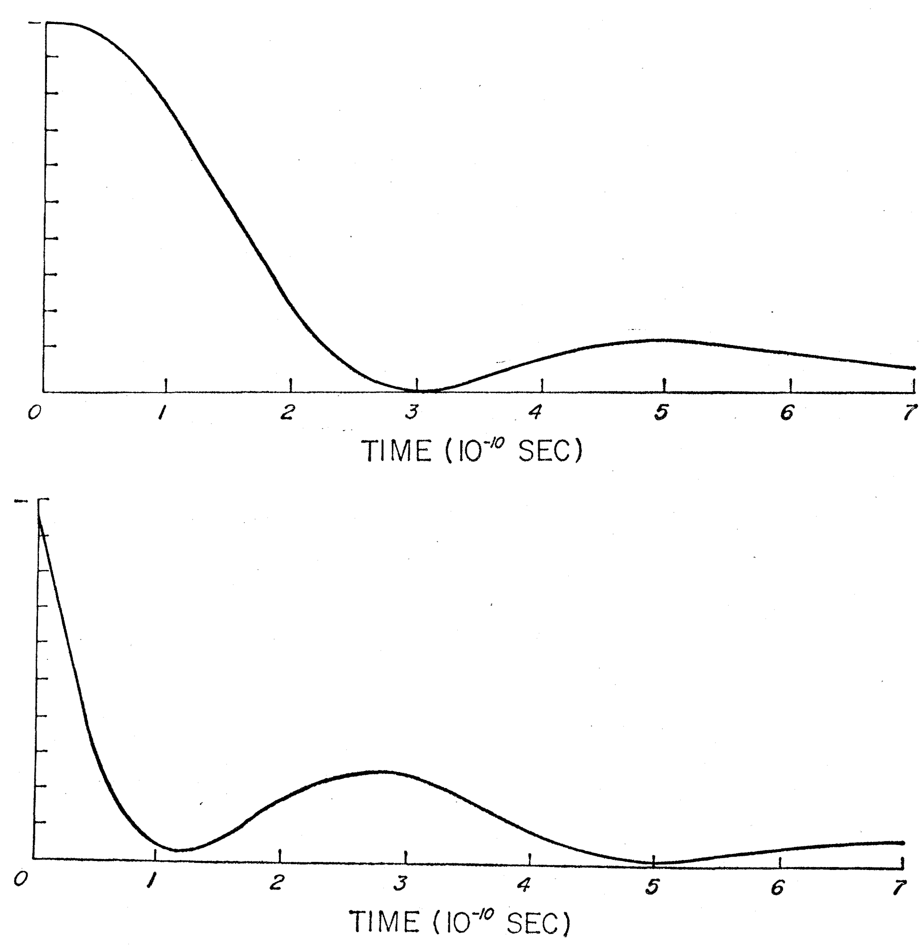

Fig. 5. Total rate of beta decay of a K^0-meson source as a function of time when there is a maximal failure of *CP*-invariance. The upper and lower curves correspond to opposite directions of flow of time.

and unexpected result discovered by Ely *et al.* (*18*). It means that the K^0- and the $\bar{K}^0$-meson can decay into the *same* leptonic mode, and it provides a novel means for exploring *CP*-invariance.

The test of *CP*-invariance (*19*) has to do with the fact that the transformation *CP* converts a K^0- into a $\bar{K}^0$-meson, since they are antiparticles of one another, and converts the $\pi^- e^+ \nu$ mode into the $\pi^+ e^- \bar{\nu}$ mode. Without going into details, we can state the result as follows: If *CP*-invariance is valid, the sum of the two curves in Fig. 3—that is, the total intensity of beta decay without regard to the sign of charge of the products—has the simple form of a combination of two normal (exponential) decay curves, as shown in Fig. 4. Note that the half-life of one of the exponentials is very long, about 10^{-8} second, and that this contribution is virtually constant in the figure. If *CP*-invariance fails, there is still to be expected a residue of the interference effect, which manifests itself as a kinking of the curve, as shown by either of the curves in Fig. 5. Even if *CP*-invariance is violated, no kink will appear in the curve if the K^0- and $\bar{K}^0$-mesons do not decay into the same leptonic mode. Therefore, the conclusion drawn from the experiment of Ely *et al.* is essential to this method of testing the invariance.

The number of beta-decay events so far observed for K^0-mesons is not great enough to determine the shape of the curve, but it is hoped that results on this very direct test will be available within a relatively short time.

If it turns out that there is a kink in the curve, then from the *CPT* theorem it can be concluded that *T*-invariance is broken. Comparison of the two curves in Fig. 5 illustrates the point. The upper curve may be taken to be the shape found by observer A; the lower will then be the shape found by observer B, since the interference term changes sign when the sense of time is reversed.

The connection between *T*-invariance and *CP*-invariance established through the *CPT*-theorem indicates the existence of an ambiguity in the interpretation of *any* experiment on the time direction, and the nature of the ambiguity is such that an absolute determination of the direction of time flow is, in fact, not possible, even if there is a failure of *T*-invariance. For example, let us suppose that observers A and B find the results shown in Fig. 5 when each performs the K-meson experiment in isolation. Although one possible interpretation is that their clocks are turning oppositely, another possibility is that antimatter is the basic substance of B's universe while matter is the basic substance of A's universe. A third possibility is that A and B are using the opposite convention for right-handedness and left-handedness.

As long as A and B are truly isolated from one another they cannot determine which of the three conditions is satisfied if the physical laws are *CPT*-invariant. Therefore, in the final analysis a violation of *CPT*-invariance is the key to the determination of the direction of time flow.

Although this invariance has been stated as a theorem, the proof of the theorem starts from certain physical assumptions. These assumptions are very general in character and are fundamental to the structure of modern physical theories. Assumptions they are, however, and as such they are subject to experimental test. And one of the most interesting experiments would be to test directly the *CPT*-invariance itself. An experimental demonstration of a failure of the theorem would have the deepest significance, in view of the basic character of the underlying theory. Furthermore, it could make possible an absolute distinction between the directions of time flow which would probably have some cosmological meaning.

The neutral K-meson experiment described earlier offers an opportunity to make a direct test of *CPT*-invariance in weak interactions. A detailed comparison of the experimental rates of electron and positron decay, corresponding to the two curves in Fig. 3, can be shown (*20*) to provide a test (*21*). But a comparison in the necessary detail requires many more data than the test of *CP*-invariance based on the sum of the curves. Some years may pass before sufficiently intense K-meson sources are available to make this experiment feasible. Even if the experiment reveals a failure of the *CPT*-theorem when it is done, that alone would not suffice to fix the absolute sense of time flow. Both *CPT* and *T*-invariance must be violated for this purpose, and a test of *CP* cannot be substituted for the test of *T* under these circumstances. Therefore, to resolve the original question, spin-correlation tests for *T*-invariance of the type described for the neutron might be needed. These are possible for the leptonic modes of either the Λ-hyperon or the K-meson, although, again, much more intense sources will probably be required for a reliable experiment.

Experiments like these seem to offer the only remotely promising opportunity to establish an absolute standard for directing time flow at the present time. However, it is impossible to predict what new opportunities will arise as we delve more deeply into the microscopic structure of the universe (*22*).

References and Notes

1. J. Loschmidt, *Wien Ber.* **73**, 139 (1876); *ibid.* **75**, 67 (1877).
2. P. and T. Ehrenfest, *Encyklopadie der Mathematischen Wissenschaften* (Leipzig-Berlin, 1911), vol. 4, pt. 32 [translated as *The Conceptual Foundations of Statistical Mechanics* (Cornell University Press, Ithaca, N.Y. 1959)]; see especially the preface to the translation written by T. Ehrenfest.
3. E. P. Wigner, *Nachr. Ges. Wiss. Goettingen, Math-Physik Kl. No. 32* (1932), p. 546.
4. W. Pauli, in *Neils Bohr and the Development of Physics* (Pergamon, New York, 1955), p. 30.
5. G. Luders, *Kgl. Danske Videnskab. Selskab, Mat-Fys. Medd.* **28**, No. 5 (1954).
6. To each particle of physics there corresponds an antiparticle having "opposite" properties. Particle and antiparticle have opposite signs of the electric charge and magnetic moments as well as opposite strangeness properties. Examples are electrons and positrons, protons and antiprotons, and so on. Material made up of atoms with nuclei composed of antiprotons and antineutrons surrounded by positrons is called "antimatter."
7. R. Jost, *Helv. Phys. Acta* **30**, 409 (1957); ———, in *Theoretical Physics in the Twentieth Century*, M. Fierz and V. F. Weisskopf, Eds. (Interscience, New York, 1960), p. 107.
8. C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, R. P. Hudson, *Phys. Rev.* **105**, 1413 (1957).
9. T. D. Lee and C. N. Yang, *ibid.* **104**, 254 (1956).
10. v is actually a vector, for which a direction as well as a magnitude must be specified. A change in the sign of v is equivalent to a reversal in the direction of the vector.
11. However, note the qualification of this statement because of quantum-mechanical effects discussed later.
12. M. T. Burgy, V. E. Krohn, T. B. Novey, G. R. Ringo, V. L. Telegdi, *Phys. Rev. Letters* **1**, 324 (1958).
13. The amplitudes are, in general, complex numbers, and the relationship between them is that they have the same phase. See K. M. Watson, *Phys. Rev.* **95**, 228 (1954), especially the appendix.
14. J. W. Cronin and O. E. Overseth, *Proceedings of the 1962 International Conference on High Energy Physics* (CERN, Geneva, 1962), p. 453.
15. M. Gell-Mann and A. Pais, *Phys. Rev.* **97**, 1387 (1955).
16. These are calculated curves based on the results of U. Camerini, W. F. Fry, J. A. Gaidos, H. Huzita, S. V. Natali, R. B. Willmann, R. W. Birge, R. P. Ely, W. M. Powell, and H. S. White, *ibid.* **128**, 362 (1962).
17. S. B. Treiman and R. G. Sachs, *ibid.* **103**, 1545 (1956).
18. The curves are calculated on the basis of results of R. P. Ely, W. M. Powell, H. White, M. Baldo-Ceolin, E. Calimani, S. Ciampolillo, O. Fabbri, F. Farini, C. Filippi, H. Huzita, G. Miari, U. Camerini, W. F. Fry, and S. Natali [*Phys. Rev. Letters* **8**, 132 (1962)], under the assumption that *CP*-invariance is valid.
19. R. G. Sachs and S. B. Treiman, *Phys. Rev. Letters* **8**, 137 (1962).
20. R. G. Sachs, *Phys. Rev.* **129**, 2280 (1963).
21. Other tests of *CPT* invariance have been suggested—for electromagnetic interactions, by J. Bernstein and L. Michel [*Phys. Rev.* **118**, 871 (1960)] and for strong interactions, by K. Gotow and S. Okubo [*ibid.* **128**, 1921 (1962)].

22. Part of the work reported here was supported by the U.S. Atomic Energy Commission.