5 April 1957, Volume 125, Number 3249 SCIENCE

Fall of Parity

Recent Discoveries Related to Symmetry of Laws of Nature

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A number of recent experiments in nuclear physics have revealed that some of the very basic properties of nature seem to be different from what we believed them to be. It is rare in the history of physics that the results of only a few experiments force upon us a change in our fundamental principles. This is just what has happened now, and this essay tries to explain the situation.

Before describing the experiments themselves, we will discuss the basic principle which is attacked by their results. It is the *principle of parity*. This principle can be stated in the following form: any process which occurs in nature can also occur as it is seen reflected in a mirror. Thus nature is mirror-symmetric. The mirror image of any object is also a possible object in nature; the motion of any object as seen in a mirror is also a motion which would be permitted by the laws of nature. Any experiment made in a laboratory can also be made in the way it appears as seen in a mirror, and any resulting effect will be then the mirror image of the actual effect. In more elegant language, the laws of nature are invariant under reflection.

As an example, take a perfectly uniform bar supported in the middle by a pivot, as in Fig. 1. We all know that it will not tip, but let us prove this using mirror symmetry, or the principle of parity. There are three possibilities: (i) the bar could tip clockwise, (ii) it could tip counterclockwise, or (iii) it could remain horizontal. Suppose we place a mirror as in Fig. 2 (the dotted line represents the mirror). The mirror image of the bar and its support is identical with the object. However, if motion (a) were the correct one, the mirror image would show motion (b) and not the correct motion i; hence, we have a contradiction to the principle of parity. Only the possibility iii is identical with its reflection and thus must be the correct one since the object itself is identical with its reflection.

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Now we suppose the pivot to be frictionless and rotate the bar around the axis AA' (Fig. 3). The situation is unchanged since this rotation appears unchanged in the mirror. Then this rotation will not cause the bar to tilt.

Electromagnetic Radiation

Let us now look at a more sophisticated example. We will examine the radiation from an electric dipole. Such a dipole can be pictured, for example, as a charge which oscillates up and down in the z-direction (Fig. 4) We see, first of all, that the radiation pattern will be symmetric around the z-axis. This is because the electric dipole exhibits a cylindrical symmetry about this axis.

We will now use mirror symmetry to show that the intensity is the same above and below the x-y-plane. In Fig. 5 we illustrate the two cases. The mirror image of the oscillating dipole is identical with the object, apart from a phase shift of half a period. When the object moves up, the image moves down. However, the radiation intensity pattern is constant in time, and therefore it is not affected by this shift in time. We see that the mirror image of the radiation pattern labeled "right" is exactly like the actual one, as it should be, while the pattern labeled "wrong" is inverted: the object has a stronger field downward, while the image has a stronger field upward. They cannot both be right.

Let us now look at the electromagnetic field associated with this radiation. Here we examine the instantaneous position of the moving charge, and of the electric field, since we know that after each half period the direction of the dipole and also the direction of the field strength change their sign. Let us suppose that the charge is moving upward. We know that the electric field must be perpendicular to the direction of propagation, and we would like only to decide the question of the relative directions of the electric field in two beams, one going upward and the other downward. In fact, we want to decide between the two possibilities marked "wrong" and "right" in Fig. 6. Using mirror symmetry, we can rule out the possibility marked "wrong." This situation cannot hold, for the dipole is turned around in reflection, while the electric field is not. (Alternatively, if we wait half a period, the mirror-dipole will point upward again, but the electric field will have reversed its direction.) On the other hand, in the situation marked "right," the electric field has "followed" the dipole upon reflection. (Here, if we wait half a period, the mirror dipole and electric field will reverse, reproducing the present actual dipole and electric field.) Then the situation marked "right" must be the true one.

On the other hand, a quadrupole consists of two dipoles opposite each other. It is thus unchanged when it is reflected in a mirror, so that we have the reversed case; the electric field of quadrupole radiation must be invariant upon reflection in a mirror, and the case marked "wrong" in Fig. 6 would be the correct one. We say that dipole radiation has an "odd" parity since E has changed direction; quadrupole radiation has an "even" parity, since E is unchanged.

We have used the electric field in this discussion since it alone specifies a direction (the direction of the force on a positive charge). This direction becomes the reflected direction when seen in a mirror. The magnetic field does not specify a direction, but only a sense of rotation (for example, the sense of rotation of a moving charged particle which produced it). However, the sense of rotation is unchanged under reflection. It is important to remember here that the "direction" of the magnetic field is usually defined in terms of an arbitrarily chosen "right-handed screw." That is, we associate the magnetic field with a screw, which arbitrarily ascribes a direction to a sense of rotation in order to express it by a vector. This situation is usually described by saying that the electric field is described by a polar vector which changes direction under reflection, while the magnetic field is described by an axial vector, which does not change direction under reflection.

Let us now consider an object such as a screw which has a "spirality"—that is, a direction of motion associated with a sense of rotation (Fig. 7). Its mirror image has the opposite spirality and must also exist in nature, by our principle of parity. Thus, in Fig. 7, we see that we may place our testing mirror in two positions, one of which reflects the direction of motion but leaves the sense of rotation unchanged, while the other has the reverse effect. In either case, the spirality is changed.

An example is the tetrahedral molecule of Fig. 8. We see that the reflected molecule cannot, by any rotation, be made to be identical with the original molecule (just as we cannot turn our left hand in such a position that it looks like our right hand). Thus these are distinct molecules which, by the principle of parity, must both exist in nature. An example of this situation is the quartz crystal, composed of many of these molecules. This crystal illustrates on a large scale this "handedness." The principle of parity requires that both types of crystals be found in nature.

A well-known example is the fact that sugar occurs in two varieties. However, it is only the right-handed kind, glucose, which is found in living matter. As physicists, we do not believe that this indicates an inherent handedness of nature; rather, we believe that it can be attributed to an accident which occurred at the origin of life. Life could just as well have developed by using levose instead of glucose.

Beta Decay

We now proceed to consider the actual experiments which have shed new light on this principle of parity, in particular, experiments on beta decay. All we need

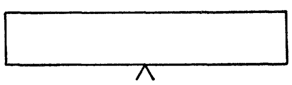

Fig. 1. Uniform bar pivoted in the middle.

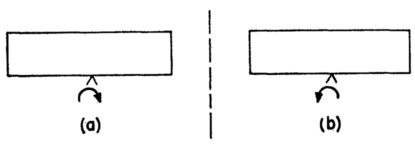

Fig. 2. Mirror image of bar. This illustrates the lack of mirror symmetry if the bar should rotate.

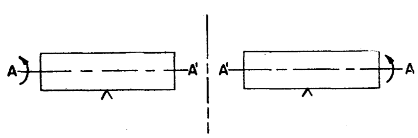

Fig. 3. Rotating bar viewed in mirror. The sense of rotation is unchanged by reflection.

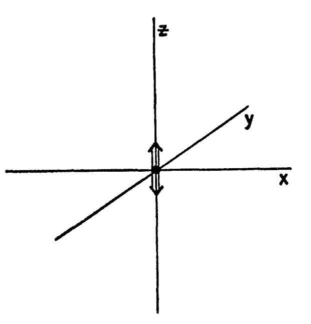

Fig. 4. Oscillating dipole.

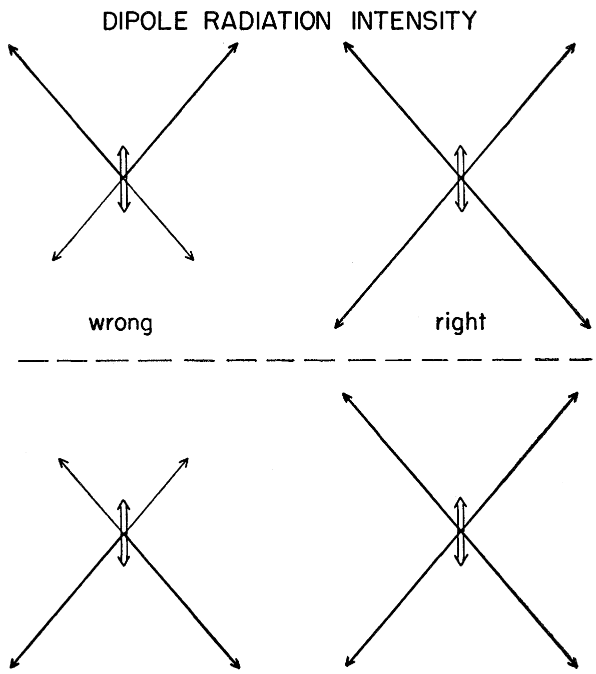

Fig. 5. Dipole radiation-intensity patterns and their mirror images. The pattern marked "right" emits the same intensities into the upper and lower hemispheres; the pattern marked "wrong" emits more into the upper hemisphere than into the lower.

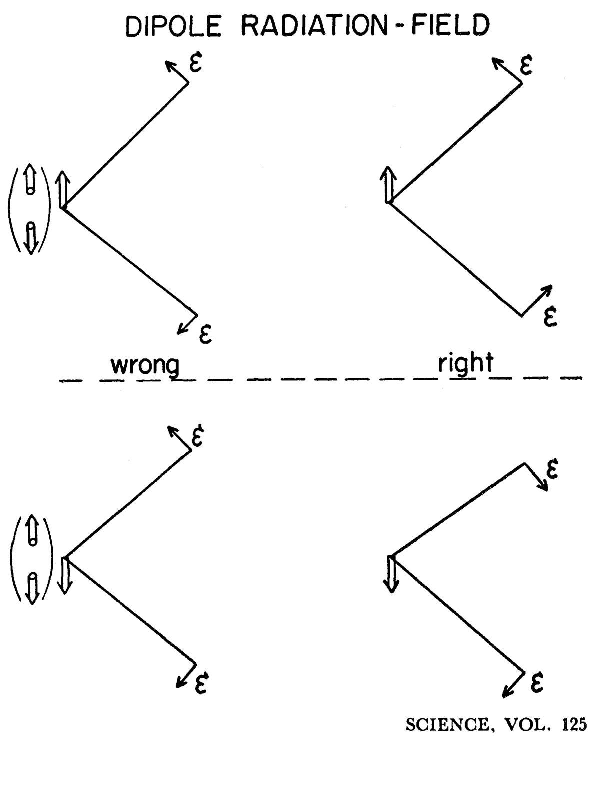

Fig. 6. The electric field distribution of a dipole radiation and its mirror image. The little arrows marked ε represent the direction of the electric field at a given time in the wave emitted in the direction shown. The heavy arrow in the center shows the displacement of the dipole at that time. The two heavy arrows in parentheses symbolize a quadrupole source.

to know here is that there are atomic nuclei which emit electrons along with neutral, massless particles known as neutrinos. For instance, the isotope of cobalt known as cobalt-60 becomes nickel-60 and emits an electron (e^-) and a neutrino (ν)

$$Co^{60} \rightarrow Ni^{60} + e^- + \nu$$

The cobalt nucleus has a spin—that is, it is rotating with a well-defined angular momentum when it is in its normal state. Now we ask: In what directions will the electrons emerge? In a normal piece of cobalt, electrons will emerge in all directions because nuclei are oriented in all directions because of the heat motion.

Suppose we orient the nuclei—that is, force all the nuclei to align their axes of rotation parallel to a given direction and have them rotate in the same sense. This is the difficult part of the experiment since it is so hard to "get hold of" the nucleus. The only way is through the magnetic moment arising from the spin. The spin can be forced into a given direction by an external magnetic field if we can reach temperatures of less than 0.1°K. Then it is possible to orient the nuclei.

What do we now expect? The nuclei are all rotating in the same sense. Let us apply the principle of parity. In a mirror (Fig. 9) they rotate the same, but the direction of the electrons is reversed. Thus the situation marked "wrong," in which more electrons emerge in one direction than in the other, violates the principle of parity: the mirror image contradicts the actual situation. Since the parity principle requires both to be right, we must exclude this case. Hence, we expect the same number of electrons to emerge in each direction.

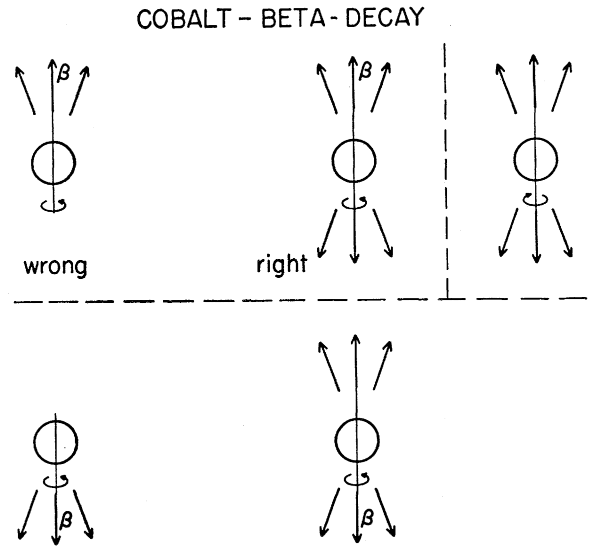

Fig. 9. Cobalt beta decay. Possible electron decay patterns and their mirror images. Only the choice which is mirror-symmetric should occur if the principle of parity is valid.

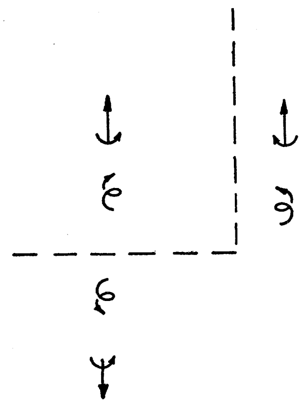

Fig. 7. A spiral and its mirror images. The horizontal mirror changes the direction but not the sense of rotation. The vertical one changes the sense of rotation, but not the direction.

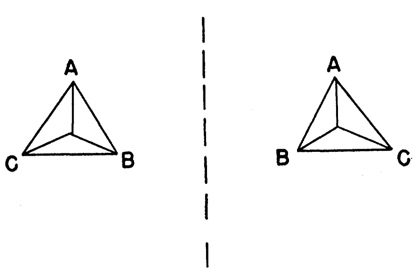

Fig. 8. An asymmetric tetrahedral molecule viewed in a mirror.

This now sets the scene for the experiment. It was performed at the National Bureau of Standards in Washington, D.C., where the cryogenic equipment was available for experimenting at very low temperatures. The physicists who did it were C. S. Wu from Columbia University and E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson of the National Bureau of Standards. They oriented the rotation of cobalt nuclei and compared the electron intensities in the two opposite directions along the axis of rotation.

There are several remarkable features about this experiment. It is one of those experiments which only a few people would perform because the result "obviously" follows from mirror symmetry. Great discoveries are always made when one doubts the "obvious." In this case, it was the insistence of two theoretical physicists, T. D. Lee of Columbia and C. N. Yang of the Institute for Advanced Study, which prompted the experimenters to look for the effect. Lee and Yang suspected that the principle of parity may be invalid for certain weak interactions like beta decay.

Another remarkable feature of this experiment is the size of the effect which was measured. The intensity of electrons in one direction along the axis of rotation was found to be 40 percent larger than it was in the other. It is very rare in the history of physics that the failure of an established principle shows up with such large effects in the first experiment. Usually the first doubts are based on small deviations which hardly exceed the limits of error, and only after the passing of time and the application of great effort by many people are effects as large as 40 percent found.

In view of the historic importance of this experiment, it is perhaps worth while to show the actual curves as measured. They are reproduced in Fig. 10. The scale labeled "time" is actually a scale of temperature. The cobalt sample is cooled to a temperature at which its nuclei are aligned, and then it slowly warms up in the course of time. The curve labeled "gamma anisotropy" really tells us the fraction of nuclei which are oriented. For a large anisotropy, most of the nuclei are aligned. As the cobalt warms up, the heat motion causes the alignment to become more random, and the gamma anisotropy decreases.

The curve labeled "β-asymmetry" is the significant one. This tells us the number of electrons emerging in the direction of the magnetic field, and the number emerging in the opposite direction. We see that there are more in one direction than in the other, that the electrons go up when the spin is turning one way and down when the spin is turning the other way. This shows that the principle of parity does not hold in this experiment. Remember that the spin of the nucleus tells only a sense of rotation. And yet the electron emerges in a preferred *direction*. This is the mark of the parity violation. The fact that there is a direction associated with a sense of rotation shows that there is a definite "handedness" exhibited in the beta decay of cobalt-60. The mirror image of the decaying cobalt nucleus would have the opposite handedness and seemingly does *not* occur in nature.

The same experiment has also been

done with cobalt-58, which is a *positron* emitter. It goes over into iron-58 and emits a positron (e^+) and an antineutrino

$$Co^{58} \rightarrow Fe^{58} + e^+ + \bar{\nu}$$

where $\bar{\nu}$ denotes the antineutrino. Whenever a negative electron is emitted in a beta decay, as in cobalt-60, it is accompanied by a neutrino, and whenever a positron is emitted, it goes with an antineutrino. Most significantly, the same group of physicists have found the opposite handedness in the positron case. For the same rotational sense of the nucleus, negative electrons seem to emerge in one direction and positrons in the other.

Spirality

A possible explanation of these new phenomena has been proposed by Lee and Yang, and independently by L. Landau in Moscow and by A. Salam in England. They suggest that the spirality is associated with the neutrino, since all other phenomena in nuclear physics, which involve no neutrinos, exhibit perfect mirror symmetry. With this hypothesis, the difficulty is isolated from the rest of physics. It "minimizes the damage" and puts this strange property on the neutrino, which is already a strange particle.

Lee, Yang, Landau, and Salam argue that the neutrino is a spiral. Its sense of rotation and its direction of propagation are connected such that they form, say, a left-handed screw. The neutrino has the property that its spin (its rotation) must be such that its axis is parallel to its motion and its sense such as to form a left-handed screw. The antineutrino is supposed to have the opposite properties. It forms a right-handed screw.

It is interesting to note that particles with such properties must always move with the velocity of light c and, therefore, necessarily have a zero rest mass. If they would move with a velocity v less than c, they would reverse their spirality for an observer moving faster than v in the same direction. Hence, their spirality would be dependent on the observer and could not be an intrinsic property.

With these helical neutrinos, the observed effects can indeed be explained (Fig. 11). The emitted particles must take along some of the spin of the emitting nucleus. Hence, the sense of rotation of the neutrino will be the same as the one of the cobalt nucleus. Its direction of emission must then be such that a left-handed screw is formed. Hence, the neutrino will be emitted only in one direction—namely, the one which forms a left-handed screw with its sense of rotation. The electrons are emitted mostly in the same direction as the neutrino. Thus, we get a preferred direction of emission for the electrons, as observed.

A good support for this explanation is found in the experiment with cobalt-58, in which the emitted particles are a positron and an antineutrino. If the hypothesis is correct, the preferred direction of the positrons must be opposite here to the preferred direction of the electrons in cobalt-60, for the antineutrino has the opposite spirality (*1*). In fact, that is just what the experiment has shown!

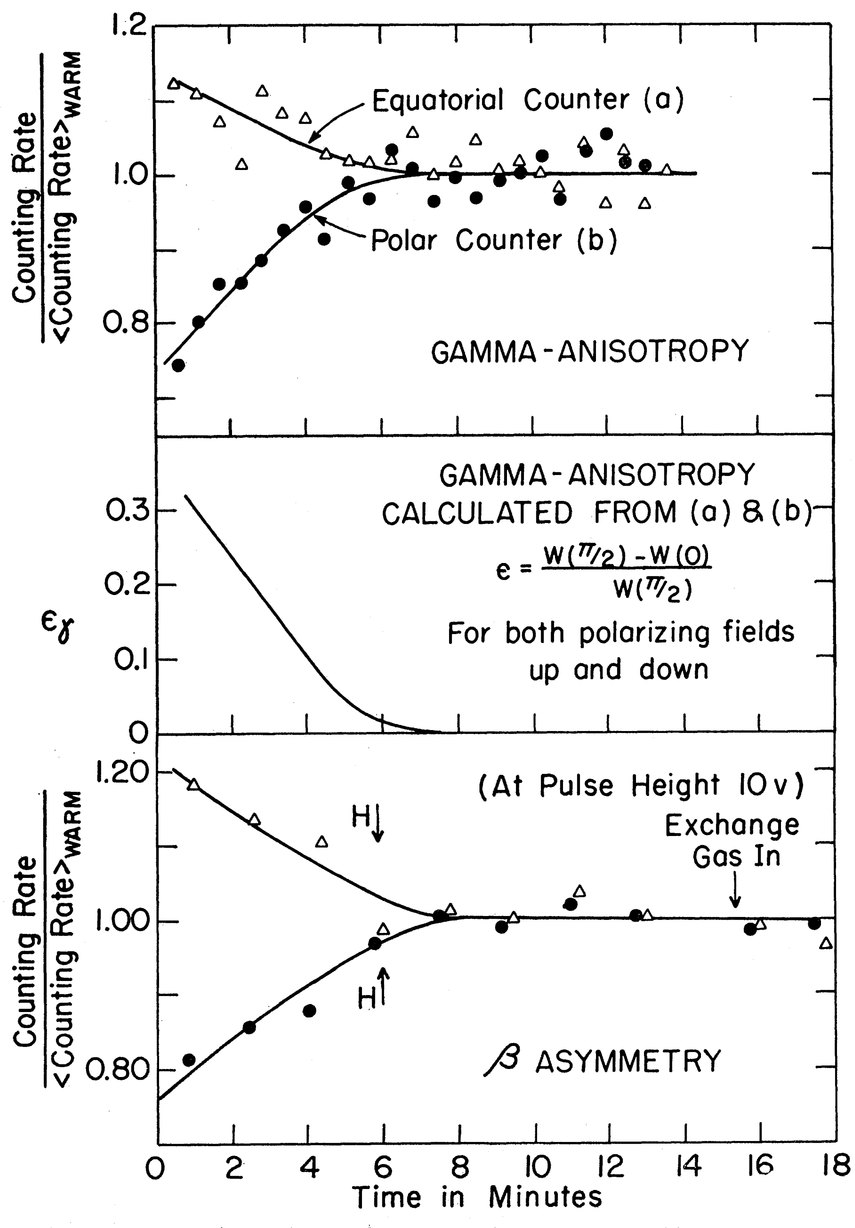

Fig. 10. Experimental observations on β-decay of cobalt-60 (Wu, Ambler, Hayward, Hoppes and Hudson). The gamma anisotropy measures the orientation of the nuclei. The β-asymmetry measures the number of electrons which emerge parallel, and antiparallel, to the magnetic field.

Experiments on Mesons

There is a second kind of experiments in which a similar violation of the parity law has been observed. These experiments have to do with some of the newly discovered short-lived particles, the mesons. The most important meson is the π-meson, which is probably the "quantum" of the nuclear force field. It is responsible for the binding forces in the nucleus. It occurs in three varieties, positive, negative, and neutral; it has a mass 265 times that of an electron, and it is known to have no intrinsic spin. When it is in free motion, the charged π-meson has a very short lifetime (*2*) of only 10^{-8} second and decays into a μ-meson and a neutrino. The μ-meson is a particle very similar to an electron. It has a charge (positive or negative) and a spin of $\frac{1}{2}\hbar$ just like the electron,

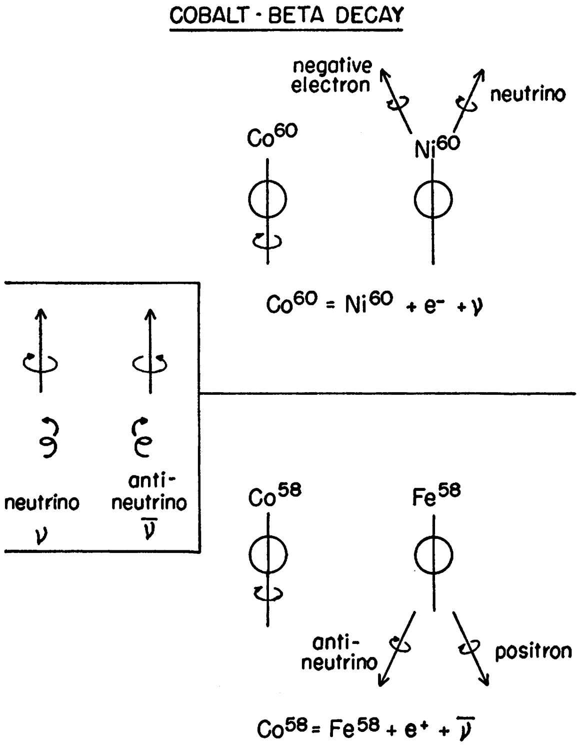

Fig. 11. The Lee-Yang-Landau explanation of the asymmetric beta decay of cobalt-60 and cobalt-58.

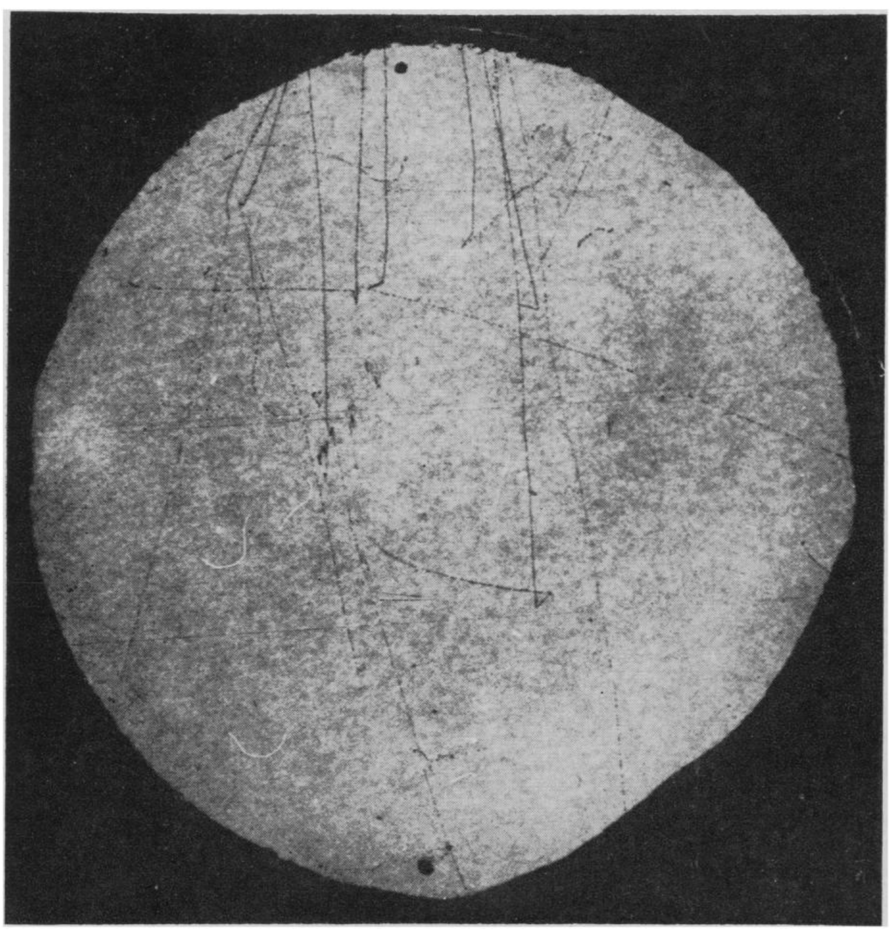

Fig. 12. Bubble chamber photograph of the π-μ-e decay chain (Pless and Williams). Dark tracks entering the chamber from above are π-mesons. Short dark tracks at the ends of the π-meson tracks are μ-mesons produced in the decay of the π-mesons. The long light tracks are electrons produced in the decay of the μ-mesons. The electron tracks emerge in a predominantly-backward direction relative to the direction of the μ-meson tracks.

but its mass is 250 times larger. It too is unstable and decays after 10^{-6} second into an electron and two neutrinos. This double decay chain

$$\pi \longrightarrow \mu + \nu \longrightarrow e + 2\nu + \nu$$

is a very interesting phenomenon and has been studied in detail.

Figure 12 shows a bubble chamber photograph of such processes, made recently by I. Pless, R. Williams, and coworkers. What one sees in such a picture are the charged particles only and not the neutrinos. One observes π-meson tracks coming from above which end when the π-mesons come to rest. They then decay, and one sees a (short) μ-meson track emerge from the end point of the π-meson track. At the end of this track a third track emerges which is the track of the electron. The last track is longer again and is not very straight because the light-weight electron can easily be deviated from its path. A careful observer will find in Fig. 12 that in five out of the six decay chains the electron is emitted "backward" in reference to the motion of the μ-meson. This effect has been established by more careful experiments, at Columbia University by Garwin, Lederman, and Weinrich, at the University of Chicago by Friedman and Telegdi.

Why are the electrons emitted backward? Again, this is an example of the breakdown of the parity rule. When the μ-meson comes to a rest at the end of its short track, the only motion left to it is its rotation. How can a rotation determine a preferential direction of decay? Only by defining a preferential "handedness" or screw sense. This, of course, is a violation of the parity law, for the mirror image of the process would show the opposite preference.

The Yang-Lee hypothesis, ascribing a spirality only to the neutrino, would also explain these meson experiments. This is shown schematically in Fig. 13. The π-meson decays into a μ-meson and a neutrino. The spin of the neutrino is always supposed to form a left-handed screw with its direction of propagation. From this it follows directly that in this decay the μ-meson also must form a left-handed screw with its rotation and its velocity since the spin and motion of the π-meson before decay were zero, and, consequently, the spin and motion of the two decay particles must be opposed. (In general, the spin of the μ-meson is not fixed relative to its direction of motion; Yang and Lee assume such coupling to be compulsory only for neutrinos. However, in this case its spin axis is parallel to its motion, and its sense of rotation is left handed.)

Now we look at the second decay in the chain, the decay of the μ-meson into two neutrinos and an electron. The conservation of momentum requires, for those cases in which the electron obtains large energies, that the two neutrinos be emitted in one direction and the electron in the opposite one. The two neutrinos are necessarily emitted in the direction of the μ-meson motion because of the fact that their sense of rotation will coincide with the one of the μ-meson (conservation of spin) and because of the necessity of forming a left-handed screw. Hence, the electron will be emitted mostly backward, as observed (*3*).

Novelty of the Phenomenon

Let us now discuss two experiments which in all probability cannot actually be performed. A discussion of them is instructive, however, because it illustrates the essential novelty of the phenomenon.

We first return to the pivoted bar with which we began this discussion. Suppose it is made of cobalt-60, and suppose we rotate it about the axis *AA′* (Fig. 3). (This example was suggested by E. M. Purcell.) As it rotates, the nuclear spins align themselves and the bar becomes very slightly magnetic. (This is the Barnett effect.) The electrons will then be emitted in a given direction; they will be absorbed in the bar, and one end will contain more energy than the other. (Actually, under normal conditions, this effect is so small that it cannot be observed at all.) Since the theory of relativity tells us that energy and mass are related, one end will be heavier than the other. Then, theoretically at least, the bar *will* tilt. Thus, a microscopic process

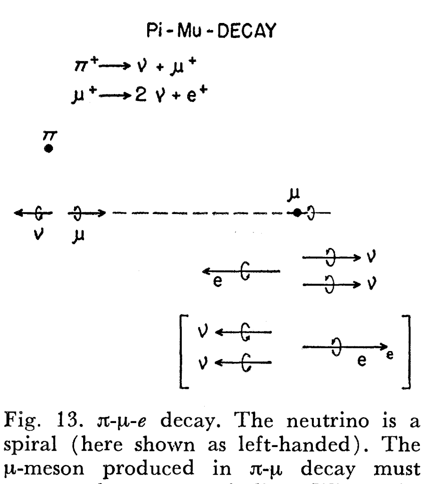

Fig. 13. π-μ-*e* decay. The neutrino is a spiral (here shown as left-handed). The μ-meson produced in π-μ decay must possess the same spirality. When the μ-meson decays, two neutrinos are emitted in a direction opposite that of a high-energy electron. Because of the inherent spirality of the neutrinos, the relative directions must be as shown. The mirror image of this decay process is shown in brackets. By the parity principle, this should also be a possible decay process; experiment shows that it is not.

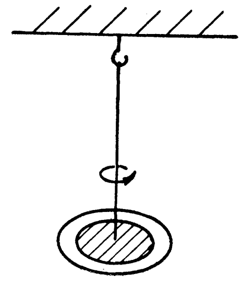

Fig. 14. Aluminum disk suspended by a thin wire. If the disk is coated on top with cobalt-60 it will spontaneously rotate as shown.

(beta decay) which violates the principle of parity could lead in principle to a macroscopic observation of its violation.

An even more dramatic experiment has been suggested by J. R. Zacharias. Suppose a small round disk of aluminum is coated on the top with a thin film of cobalt-60 and suspended in a horizontal position by a thin wire attached to its center, as shown in Fig. 14. The disk will begin to rotate! And, if the experiment is repeated, it will always rotate in the same direction! This can be understood from our previous discussion of beta decay, if we observe that the electrons which are emitted downward will be stopped in the aluminum, while those which are emitted upward will escape (the neutrinos escape in either case). One can think of the electrons which are stopped as transmitting their spirality to the block, which then begins to rotate. If the cobalt coating were on the lower side, the rotation would be in the other direction.

Antimatter

It is very suggestive to consider the violation of the principle of parity in connection with another somewhat better known asymmetry in our physical world. This is the asymmetry with respect to electric charge. The massive atomic nuclei are all positively charged, and the light electrons are negative. Physicists began to suspect that this asymmetry was only apparent after the discovery of the positive electron, the positron, in the early 1930's. It was shown that one can produce an electron pair, a negative and a positive electron, with light quanta of sufficient energy. The positron is in all respects the exact opposite of the negative electron; it is its so-called "antiparticle." If a positron hits an ordinary electron, the two particles annihilate each other (the opposite process of pair creation), and their masses are transformed into light energy. The question of charge symmetry was completely cleared up after the discovery last year of the antiproton and the antineutron. The antiproton is a negative proton; it is antiparticle to the ordinary proton. It was produced with the very high energies now available from the large accelerators. The antineutron is the antiparticle of the ordinary neutron; it is just as neutral in respect to charge, of course, but it is opposite to the neutron in all respects. For example, it has the opposite magnetic moment, and it will annihilate into γ-rays or other forms of field energy with any neutron it meets, just as the negative proton will when it encounters a positive proton.

Hence, it seems that the charge asymmetry of matter is only apparent. One could also build up "antimatter," as it were, by using antiprotons and antineutrons for nuclei and positrons around them instead of electrons. Such antimatter would be the exact replica of our matter, with opposite charge: negative nuclei and positive electrons. It just so happens that our world is made of one type of matter. Some distant galaxies might be made of the other type.

We do not know much about the properties of antimatter, but it is highly plausible that there exists an interesting reciprocity in respect to the parity problem. We have mentioned that cobalt-58, which is a positron emitter, has shown the opposite spirality to the negatron emitter, cobalt-60. Cobalt-58 emits antineutrinos, which are the antiparticles to the neutrinos emitted by cobalt-60. Hence, antiparticles seem to have the spirality opposite to that of the particles. Thus, it is most probable that "anticobalt-60" would emit its positrons in the opposite direction to cobalt-60. If this is so, the violation of the mirror symmetry appears in a new light: we argued before that the mirror image of cobalt-60 decay does not correspond to any possible process in nature. Now we see that this mirror image might be just the decay of "anticobalt-60"! By bringing together the two asymmetries in nature, the charge asymmetry and the mirror asymmetry, we might be at the threshold of the discovery of a new and higher *symmetry,* which Landau has called the Combined Parity Principle. This principle says that the mirror image of any process in nature is also a possible process, but only if all charges are replaced by their opposite charges or if matter is replaced by antimatter. Since matter and antimatter are completely equivalent, the mirror symmetry of nature would be reestablished in a new and more interesting form.

We have seen in these developments how the increase in our knowledge of the properties of nature sometimes rocks the foundations of our understanding and forces us to a greater awareness of unsolved problems. The more the island of knowledge expands in the sea of ignorance, the larger its boundary to the unknown.

Notes

1. Many authors, in fact the majority, reserve the name "neutrino" for the particle which accompanies the positive β-decay, and call "anti-neutrino" the particle which is emitted in the negative β-decay. This choice is opposite to ours and would result in giving the neutrino a right-handed spirality. Our choice was done solely for the convenience of introducing the neutrino before the anti-neutrino.
2. The uncharged π-meson has an even shorter lifetime, but it will not be considered here.
3. In order to make this difficult chain of reasoning as simple as possible, we have made the assumption that the two neutrinos emitted by the μ-meson are identical. Actually, it seems more probable that they are of different kinds, neutrino and antineutrino. Under these conditions, the same conclusion can be reached, but only in a more subtle way.

Outer Space in Plants

Some Possible Implications of the Concept

Paul J. Kramer

For many years, work on the absorption of ions by plants has been dominated by the assumption that ion accumulation is *the* important process in ion absorption. For readers who are not familiar with the terminology of this field, these processes may be defined as follows. *Absorption* is a general term referring to the entrance of a substance into cells, tissues, or organs by any mechanism such as diffusion, mass movement, or active transport. Accumulation is a special type of absorption involving entrance against a concentration gradient by active transport. Accumulation requires the expenditure of metabolic energy by the cells or tissues in which it occurs; other absorption mechanisms do not. Active transport refers to movement of substances against a concentration or activity gradient, in contrast to passive movement, by diffusion along an activity or concentration gradient. The mechanism of active transport is not fully understood as yet, although theories involving carrier systems are popular at present (*1*).

There is increasing evidence that ion accumulation in cells may be a subsidiary process of importance chiefly at the cellular level and that ion absorption and translocation in intact plants occur more or less independently of accumulation. This possibility has been greatly increased by the development of the concept of outer space or apparent free space. By outer space is meant that fraction of the tissue volume into and out of which ions can move freely by diffusion.

Volume and Location

Hope and Stevens (*2*) seem first to have studied quantitatively this space in roots. They observed that up to 13 percent of the volume of *Vicia faba* roots consisted of space into and out of which ions are free to diffuse and termed it "apparent free space" (often abbreviated AFS). Butler (*3*) established the existence of free space in wheat roots by several methods and found that it comprised 24.5 to 33.5 percent of the root volume. Epstein (*4*) found that passive, reversible diffusion of several ions occurs into and out of a space in barley roots that is equivalent to 23 percent of their volume. Following the terminology of Conway and Downey (*5*), who had previously observed a similar situation in yeast cells, Epstein (*4*) termed the fraction of the root volume that is reversibly accessible to ions by diffusion "outer space.' The fraction of the tissue in which ions are accumulated by an active transport system was termed "inner space." The existence of space in cells accessible to various solutes by diffusion has also been observed in bacteria (*6*), in yeast (*5*), and in kidney tissue (*7*).

Although Epstein did not identify outer space with any particular region of cells, Hope and Stevens (*2*) and Butler (*3*) assumed that it included both cell walls and cytoplasm. It would be difficult to account of the volume of outer space observed in roots by various workers without including at least part of the cytoplasm. This means that the differentially permeable membrane which controls accumulation of ions is the tonoplast or vacuolar membrane rather than the outer surface of the protoplast or plasmalemma, as is often supposed.

That diffusion of ions into the cytoplasm occurs is indicated also by other types of experiments such as those of Brooks (*8*), Hoagland and Broyer (*9*), and Sutcliffe (*10*). Hope and Robertson (*11*), after reviewing previous work, concluded that the vacuolar membrane, rather than the plasmalemma, is the principal membrane in cells that is impermeable to solutes. Thus, inclusion of at least a part of the cytoplasm in outer space seems highly probable, although it has not been proved. Some binding of ions occurs in the cytoplasm, and apparently mitochondria accumulate ions and ought therefore to be excluded from outer space.

Thus far outer space has been discussed only in connection with the absorption of ions by roots, but if it occurs in roots it almost certainly also occurs in stems, leaves, and other plant structures. Perhaps practically all of the water-permeable structure of plants can be regarded as outer space, except the vacuoles, mitochondria, and ion-binding sites in the cytoplasm. Intercellular spaces are not included, because they ordinarily are occupied by air. Regardless of exactly what is included in outer space, the existence of a considerable volume in plant tissues into and out of which ions can diffuse freely must have important effects on other plant processes besides salt absorption.

Aids in Explaining Diverse Phenomena

The concept of outer space makes it possible to explain a number of phenomena which are difficult to explain if it is assumed that most of the ions in plants move from vacuole to vacuole by active transport, or are accumulated in vacuoles behind differentially permeable membranes. Examples are the increased absorption of minerals accompanying the increased absorption of water, the wide variety of ions found in plants, the absorption of large molecules such as chelates and antibiotics, and the leaching of ions from leaves by rain.

Outer space provides a pathway by which ions may move from the soil solution to the leaves without passing through the vacuole of a single cell. Furthermore, according to this concept, a considerable fraction of the salt, and perhaps of other solutes, is not irreversibly accumulated in vacuoles, but occurs in outer space where it can move freely by diffusion, aided by cytoplasmic streaming, or can be carried by mass flow. All movement of materials in the xylem and probably

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