CP symmetry violation

In an informal discussion that grew out of a recent talk to physics teachers in Chicago, the codiscoverer of CP asymmetry recalls the circumstances of the observation and discusses its implications.

James W. Cronin and Margaret Stautberg Greenwood

Sixteen years before the discovery of charge-conjugation–parity nonconservation in the decay of K mesons, a very fine high-school physics teacher got me interested in physics. I'm not sure that I wouldn't have been interested in it anyway, but nevertheless he was a remarkable gentleman in a high school in Dallas, Texas. I think high-school physics teachers continue to play a crucial role today, so I want to make one or two remarks about physics teaching before I describe the fascinating behavior of K mesons and discuss some of the historical and human aspects of the research that Val Fitch and I did on their decay.

In my high school, physics was said to be the toughest and most difficult class, so if you got in that physics course and passed, you felt very proud. The very nature of the course gave us that kind of incentive. In particular I remember that in the spring term our teacher had us do two projects. One was to go home and somehow build an electric motor, something that would go around when you put six volts to it. That was quite fun to do, but the one that turned out to be even more challenging was to make a transformer to step down 110 volts to 6 volts. The important thing, he said, was that it had to drive a certain load. That was the test. So each student would come up, connect his or her transformer, and drive a load. Some people didn't realize that you had to consider more than the ratio of turns to drive this load, and there were some spectacular explosions. He had this wonderful way of teaching by a very demonstrative method.

Another thing I'd like to comment about is the decline in the number of high-school physics teachers, although it is probably difficult to do much about this. I have seen newspaper reports saying that on the average there is only half a physics teacher per high school in the Chicago school system.[1] I think this is really a very serious matter, and the fact that we are not doing a good job of teaching mathematics, physics and science to the young people is ultimately going to have a very serious effect on the nation.

Neutral K mesons

Now let me turn to the question of K mesons, which were not even known when I was in high school. These particles were discovered in cosmic rays by physicists in Europe shortly after the end of the Second World War. They appeared as neutral particles that decayed into positive and negative pions, which were thought to be the nuclear glue, or the particles that transmitted the nuclear force.

The first thing that was so fascinating about the K meson was that it lived so long. It had a lifetime of 10^{-10} seconds, which seems short by macroscopic time scales, but a particle decaying via the strong interaction would have a lifetime of only 10^{-20} seconds. So there is a great inhibition to decay here, and this was understood finally by postulating that the particle has a quantum number called "strangeness." Murray Gell-Mann coined this term while he was at the University of Chicago. The K^0 meson was assigned a strangeness of $+1$ and the pions were each said to have a strangeness of 0.

$$\begin{array}{lcccc} & K^0 & \rightarrow & \pi^+ & + \ \pi^- \\ s: & 1 & \rightarrow & 0 & 0 \end{array}$$

If a decay requires a change of strangeness, it is inhibited and, in fact, it takes place via the weak interaction.

According to dogma, every particle is thought to have an antiparticle. Now, a proton and an antiproton are oppositely charged. For a neutral particle, you might ask, what's the difference between the particle and its antiparticle? The neutral pion, for example, is identical to its antiparticle. But the neutron and the antineutron have quite different properties; their magnetic moments, for example, have opposite signs. The antineutron is an antibaryon, and when it interacts with a neutron, they annihilate.

Unlike the neutral pion, the K^0 and its antiparticle $\overline{K^0}$ cannot be identical, because the $\overline{K^0}$ would have a strangeness of -1. The K^0 is a particle of zero spin, so the difference between K^0 and

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Apparatus for neutral K-meson experiment. Housings contain spark chambers and cameras. Researcher is standing near the triggering system electronics. (Photograph courtesy of Brookhaven National Laboratory). Figure 1

$\bar{K}^0$ is subtle; it is controlled by this strangeness quantum number. Since the $\bar{K}^0$ also decays to two pions via the weak interaction, how is that difference manifested?

$$\bar{K}^0 \rightarrow \pi^+ + \pi^-$$

What is really fascinating is that the final state of the K^0 and $\bar{K}^0$ are the same. In fact, that very point was made in a class I attended. I was a graduate student at the University of Chicago in the spring of 1954. Gell-Mann was a very young man then—I guess he's still a young man by his own standards—and he was giving a course in which he outlined his ideas about strangeness. One quite distinguished person in this class was Enrico Fermi. He asked Gell-Mann: If K^0 and $\bar{K}^0$ both decay to the same final state, what's the difference between them? Even Gell-Mann didn't have an answer for that—right away. He went to the Institute for Advanced Study and presumably thought a lot about this question. In 1955 he wrote a remarkable paper[2] with another physicist at the Institute, Abraham Pais. They predicted some very bizarre effects due to the fact that a particle and an antiparticle, even though distinct from one another, have a common decay mode.

There is an analogy in a pair of pendulums—say, a red one that represents the K^0, and a white one that represents the $\bar{K}^0$. Suppose you hang them on a common ring stand so there is a little coupling between them. When you describe the motion of these pendulums you talk not about one or the other, but about the normal modes of the coupled pair. There are two normal modes, each with its own period: the symmetric mode, where the pendulum bobs move together, and the antisymmetric mode, where they move oppositely. Essentially, what Gell-Mann and Pais pointed out is the same thing: The K^0 and $\bar{K}^0$ are coupled via their common final state, and in decays are observed not separately but in two "normal modes" characterized by two different lifetimes. So it's very similar to the coupled pendulums.

And it is similar algebraically, too, as we will see later. For now, recall that in the case of pendulums, if you let x_1 and x_2 represent the displacements of the bobs from their equilibrium positions, then you must solve two differential equations to describe their motion. But each equation contains terms involving x_1 and x_2. Substituting $x_1 = \frac{1}{2}(X_1 + X_2)$ and $x_2 = \frac{1}{2}(X_1 - X_2)$ you obtain two simpler equations: one containing only X_1, and the other, only X_2. X_1 and X_2 are called the normal modes. From these equations you obtain the characteristic frequency of each normal mode. The normal mode X_1 corresponds to the symmetric motion of the pendulum bobs ($x_1 = x_2$), and the normal mode X_2 corresponds to the antisymmetric motion ($x_1 = -x_2$).

CP symmetry

Gell-Mann and Pais asked, what is the guiding principle that would establish the effects of this coupling? At the time they said that there is a symmetry of charge conjugation. That is, if you take a system and change every particle into its antiparticle, the laws of physics should be the same. Furthermore, one can characterize the quantum mechanical states, or assemblies of particles, by a quantum number related to this symmetry of charge conjugation.

Now that was before the discovery in 1957 of parity violation, where nature was found to have preference, a handedness if you like: The laws of physics are not symmetric under the operation of space reflection. That is, if you describe a system and then reverse all of the coordinates, the physical laws are not quite the same in certain weak interactions. So when that happened, the Gell-Mann–Pais argument was modified slightly to include parity violation. The argument that I will present to you will discuss these K mesons under the combined operation of charge conjugation C and parity P.

Gell-Mann and Pais said that the controlling principle that will tell us about the "normal modes," the proper linear combinations of K^0 and $\bar{K}^0$, is CP symmetry. What does this mean? Let's discuss it for the final state that consists of a π^+ and a π^- when they are in a state of zero angular momentum. When I operate on this state with charge conjugation C, the π^+ becomes a π^-, and the π^- becomes a π^+. The order in which I write down the pions certainly doesn't matter. It turns out that under space reflection the wavefunction of a particle can have either an even or an odd symmetry. The pions are odd under space reflection, giving us a factor of $(-1)^2$ because there are two pions. The zero angular momentum wavefunction is even under space reflection. The net result of charge conjugation and space reflection, then, is that I get the state back again with a plus sign. So this final state has a CP eigenvalue of $+1$.

$$\begin{aligned} CP|\pi^+\pi^-\rangle &= |\pi^-\pi^+\rangle(-1)^2 \\ &= +|\pi^+\pi^-\rangle \end{aligned}$$

As a second example consider a system of three pions: π^+, π^- and π^0. When I operate on this with CP, the final state has the opposite sign.

$$\begin{aligned} CP|\pi^+\pi^-\pi^0\rangle &= |\pi^-\pi^+\pi^0\rangle(-1)^3 \\ &= -|\pi^+\pi^-\pi^0\rangle \end{aligned}$$

If the interaction responsible for the decay of the K meson system respects CP, then it can decay to a final state that contains either two pions or three. I think it's not too hard to see that the particles that have a definite lifetime are either symmetric or antisymmetric combinations of K^0 and $\bar{K}^0$:

$$K_S = (1/\sqrt{2})(|K^0\rangle + |\bar{K}^0\rangle) \qquad (1)$$

$$K_L = (1/\sqrt{2})(|K^0\rangle - |\bar{K}^0\rangle) \qquad (2)$$

The subscripts indicate short-lived and long-lived mesons; we will see later why the lifetimes are different.

If we solve for $|K^0\rangle$ we find

$$K^0 = (1/\sqrt{2})|K_S\rangle + (1/\sqrt{2})|K_L\rangle$$

James W. Cronin, university professor of physics at the University of Chicago, responded to questions from the Chicago section of the American Association of Physics Teachers on 3 October 1981. Margaret Stautberg Greenwood, currently the section president, transformed Cronin's talk into this article. Greenwood, associate professor of physics at DePaul University in Chicago, is author of *Physics: The Excitement of Discovery* (Wadsworth, Belmont, Calif., to be published in 1983).

Thus, a beam of K^0 mesons produced at a particle accelerator contains equal mixtures of short-lived mesons K_S and long-lived mesons K_L. The short-lived mesons decay into two pions and the long-lived mesons into three pions. After some time has passed, the beam contains only the long-lived mesons. (The apparatus shown in figure 1 was positioned to observe the decay of long-lived mesons.) From equation 2 we see that K_L contains equal mixtures of K^0 and $\overline{K^0}$.

Coupled pendulums

The situation is analogous to the coupled pendulum where the normal modes are characterized by either a symmetric or an antisymmetric motion. In fact, the pendulum analogy can be pushed a little further if you imagine two ideal pendulums connected by a slide immersed in some viscous oil, as I suggest in figure 2. Clearly, if you took this system and started it out with the pendulum bobs going some arbitrary way, the antisymmetric mode (with the bobs going in opposite directions) would damp out right away and the other mode (with the bobs going in the same direction) would persist. Now, we are going to see the same kind of phenomenon going on with K mesons. That is, the damping, or the lifetime, of these two linear combinations is going to be quite different. Now why will they be quite different?

Let's look at the two linear combinations and let CP act on them. Well, you won't like this, I'm sorry, but in quantum mechanics one has a lot of freedom to define phases, and one can by definition—you won't like this at all—declare that CP acting on K^0 gives $\overline{K^0}$.

$$CP|K^0\rangle = |\overline{K^0}\rangle$$

That's the way it is; you are free to choose that phase. We could spend a lot of time talking about those phases. Anyway, if you'll accept that very unpleasant assertion, then you can see that CP acting on the symmetric combination gives the same state back again with a plus sign.

$$\begin{aligned} &CP(1/\sqrt{2})(|K^0\rangle + |\overline{K^0}\rangle) \\ &\quad = +(1/\sqrt{2})(|\overline{K^0}\rangle + |K^0\rangle) \end{aligned}$$

In other words the symmetric combination of K^0 and $\overline{K^0}$ is even under CP, and now you can see clearly that CP acting on the antisymmetric combination is odd.

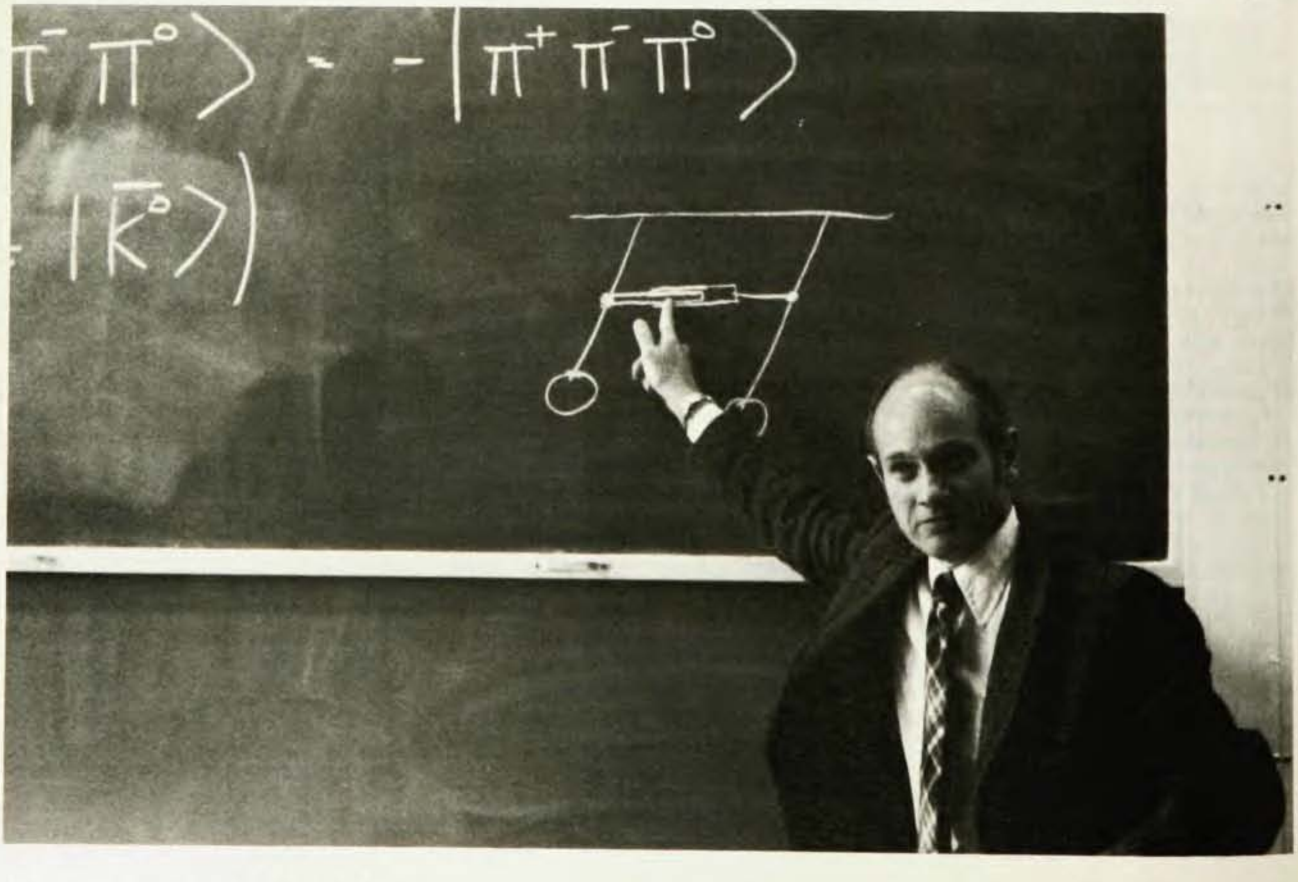
$$\begin{aligned} &CP(1/\sqrt{2})(|K^0\rangle - |\overline{K^0}\rangle) \\ &\quad = (1/\sqrt{2})(|\overline{K^0}\rangle - |K^0\rangle) \\ &\quad = -(1/\sqrt{2})(|K^0\rangle - |\overline{K^0}\rangle) \end{aligned}$$

Now if CP is respected, the symmetric combination is free to go to two pions but not to three, and the antisymmetric state can only go to three pions.

Now then, this is an interesting thing because it predicts that the lifetime of these two different "normal modes" of the K^0-$\overline{K^0}$ system will be quite distinct. When a particle system decays, the rate depends upon the excess energy available, the "Q value." Because the K meson has a mass of about 500 MeV and the pion a mass of 140 MeV, the Q value is greater for two-pion decay than for three-pion decay. There's not much excess energy for the decay to three pions—only about 75 MeV—so the decay just goes slower. The lifetime of the K_L meson is about 5×10^{-8} seconds.

So these gentlemen, Gell-Mann and Pais, predicted[2] that in addition to the short-lived K mesons, there should be long-lived K mesons. They did it beautifully, elegantly and simply. I think theirs is a paper one should read sometime just for its pure beauty of reasoning. It was published in the *Physical Review* in 1955. A very lovely thing! You get shivers up and down your spine, especially when you find you understand it. At the time, many of the most distinguished theoreticians thought this prediction was really baloney.

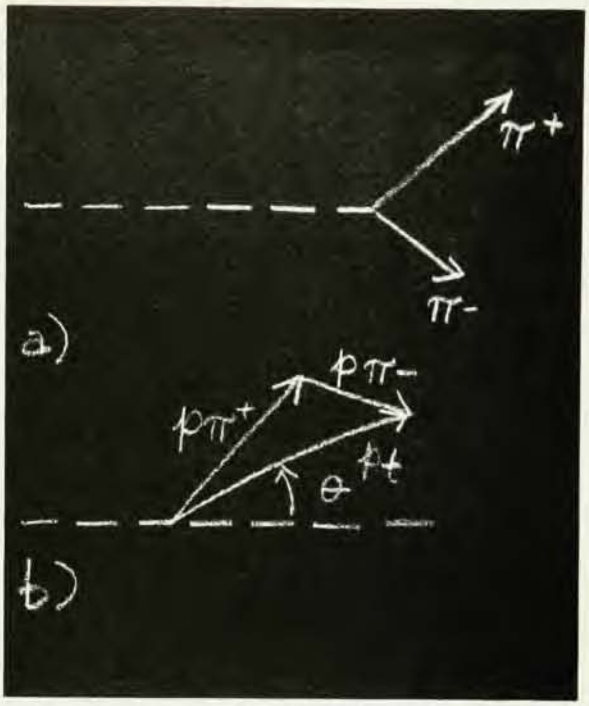
Coupled pendulums exhibit behavior that is analogous to that of the two-component K-meson system, whose "normal modes" are superpositions of the K^0 and its antiparticle. In this photograph, Cronin points to a coupling device in the schematic diagram. Figure 2



The short-lived decays were rather easy to see in cosmic rays. You could see the whole thing in a cloud chamber. There would be an interaction and the neutral K meson (which would not leave a track) would travel, considering its lifetime, from three to ten centimeters before decaying into two pions. The K_L mesons will go many meters on the average before they decay, and are not so easy to observe.

In 1956 Leon Lederman and colleagues at Brookhaven National Laboratory discovered the K_L meson in cloud-chamber photographs. The signature of the K_L meson was that it decayed into three pions. Now how can you tell that? Only the π^+ and the π^- make tracks in the cloud chamber; the π^0 doesn't because it is neutral. What you notice is that the momentum of the π^+ plus that of the π^- does not give a vector pointing in the direction in which the K_L was traveling. That's because the momentum of the π^0 is missing. So it is quite easy to see how they observed the long-lived K meson and to see that it decays into three pions. There are other three-body decay modes, but that would just complicate matters.

You can push this a little bit further and see how CP symmetry comes in. The fact that CP is odd for a long-lived K meson means that K_L could not decay into a π^+ and a π^-. If it does—and that was our observation—then there is something wrong with the assumption that the CP quantum number is conserved in the decay.[3]



Decay of neutral K meson into several pions (**a**). Horizontal line represents path of K meson, which leaves no trail because it is neutral. In the case of two-body decay, that is, when there is no neutral third pion, the vector sum of the momenta of the two charged pions (**b**) is horizontal ($\theta = 0$). Figure 3

Eureka?

I should explain how we did the work. Sometimes there are discoveries in which you rush out of the lab and shout "Eureka!" This was certainly not the case for us. First of all, the primary motivation for doing the particular studies that led to our discovery was not really, not even in our own minds, to study this question. It just seemed evident that CP symmetry should hold. People are very thick-skulled. We all are. Even though parity had been overthrown a few years before, one was quite confident about CP symmetry.

We were led into our research by some other anomalies associated with the decay of K mesons and their interactions with matter, which I won't go into. The idea of doing these experiments grew out of many lunch-table conversations with Val Fitch while we were working on different experiments at Brookhaven National Laboratory. I was working at the Brookhaven Cosmotron. At the time, Brookhaven had two machines: the Cosmotron, which was a 3-GeV accelerator, and the Alternating Gradient Synchrotron, a 30-GeV proton accelerator.

The protons crash into a target and make, among other things, K mesons. One can make a beam of long-lived K mesons by getting far enough away from the target so that the short-lived K mesons have decayed. I had some apparatus that was ideally suited to investigate K-meson decay at the Alternating Gradient Synchrotron. The idea came in March or April, and by July we had moved all the apparatus over there. There was a little place on the inside of the ring, referred to as Inner Mongolia, where we placed our equipment. Others had looked for the $\pi^+\pi^-$ decay of K_L and had found an upper limit: No more than 1 in 300 of the decays was of this CP violating type. We realized right away, in the course of setting up this experiment, that we could very easily push that limit down to 1 in 10 000.

The data tracks were recorded in devices called spark chambers, where you photograph the trail of sparks made by a charged particle passing between many condenser plates. It is clear that right on the spot you can't really tell what's going on. You have to go back and measure the photographs. And you have some priorities on what you are going to measure first. We studied another effect first, so it was six months before we even got around to looking at the film that had the data relevant to the question: Does K_L decay to a π^+ and a π^-? So there was zero excitement at the time of running the experiment. The excitement came when we finally analyzed these events and found a number of two-body decays.

If the momenta of the π^+ and π^- are added vectorially and the sum points in the beam direction, then you know you have a two-body decay. The result was that one K_L meson in about 500 decays to a π^+ and a π^-. That seems small, but in subsequent years people looking for other things have done experiments in which this is only a calibration rate, very mudane. At first you don't believe it. You also know that you are going to be under great attack by all of your colleagues because nobody wants to believe it. So you work very hard to be sure it's right. By July we were quite convinced it was right and we published it. So that's how it happened. No Eurekas.

Measurement and verification

Let me describe in a little more detail what one measures. A K meson comes along, which I represent in figure 3 with a dashed line because it it neutral. Then all of a sudden out of nowhere appear two charged particles. The momenta of these two particles are added to give p_t. The angle between p_t and the direction of the K_L meson is called θ, as in figure 3b. If it were a two-body decay, θ would have to be zero. From the momenta of the π^+ and π^-, you can reconstruct the mass of the parent ($m_{\pi^+\pi^-}$), which must have the mass of the K meson.

As an example of reconstructing the mass of the parent, let's consider the case where $\theta = 0$. In the experiment we measure the momentum of each pion. The relativistic relationship between energy and momentum, $E^2 = p^2c^2 + m_0^2c^4$, gives us the energy of each pion, E_+ and E_-. From conservation of momentum we know that the momentum of the parent must be the total momentum p_t. And conservation of energy tells us that the energy of the parent is the sum of E_+ and E_-. Finally, from the momentum and energy of the parent, the relativistic relationship yields the mass of the parent.

When you plot the number of events against the angle θ and require the mass of the parent to be 498 ± 5 MeV, you get a peak at $\theta = 0$. When we made the same kind of plot with a greater or lesser mass for the parent, say 508 MeV or 488 MeV the distribution was flat. So the evidence for CP nonconservation was this peak on the graph at $\theta = 0$, which is shown schematically in figure 4. There were something like 50 events in the peak with a background of about 10 events. So it wasn't all that sensational, but it was very clear.

Traditionally, when you find something unusual in an experiment, you go back and repeat it. Here that was not so easy to do because the apparatus had been removed from the beam line. On the other hand, when one records data photographically, there is not a question of, say, misreading the meter. We did, in fact go back and remeasure every one of the 5000 or so events. We first began with rather inaccurate measuring machines, but it didn't seem to matter that much. When we remeasured, the width of the peak sharpened up and was zero within the resolution that we had. In that sense, one can go back and check. A particle-physics experiment done at a large accelerator is very hard to repeat, but we did go back and do many other things to follow it up.

If you do an experiment that is quite striking, people at other laboratories usually rush to confirm it, and that's what happened. Of course, one is delighted to see that. At the time there were probably about six laboratories in the world where this experiment could have been done. Three in the US, one each in England, the Soviet Union and Geneva. Within three or four months the work was confirmed, because people had apparatus that could be adapted to look at this problem. It was nice for someone else to see what we saw. We felt maybe we were right after all.

P, CP and CPT

I mentioned that physicists were quite confident that CP was universally conserved even after it had been found that parity was not always conserved. I would like to explain this and then say something about time reversal, because we now believe in CPT invariance.

In the original experiments that demonstrated parity violation, the magnetic moments of cobalt nuclei were polarized by a magnetic field and more electrons came off opposite to the direction of the magnetic moment, as figure 5a indicates. Let's do a space reflection around the plane. The result, shown in figure 5b, is a change in the direction in which the electrons travel, but no change in the direction of the magnetic moment. The magnetic moment remains unchanged because it depends upon the angular momentum and charge of the nucleus, neither one of which changes sign under space reflection. Because the angular momentum is defined as the cross product of **r** and **p**, both of which change direction under space reflection, the angular momentum itself stays in the same direction.

If I operate on the nuclei represented in figures 5a and b with charge conjugation, I see some interesting results. The nuclei become antinuclei and the electrons, positrons. Operating on the original nucleus with charge conjugation only (figure 5c), more positrons come off in the direction of the magnetic moment. This is a way of seeing that charge conjugation is violated. Operating with space reflection only (figure 5b), I see a parity violation for the same reason. However, the combined operation CP (figure 5d) shows that CP is conserved, because more positrons come off opposite to the direction of the magnetic moment. The violations of parity and charge conjugation, in a sense, were discovered at the same time.

Although you might not think it is the case, CP determines whether there is really a symmetry between the universes of matter and antimatter. If charge conjugation and parity are both violated in such a way that CP is a conserved quantity, then there is no experiment a person in an antiuniverse can do (and call you up on the telephone and explain) that will show that he's different from you. The more technical point is that the discovery of parity violation led to a great simplification of our understanding of weak interactions. The nature of that understanding had CP symmetry built into it from the very beginning.

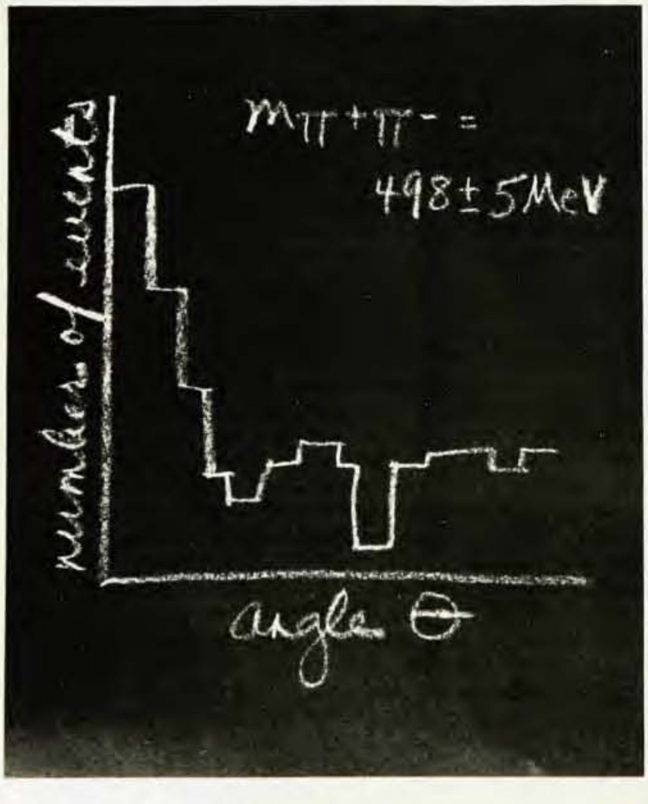
The essential point—the more universal point—is that violation of CP symmetry permits one to do experiments that can distinguish between a universe of matter and one of antimatter. Now that's not very manifest in what I described to you: a neutral K meson decaying into a π^+ and a π^-. Where's the asymmetry between matter and antimatter? There are other three-body decay modes that I conveniently swept under the rug. For example, K_L has decay modes that lead to electrons or positrons:

$$K_L \to \pi^+ + e^- + \nu$$
$$K_L \to \pi^- + e^+ + \nu$$

One finds that there's a slight asymmetry:

$$\frac{(\text{no. of } e^+) - (\text{no. of } e^-)}{(\text{no. of } e^+) + (\text{no. of } e^-)} = 3\times10^{-3}$$

This is an unmistakable effect of asymmetry between matter and antimatter because there are simply more positrons emitted than electrons. Because there is no absolute sense of plus or minus, I tell my colleague in the antiuniverse, "I see an excess of positrons, electron-like objects that have the same



Peak at $\theta = 0$ in the graph of the number of events versus angle. This is evidence for the two-pion decay of K_L, a violation of CP symmetry. Figure 4 sign of charge as my atomic nucleus." Because his atoms contain antiparticles, he says, "I see an excess of particles that correspond to my electrons." You wouldn't agree about the results of the experiment. Therefore, you would be aware that there is a difference between your universe and your colleague's universe. So it is this kind of *gedanken* experiment that brings out the significance of CP violation.

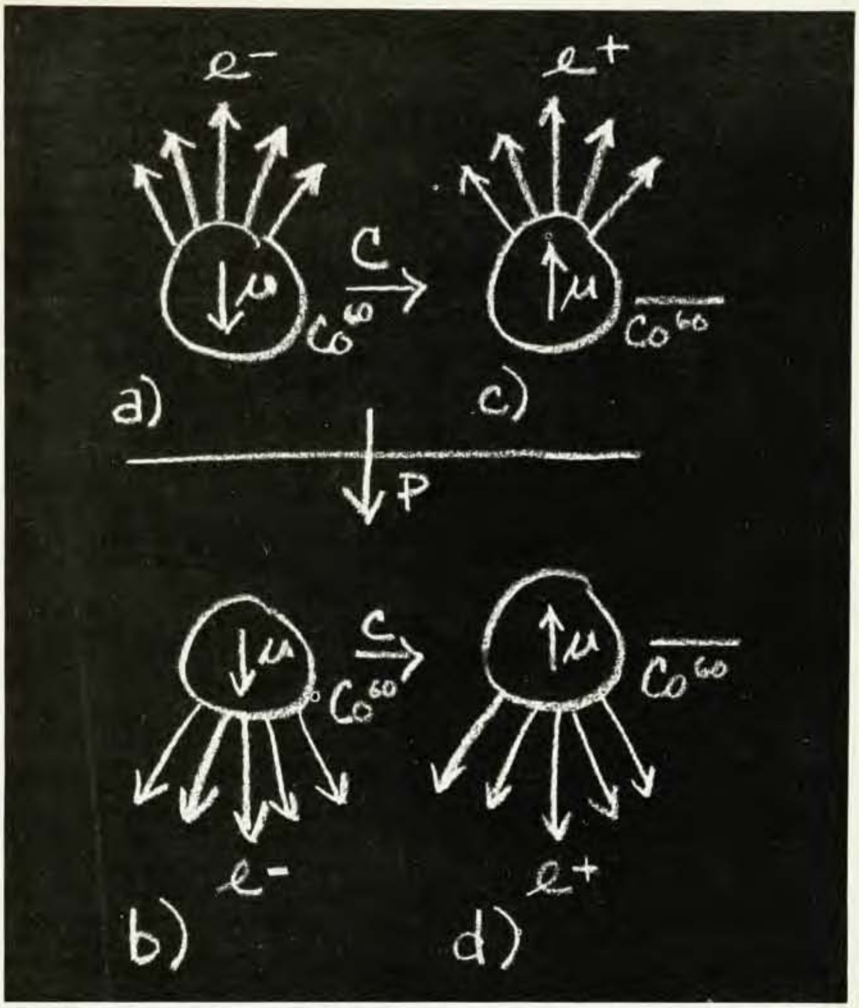
Now, what about time reversal? In the expressions for K_S and K_L given in equations 1 and 2, CP asymmetry requires the coefficients to be unequal and to differ slightly from $1/\sqrt{2}$. In a beam of K^0 mesons (or $\overline{K^0}$) the short-lived component K_S decays, leaving the long-lived component K_L. However, because the coefficients are now slightly different from $1/\sqrt{2}$, the rate at which K^0 transforms into $\overline{K^0}$ is not equal to the rate at which the reverse occurs.

Let's consider now the combined symmetry CPT. What do you mean when you say that something is symmetric under time reversal? It's a very technical thing. You have equations in which some law says that an observable is going to behave as some function of time $f(t)$. If you let $t \to -t$ and appropriately change the boundary conditions, as you always have to do, then there is no change in the laws of physics. That's what time-reversal symmetry means.

Now it is considered on fairly solid theoretical grounds, much deeper than I am able to comprehend myself, that any system undergoing the combined operations CPT should obey the same physical laws. This means that if CP is violated then you would also have to have T violated in such a way that the combination retains symmetry. So if one believes in CPT symmetry, then the implication of CP asymmetry is that there is a violation of time reversal.

In fact, detailed analysis and auxiliary measurements carried out on the K-meson system in the ten years following this discovery quite independently suggest both CP violation and time reversal violation. These time-reversal violations are not of the manifest type where you set the boundary conditions correctly and see forward and backward going reactions to be unequal. All kinds of searches and experiments have been done for a more manifest violation of time reversal, but none has been found. In fact, the only place this tiny effect appears is in the K-meson system.

Well, you might shrug you shoulders and say, "OK, it's a little anomaly and doesn't matter." But it does matter because it relates to one's fundamental understanding of space and time. But there is a lot more, we pray, to find out about this.



Parity violation in the beta decay of the cobalt-60 nucleus. **(a)**: Electrons are more likely to be emitted opposite to the direction of the magnetic moment μ of the nucleus. **(b)**: After parity operation P. **(c)**: After charge conjugation C. **(d)**: After CP. Figure 5

These asymmetries do not necessarily mean we live in a disorderly universe. There is a hierarchy: It is orderly at various levels. In fact, the violations are not exactly disorderly. For example, even though parity is violated, the neutrino is always lefthanded, never any other way. Here lefthanded means that the neutrino's spin and velocity always point in opposite directions. So there is a violation of symmetry, but the violation is maximal. It's clean, neat. Aside from the K meson's violation of CP, things are in order. We live in a universe where there is a favor toward the left hand. Of course, with antineutrinos, it's the reverse. So in a sense, there is still symmetry.

Regeneration

Another of the very beautiful set of phenomena related to the K-meson system is regeneration. Aside from what this system teaches us about nature, it has a certain aesthetic beauty.

Regeneration is the following phenomenon. Suppose we prepare a beam of K_L mesons by getting very far away from the source so that all the K_S mesons have decayed away. Now we let that K_L beam impinge on a target. Coming out of the target you'll find not only K_L mesons, absorbed somewhat because of the material, but also a significant component of K_S mesons. That is regeneration. Now how does it work?

The decay of particles is controlled by CP conservation—or nearly so, now. However, we have to remember that K_L is a quantum mechanical superposition of K^0 and $\overline{K^0}$. When these particles are passing through matter we have to think about their strong interaction. That is, the K^0 and $\overline{K^0}$ get absorbed by different amounts. It turns out that the cross section, or absorption coefficient, for a particle with strangeness -1 is greater than that for a particle with strangeness $+1$. So when this wave of pure K_L, goes through the material, its $\overline{K^0}$ component is attenuated more than its K^0 component. Recall from the definition of K_L (equation 2) that the coefficients of K^0 and $\overline{K^0}$ are both $1/\sqrt{2}$. When the beam comes out of the target, you don't have this balance any more. You have a little less contribution from the $\overline{K^0}$ component because it has been attenuated more.

You can, however, write this new wave function as a superposition of K_L and K_S. As an example, suppose that after the pure K_L beam passes through the material, there are 1.78 times as many K^0 as $\overline{K^0}$. The normalized wavefunction representing this situation is

$$\Psi = 0.8|K^0\rangle - 0.6|\overline{K^0}\rangle$$

where $0.8^2/0.6^2 = 1.78$. We can write this wavefunction as

$$\Psi = 0.7(|K^0\rangle - |\overline{K^0}\rangle) + 0.1(|K^0\rangle + |\overline{K^0}\rangle)$$

Using the definitions of K_S and K_L (equations 1 and 2), this becomes

$$\Psi = 0.990K_L + 0.141K_S$$

So 98% of the decays will be three-body decays from the K_L component, and 2% will be two-pion decays due to the K_S component. (We have neglected K_L's small contribution to two-pion decay via CP violation.)

Hence, we have regenerated a small component of K_S in the beam. Because K_S mesons have a very short lifetime you'll immediately see two-body decays appear. It's a beautiful phenomenon. You take a K_L beam and put a piece of material in its path—copper, lead, carbon, whatever—and two-pion decays occur. It's also nice for experimental purposes because you can insert a piece of material at the K_L decay distance and calibrate your detector to see how it will behave when you really have a CP-violating two-body decay of K_L.

Future

In thinking about future research more generally, nucleon structure immediately comes to mind. One is finding that the proton and neutron almost certainly have a very definite substructure, and are composed of quarks. Quarks have an unusual nature in that their binding to one another is so strong that you really can't get them to be free. These are the notions.

We have found in recent years that quarks come in families. The nucleon is composed of "up" and "down" quarks. The K meson, because of its strangeness, is made up of a "strange" quark and a down quark. There is now strong evidence that there is a third family. We've discovered a "bottom" quark and it is expected to have a partner, called the "top" quark, which still needs to be found. We had better find the top quark and be sure that the families aren't broken up.

We have made enormous progress in understanding interactions because the weak and electromagnetic interactions are almost certainly of the same nature. This means we have not only a photon, but a "heavy photon," so to speak, called Z^0, that has a mass slightly below 100 GeV. We'd like to check and find that!

One result of all the understanding that has come in the last ten years is the possibility of including the strong interaction in the unification of the weak and electromagnetic interactions. As a consequence, one expects the nucleon—the proton itself—to be unstable with a very, very long lifetime, something like 10^{31} to 10^{33} years. A number of large experiments are being constructed down in mines to look for proton decay. If the lifetime is 10^{32} years, it takes on the order of 10 000 tons of material to get a few dozen counts per year. Although these are large experiments, they are examples of the fact that not all particle-physics experiments require high-energy accelerators.

At the present time people are cocksure they understand many of the broad outlines and details about the nature of particles and energies. Experimentalists want to find out whether that is the case. There are all sorts of beautiful—lovely—special phenomena that experiments reveal even after you think you understand everything. Superconductivity is an example of this—I don't think anybody would have predicted superconductivity even if they had known the basic underlying physics.

Another thing people speculate about is that neutrinos, those massless particles that I have not discussed much here, may not be massless. One can go into the laboratory and measure the endpoint of the beta decay spectra and measure the rates of electron capture in certain special nuclei to shed light on that particular question.

The basic goal of all these experiments and theories is the same: What's everything made out of? What are the laws? What are the different forces? Can we unify them? How are you going to get an understanding?

So, intellectually these problems are of very high order. The pity is that it takes expensive—and enormous—devices. You have to spend lots of the public money, and to carry out these projects you have to form research groups that might have a hundred individuals, either all physicists or some physicists and some engineers. But the intellectual imperative, if you like, is there. One has just got to do it.

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