FEATURE

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Research Area: Theoretical Physics

Impact of Large-Mixing-Angle Neutrino Oscillations

1. Atoms, Electrons, and Mass

Everything that we encounter daily is made of atoms. There are as many as some hundred species of atoms, all having different properties. These different species of atoms are named hydrogen, helium, carbon, oxygen, iron, copper, silver, gold, uranium, etc. It is known that all species of atoms have a structure depicted in Fig. 1, namely, electrons are circulating around the nucleus which comprises tightly packed protons and neutrons; the different properties of different species of atoms such as carbon, hydrogen, and iron solely originate from the different number of protons in the respective nucleus. The properties of various materials such as chemical changes and superconductivity can be understood based on the properties of these atoms, nuclei, and the electron, and in particular, based on the properties of the positively charged protons and the negatively charged electrons.

Why, then, the protons and neutrons are tightly packed on the one hand, and the electrons circulate around them on the other hand? Actually, the radius of the nucleus that comprises the protons and neutrons is about five orders of magnitude smaller than the electron's radius of activity. Suppose that the size of the nucleus is enlarged to 1 cm, then the electron's range of activity would be 1 km. Where

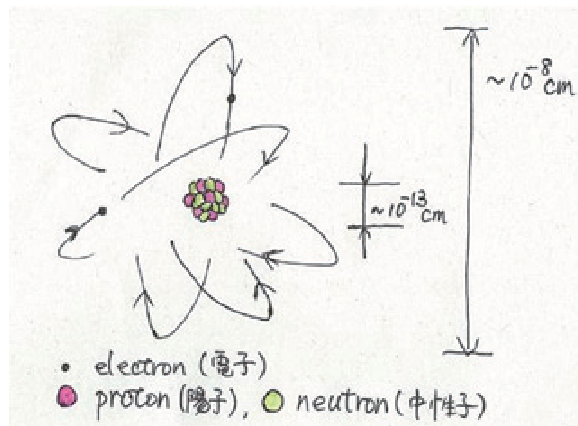


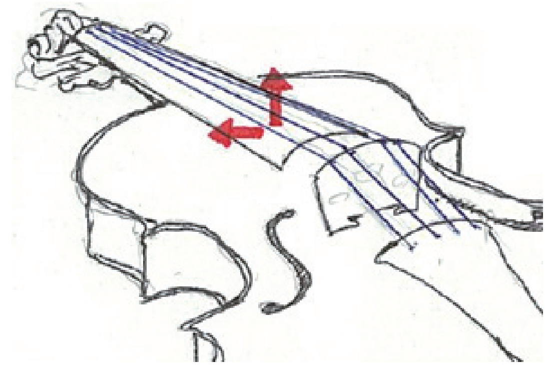
Figure 1. A conceptual diagram showing an atom and a nucleus inside it. In this figure, the size of the nucleus is illustrated as if it were about 1/10 of the size of the entire atom, instead of the actual ratio of 1/100,000.

does this significant difference come from?

Hideki Yukawa's meson theory in 1934 was motivated to find, within the framework of quantum mechanics, the mechanism that enables the nucleus, which comprises a number of protons and neutrons, to be tightly packed. Meson theory claimed that if there should be a new particle which was yet unknown at that time, it would do the job, and the size of the packed nucleus was determined by the new particle's mass. It was expected that the new particle's mass had to be about 200 times that of the electron for the radius of the nucleus to be five orders of magnitude smaller than the electron's radius of activity.[1]

[1] The reason why the meson's mass should be 2, and not 5, orders of magnitude heavier than the electron's mass is that the value of the "strength of the electromagnetic force" is also to do with the ratio of the nucleus's radius to the electron's radius of activity.

Figure 2. The sea wave is described by a single number —the "wave height"—at each point on the surface of the sea. On the other hand, the movement of the chord of a violin is described by the two numbers at each point along the chord, namely, "the position (or deviation) in the two directions shown by the red arrows in the figure." Therefore, it is described by the wave having 2 degrees of freedom.



2. Discovery of the Muon: "Who Ordered That!?"

An orthodox method to prove the validity of meson theory is to show the existence of the new particle that was called the *meson*. With the experimental technique in those days, it was difficult to create the mesons in the laboratory. There was a hope, however, that the mesons could be found among high-energy particles coming down from the top of the atmosphere. Therefore, experiments to observe the properties of the fast particles coming down in the atmosphere were conducted in the latter half of the 1930's. Strangely enough, experiments by Anderson-Neddermeyer, Street-Stevenson, and Yoshio Nishina did find a new particle having nearly the same predicted mass of, but different properties from, the meson. Later, people celebrated the discovery of the predicted meson in such experiments and the unexpected new particle was named the muon for the time being. Scientists at that time were all puzzled, however. The muon had exactly the same properties as the electron such as the charge, etc. Only the muon mass was different from the electron mass. It was entirely unknown why such a particle had to exist and for what it would be useful. I. Rabi, who won the Nobel Prize in Physics, said: "Who ordered that?"

It looks too simple a question, but even present-day particle physics does not have an answer at all.[2]

3. What is the Height of a Wave?

The behavior of the "light = electromagnetic wave" is determined by the equations for the waves of electric and magnetic fields. Likewise, the behavior of the particles such as the electrons, protons, etc. is determined by the equations for the electron waves, proton waves, etc. It is quantum mechanics that gives those equations.

Even though we put aside the question, "Why a new particle called the muon exists?" for the time being, it is certain at least that we have to introduce the "muon waves" newly to describe the behavior of the particles. What are these waves of electromagnetic fields, electron waves, proton waves, muon waves, and so on?

If we are talking about "sea waves," it is a simple story. It goes like this: at any given time, at each point on the surface of the sea, the sea wave is high/low according to the extent that the height of the surface of the sea deviates from the mean sea level. Also, you may not feel uneasy even if there are different types of waves. For the "waves of the

[2] There might be a close relationship between the fact that muons exist in nature and the fact that antimatter scarcely remains in our universe. It is controversial, however, whether or not it is appropriate to say that it is the answer to Rabi's question.

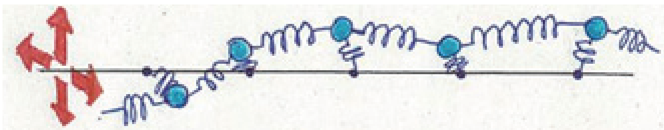


Figure 3-1. A dynamical model reproducing the movement of the chord of a violin. Each weight (blue bead) can move into the two directions shown by the red arrows. They are tied to the respective stable position by a spring. Also every adjacent pair of weights is connected by a spring.

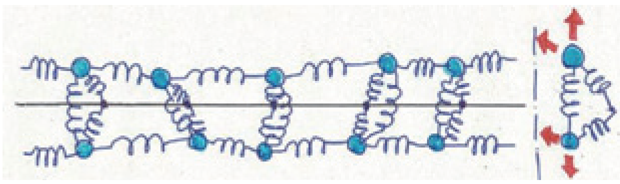


Figure 3-2. A slightly more complicated dynamical model. A dynamical system sitting at each point is replaced by what is comprised of the two weights and 3 springs shown at the right end. This is called a dynamical system with 4 degrees of freedom, because the configuration of this dynamical system at each point is described by the "4 movements (numbers) shown by the red arrows." The behavior of this dynamical model as a whole is described by using 4 kinds of waves.

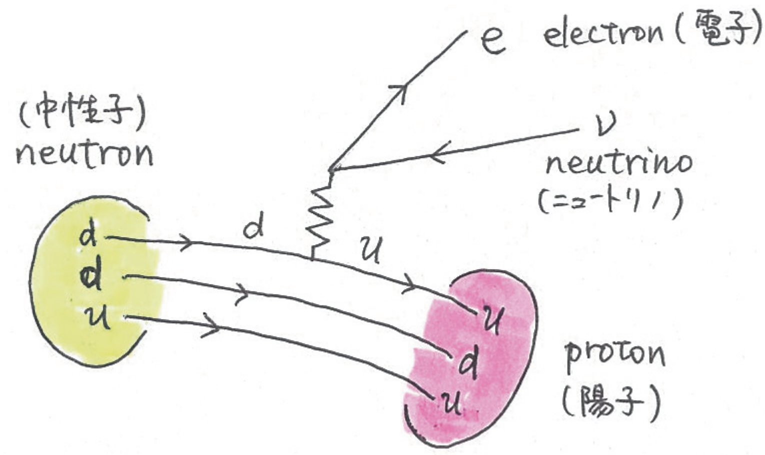
chord of a violin," we can interpret the deviation of the chord in the two directions from its standard position as the heights of the two different types of waves as shown in Fig. 2. It is said that the tones (wave types) of the violin are a bit different depending on the direction to which the chords vibrate.

As a preparation for thinking on a bit more complicated example, let me point out that the behavior of the chord of a violin can be reproduced by a dynamical model, as shown in Fig. 3-1. If you hold and shift one of the weights from the "normal position" and then release it, "2 kinds (2 directions) of the deviations from the normal position" of the weight will be propagated into the space (horizontal axis) through springs. Next, let us consider a bit more complicated model, as shown in Fig. 3-2. In this model, a certain dynamical system sits at each point along the horizontal axis; the adjacent systems are connected to each other. We now need more than one number to describe "the deviation from the stable configuration = that from the normal position" of the dynamical system at each point. For the model shown in Fig. 3-2, four numbers are needed. Therefore, the behavior of this model is described by using more than one wave. The quantum mechanical version of such a model is called quantum field theory.

At present, it is known that if we only make some assumptions on the properties of the "complicated dynamical system sitting at each point in space" in quantum field theory, we can explain very well all the experimental results on the behavior of the particles such as the electrons, electromagnetic fields, muons, and so on. In a quantum field theory model called the Standard Model, we use 58 kinds of waves, namely, 45 kinds of particles = waves such as the electron, muon, and so on, 12 kinds of electromagnetic waves and other waves having similar properties to them, and one wave called the Higgs field. Roughly speaking, therefore, the particle world in our universe is described by, "a set of dynamical systems, each having 58 degrees of freedom and sitting at one of the points in space, and the adjacent systems are connected to each other (as shown in Fig. 3)."

In the language of quantum field theory, this means that the question, "Why the particle called muon is necessary to describe our world?" can be replaced with the question "Why the dynamical system sitting at each point in space is so complicated (multiple degrees of freedom)?" Before taking on this difficult problem, however, it would be an orthodox method to ask, "What is the nature of the dynamical system sitting at each point in space and giving the description of our world?" Certainly, it is much more complicated than the dynamical

Figure 4-1. Neutron decay. The current understanding of the neutron is an entangled state of a *u* quark and two *d* quarks. Likewise, the proton is understood as an entangled state of two *d* quarks and a *u* quark. An isolated neutron decays spontaneously into three particles, a proton, an electron, and a neutrino. (In the figure, the decay reaction proceeds from left to right.) The reaction essentially results from the interactions between the quarks, electron, and neutrino.



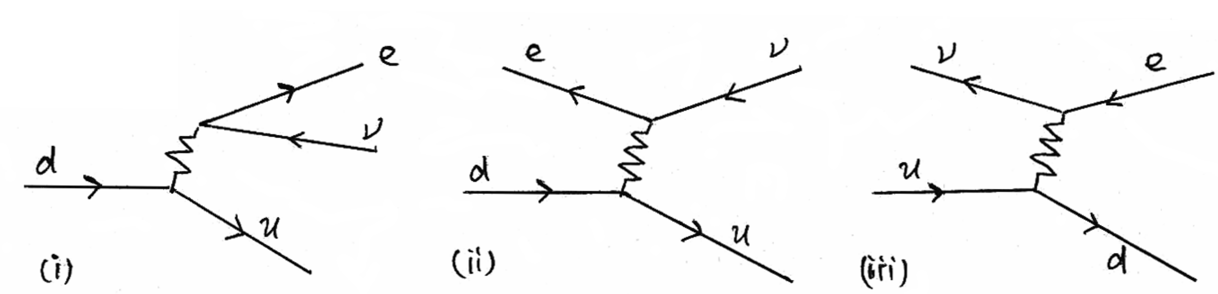


Figure 4-2. In (i), only the quarks directly involved in the neutron decay reaction shown in Figure 4-1 are focused. In nature, it is known that not only the reaction (i), but also reactions (ii) and (iii) occur. All the reactions proceed from left to right. In (ii), a reaction is shown in which an antiparticle of the electron disappears after the reaction, instead of the appearance of an electron after the reaction in (i). The reaction (iii) corresponds to the reaction (ii) if the direction of the time is inverted. As can be seen from (ii) and (iii), the weak interaction is something like the game of "Old Maid" in the following sense. Namely, in the case of reaction (ii), if one receives a "joker," one's complexion changes (the quark changes from *d*-type to *u*-type), but at the same time there is another one who is relieved by passing the "joker" to someone else (the antiparticle of the electron changes to the antiparticle of the neutrino). A jagged line connecting particles describes the transfer of the joker.

system shown in Fig. 3-2, because it has as many as 58 degrees of freedom! In order to challenge this question, we have to start with sorting out "what we can learn from the nature (experiments) about that dynamical system." We wish to extract not only the "degrees of freedom" of the dynamical system, but also as much information as possible. What can we learn from various experiments?

4. Weak Interactions and the neutrino

It is known that an isolated neutron is not stable; in a few minutes it decays into three particles, a proton, a positron (an antiparticle of the electron), and a neutrino. It is also known that the neutron and the proton are bound states of smaller particles called quarks. According to our understanding in today's particle physics, neutron decay is a phenomenon resulting from the interactions between the two kinds of quarks, the electron, and the neutrino, as shown in Fig. 4-1. It is also known that there are interactions shown in Fig. 4-2 (ii) and (iii) simultaneously with that shown in Fig. 4-1 (or Fig. 4-2 (i)).

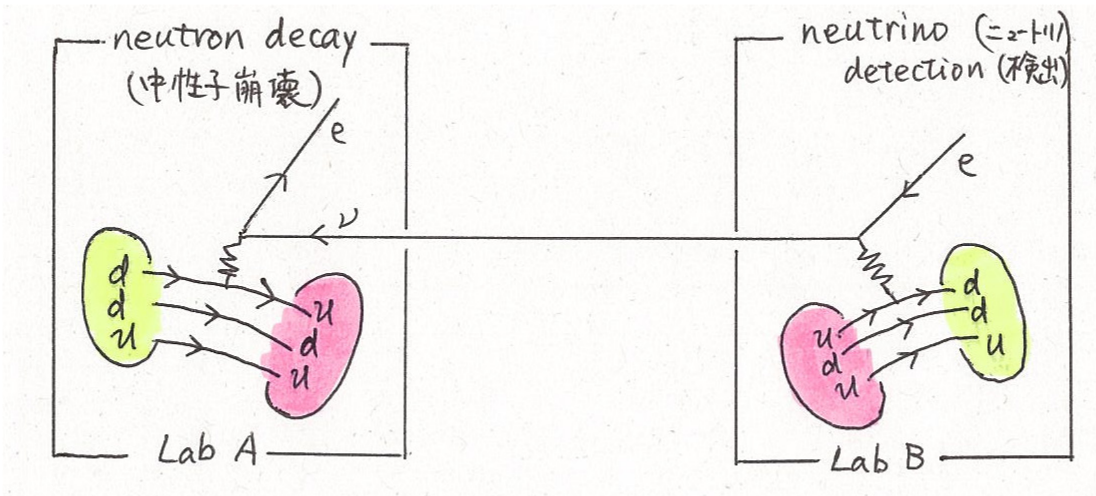


Figure 4-3. To confirm the existence of a neutrino produced in the neutron decay (at Lab A on the left side), we detect a neutron (shown in yellow) and an antiparticle of the electron produced in the inverse reaction in another laboratory (Lab B on the right side). In most of the neutrino detection experiments, a charged particle, converted from a neutrino by the weak interactions (or, received a joker), is detected.

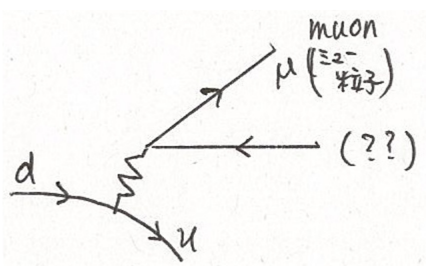


Figure 4-4. A muon can appear instead of an electron in the reaction similar to the one shown in Fig. 4-1. At the same time, the other particle denoted by (??) appears after the reaction. This particle denoted by (??) does not have a charge in the same way as the case of neutron decay.

The neutrino does not have a charge, and it interacts with other particles only via these weak interactions. This also means that we must make use of weak interactions to detect the neutrino. In fact, the neutrino, which came out from the neutron decay, was first detected by Reines and Cowan, who used the inverse reaction shown in Fig. 4-3 in their experiment in 1959.

In Section 2, it has been explained that a particle called the muon exists, which has a different mass but otherwise the same properties as the electron; they interact with the same forces, and make the same reactions, with other particles. As for the force, now it is known that their weak interactions are also the same. This means that from the weak interactions of a muon, a neutral particle that has only weak interactions comes out like the electron's case (see Fig. 4-4).

In an experiment in 1962, it was shown that the particle coming out in association with muon's weak interactions is different from the particle (neutrino) coming out in association with electron's weak interactions. It turned out that even if the particle coming out from the muon hit a nucleus as shown in Fig. 4-3, it did not (necessarily) cause an electron to come out via the inverse reaction. From this experimental fact, quantum field theory, which has been explained in Section 3, concludes this: in addition to the 2 degrees of freedom corresponding to the electron and the muon, the dynamical system sitting on each point in space has an additional 2 degrees of freedom corresponding to electrically neutral and only weakly interacting particles. These additional 2 degrees of freedom are now called the neutrinos.

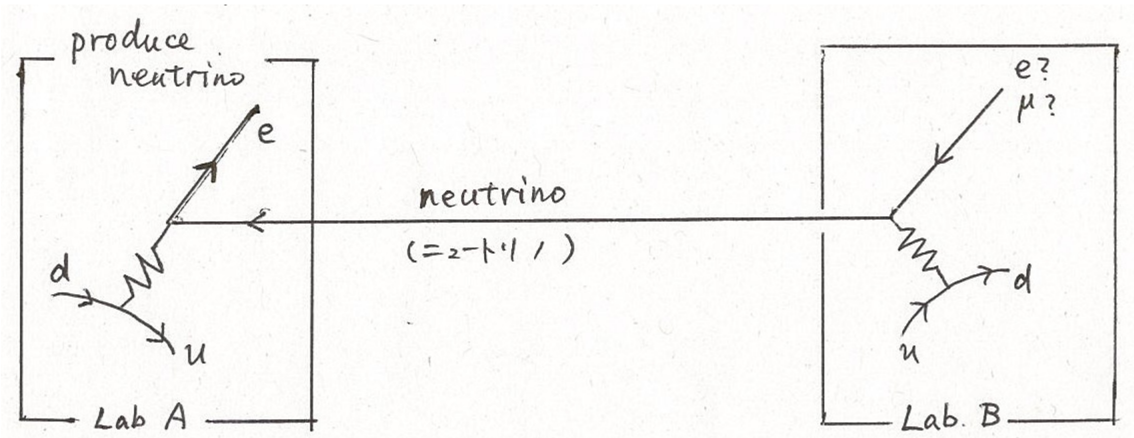


Figure 5. Neutrino oscillation experiment. At Laboratory A, an antiparticle of the neutrino is produced together with an electron. This antiparticle of the neutrino is detected at the very remote Laboratory B. Depending on the neutrino's energy and the distance between the two laboratories, either an antiparticle of the electron or that of the muon is detected at Laboratory B from the weak interactions of the antiparticle of the neutrino. This phenomenon is called the neutrino oscillation.

5. Neutrino Oscillations and the Mixing Angles

Does the neutrino that comes out via weak interactions of the electron always return to the electron via weak interactions? Is the same true for the muon and its neutrino? Actually, it is not true. A neutrino that came out from the electron sometimes returns to the electron, but sometimes it becomes a muon (if its energy is sufficiently high). Please refer to Fig. 5. If you put a rabbit in a hat, sometimes it comes out as a pigeon!! The neutrino oscillation is academic terminology for this phenomenon. (See IPMU News No. 15, pp. 4-9.)

Magic (presumably) always involves a trick. Likewise, this phenomenon has a simple explanation. Let us consider the dynamical system shown in Fig. 6-1. Let us put a marble on an oval dish and release it. The marble will then draw the trajectory shown in Fig. 6-2. As time goes on, the direction of the marble's oscillation will change. Let's rotate Fig. 6-2 in such a way that the initial direction of the marble is now the horizontal axis and its orthogonal direction is the vertical axis, see Fig. 6-3. Fig. 6-4 shows the time dependence of the marble's horizontal position and the vertical position. You can see the decreasing horizontal motion and the increasing vertical motion as time goes on. This marble's motion describes the time variation of the neutrino wave, which has 2 degrees of freedom. The horizontal amplitude of the wave describes the component that returns to the electron via weak interactions, and the vertical amplitude describes the component that converts to the muon.

There are two essential points in this oscillation phenomenon: "1. The shape of the dish is oval" and "2. The initial motion of the marble is not along the direction of the major nor the minor axis of the ellipse, but rather along a diagonal direction." Using technical terms, the first point means that "the neutrinos have the masses and their values are different." The second point expresses that, "the mixing angle is non-zero." The mixing means the rotation angle between Figs. 6-2 and 6-3.

6. Impact of the Large Mixing Angles, and…

As has been explained in Section 3, we have to introduce many kinds of particles (degrees of

Figure 6-1. Rolling a marble on an oval dish.

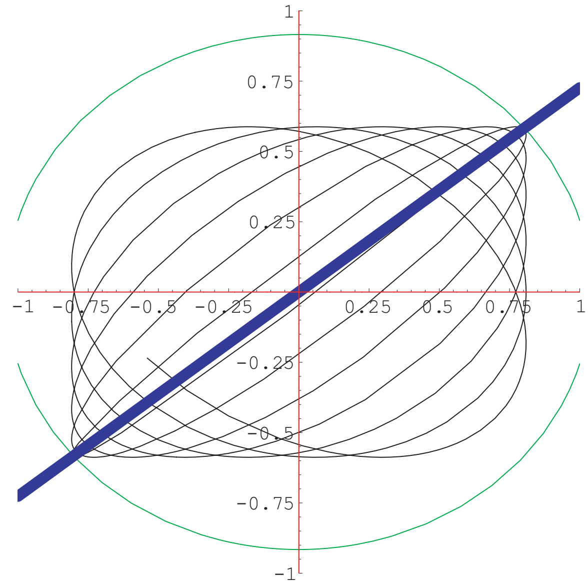


Figure 6-2. Movement of a marble on an oval dish. The green curve represents the ellipse, and its major and minor axes are shown by the red lines. If the marble is released at first from the upper right point on the blue line, it moves along the black curve.

freedom) to describe the particle reactions according to the present understanding of particle physics. Given that there are not a few, but more than 50 kinds of particles, it would be natural to consider whether or not more microscopic particles exist, as well as a fundamental (simple) description. It might be similar to the case that the existence of more than 100 kinds of atoms can be derived from "the only three kinds of building blocks, namely, the protons, neutrons, and electrons, and a single theory of quantum mechanics."

If we consider the discovery of the periodic table of the elements as a taxonomy prior to the discovery of quantum mechanics, it would be a natural idea to try to introduce taxonomy to the many kinds of standard-model particles. Using the values of the masses, the particles have been classified into 3 groups: the groups of light, medium, and heavy particles are named as the first, second, and third generations, respectively. Most researchers had thought this taxonomy to have some meaning, until the neutrino oscillation was discovered. Let me explain in a bit more detail. Before the discovery of the neutrino oscillation, most researchers supposed that in Fig. 6-3 the two red axes (corresponding to the masses of the neutrinos) would not have deviated much from the blue axes (corresponding to the electron and muon), and they grouped those particles having similar directions of mass axes and classified them as one of the "generations." This means that they supposed that the particles in a given generation would change their appearance within the same "generation = direction of the mass axes," even though a neutrino converted to either an electron or muon, and conversely, an electron or muon converted to a neutrino, via weak interactions. If this had been true, the taxonomy would have been meaningful.

The neutrino oscillation experiments have developed remarkably in these 10 years, however, and they have indicated that the red and blue axes are pointing in quite different directions, as shown

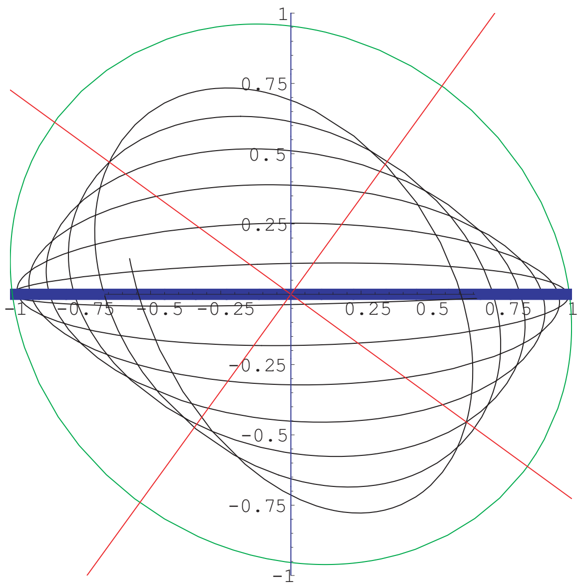


Figure 6-3. Fig. 6-2 is rotated so that the blue line becomes horizontal. At first, the trajectory along the black curve moves in the horizontal direction, but gradually, vertical movement increases.

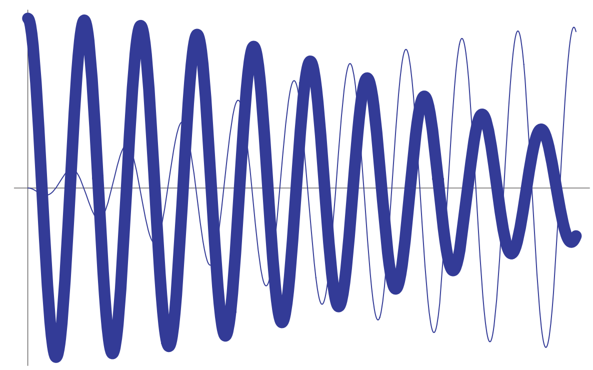


Figure 6-4. The movement along the black curve in Fig. 6-2 is decomposed into the horizontal movement shown by the thick curve and the vertical movement shown by the thin curve. They are shown as functions of time.

in Fig. 6-3. Actually, the mixing angle is large. This means that, "the particle taxonomy based on the concept of the 'generations' is broken at least to some extent." If a rabbit can easily metamorphose into a pigeon, the taxonomy to classify mammals and birds should be meaningless. We have to reconsider from the beginning.

From now on, how do we have to proceed in order to obtain a more fundamental understanding of the nature of particles? Today's particle physicists have been searching for a solution to this problem. Because a few pages up to here cover the development of particle physics in the past several decades, we have to be prepared that it will take as long as ten years to write only the next one page. Even so, researchers should explore the next step forward.

At the end of Section 3, we have set the question, "What is the nature of the complicated dynamical system sitting at each point in space?" If we ask ourselves a philosophical question "What are we?" very seriously, we finally arrive here. In response to this question, what superstring theory suggests is the way of thinking: "The nature of the complicated dynamical system sitting at each point in space is a six-dimensional space which is so small that no previous experiments have succeeded in looking at it." Although there have still been no experimental results to support this suggestion from superstring theory, there have been no results either, which give a hint that it might be wrong. If so, it can be a reasonable form of theoretical investigation to introduce such a way of thinking so as to put limits on our thinking and to try to make intellectual adventures within that framework.

In this way, we hope that we can obtain some constraints on the "realizable dynamical system." Is it possible for us to find something that is not intrinsic to quantum field theory, when particle physics encounters mathematics? Is that useful to give an answer to the question "What are we?" For years, I have been working on such things in my research.