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SYMMETRIES AND EINSTEIN

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Abstract

After a brief survey of the influence of Einstein on current particle physics, fundamental symmetry between particles and antiparticles is discussed. The existence of antiparticles is an important outcome of special relativity and quantum mechanics and the disappearance of antiparticles from the present universe is one of the mysteries in Big Bang cosmology based on the Einstein equation. Remarkable progress has been made recently in the studies of the violation of symmetry between particles and antiparticles with the use of a new type of accelerator. Some of their achievements are reported

EINSTEIN AND CURRENT HIGH ENERGY PHYSICS

Einstein laid the foundations of the physics of the 20th century. His influence reaches every field of physics. Although his direct contribution to high energy physics was limited, in view of recent developments in gauge theory and quantum gravity, his achievements are attracting renewed attention.

Special Relativity and Quantum Mechanics

It is not necessary to say much about the role of special relativity and quantum mechanics in current high energy physics. We need both theories to describe the phenomena of high energy physics. Historically, however, quantum mechanics was built on non-relativistic mechanics and special relativity was developed without quantum mechanics. It is commonly understood that the unification of special relativity and quantum mechanics was achieved by relativistic quantum field theory, which is a fundamental framework for describing relativistic particle phenomena.

Einstein, however, did not share this viewpoint. He strongly criticized the complementarity interpretation of quantum mechanics, and claimed that quantum mechanics is incomplete. Furthermore, in his mind, structure of space-time would not be that of a flat Minkowski space which is assumed in usual field theories. Probably what he imagined as the unification of quantum mechanics and relativity would be very different from the conventional one.

General Relativity

General relativity is satisfactory as a classical theory of gravity, but this is not the case for the quantum version. A straightforward quantization of general relativity has several problems. For instance, the perturbative approach faces strong divergences that we cannot control with the usual renormalization techniques. Quantum gravity is one of the most important subjects in current theoretical physics.

It is known that superstring theory includes gravitational interactions which are consistent with general relativity and it is free from the divergences encountered in straightforward quantization. Superstring theory and its developments are believed to be the most promising approach to quantum gravity.

On the other hand, the classical version of general relativity continues to play an important role in cosmology. Classical treatment of the background metric is valid except for the very early period of the universe. One of the recent topics of cosmology is the existence of dark matter and dark energy. The latter corresponds to the cosmological term, which Einstein introduced in his equation to make the universe stable. It is a famous story that he regretted it later. The modern cosmological term is required by observation. The cosmological term can be interpreted as the vacuum energy and its existence is not a mystery from the viewpoint of current field theory. The real mystery is the smallness of the vacuum energy revealed by observation.

Unified Theory

Einstein devoted his later years to the study of unified theory. His intention was the unification of gravity and electromagnetism. In spite of his effort, he could not produce any important results. A common principle underlying general relativity and Maxwell's theory is gauge symmetry. We note that the five dimensional formulation known as the Kaluza-Klein theory is an attractive approach to the unification.

Einstein did not pay much attention to weak and strong interactions. But we have learned from the history that the weak and strong interactions are also described by gauge theories of the Yang-Mills type, which are extended versions of Maxwell's theory. The proof of the renormalizability of the Yang-Mills theory enabled us to build the standard model, in which three kinds of interactions are treated on the same footing. The unification of these three interactions, known as the grand unified theory, is also within our scope.

On the other hand, the gravitational interactions of general relativity are not renormalizable, because the gauge transformation of general relativity is related to the space-time and therefore the divergences appearing in the theory are stronger than those occurred in ordinary gauge theories. But we have a new hope for unification of all the interactions. Superstring theory, which is a candidate of quantum gravity, strongly suggests the existence of extra dimensions. This opens up the possibility for a new type of the Kaluza-Klein theory.

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SYMMETRY BETWEEN PARTICLE AND ANTI-PARTICLE

Relativistic quantum field theory emerged around 1930 as a theory consistent with both special relativity and quantum mechanics and developed as a fundamental tool to describe various particle phenomena discovered thereafter. Einstein, however, did not show much interest in these developments. Hereafter, we follow the development of particle physics focusing on symmetry properties related to antiparticles.

One of the most important consequences of relativistic quantum field theory is the existence of antiparticles. Although the existence of antiparticles was predicted first by Dirac from the interpretation of the negative energy solution of the Dirac equation, the study of field theory revealed that it is a generic property, together with the spin-statistic relation.

It is known that local field theory is automatically invariant under CPT transformation. CPT is the product of charge conjugation (C), parity (P) and time reversal (T) transformations. From CPT invariance, one can conclude that the mass and lifetime of a particle are the same as those of the corresponding antiparticle.

Field theory allows non-invariance under the separate transformations, C, P and T. In fact, in 1957, the violation of parity symmetry was discovered in weak interactions. Einstein died in 1955 before the discovery of parity violation.

P violation is associated with C violation. At first, it was thought that the product transformation, CP, is not violated. But, in 1964, it was found that CP is also violated in a decay process of the neutral K meson. CP violation implies that there is an essential difference between particles and antiparticles, such that an imbalance between matter and antimatter can be generated in the course of evolution of the universe.

CP violation is also allowed in local field theory, but it is restricted to a certain extent. To see this, the standard model is a good example. In the standard model, CP symmetry is violated in the Yukawa couplings between quarks and the Higgs field, or equivalently, in the mixing parameter among the generations appearing in the charged current of the weak interaction. The condition of CP violation is that there exists an imaginary number in these coupling constants or mixing parameters which is not removable by the field redefinition. This condition cannot be fulfilled with two generations or less. To violate CP symmetry we need at least three generations. In general, we can say that the system should have a certain level of complexity to violate CP. The system of the standard model is marginally complex.

The mixing parameters of the standard model are usually expressed in the following matrix form:

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}.$$

We note that there appears only one imaginary parameter in this expression. Since CP is violated with a single parameter, the standard model has a fairly good predictive power for CP violating phenomena. In fact, large CP asymmetries are expected in the B-meson system, and the study of the B-meson system is one of the most active subjects of current high energy physics. The highlight of the study will be explained in the next section.

Another interesting subject related to CP violation is its implications for cosmology. The present universe is made of only matter. This large imbalance between matter and antimatter is one of the mysteries of cosmology. It is known that for the imbalance to be generated in the course of evolution of the universe, the following three conditions are necessary; 1) baryon number non-conservation, 2) nonequilibrium and 3) C and CP violation.

It is an intriguing question whether the standard model can account for the matter dominance or not, because all three conditions are met by the standard model: Baryon number is not conserved due to instanton effects, which may not be suppressed at finite temperature, and the nonequilibrium state could be created through the first order phase transition at the electro-weak breakdown in a certain class of Higgs potentials. This possibility is known as the electro-weak scenario of baryogenesis. Careful calculation, however, shows that the effect is not enough to explain the observed baryon number. This implies that we need new kinds of fields and interactions beyond the standard model.

CP VIOLATION AND B-FACTORY

The K-mesons have played an important role in the history of high energy physics: The first hint of P violation was given by them and CP violation was discovered with the neutral K-meson. It is tempting, therefore, to expect a similar role for the B-mesons, which are obtained by replacing the s-quark in the K-meson with a b-quark. In fact, recent studies of the B-meson system revealed that this is the case. Many interesting results have been already obtained, in particular, regarding tests of CP violation in the standard model.

When we test a model experimentally, it is important how accurately we can express the experimentally observable quantities in terms of the fundamental parameters of the model. This is particularly important in the case of CP violation, because, in some cases, observable CP asymmetries are very sensitive to strong interaction effects, which are usually incalculable. In this sense, the so-called time dependent CP violation in the B-meson system is the most attractive. To be concrete, we consider the following B-meson and its antiparticle:

$$|B_d\rangle : (\bar{b}d), \qquad |\bar{B}_d\rangle : (\bar{d}b).$$

They are mixed through the weak interactions and the mass eigenstates can be expressed as

$$\begin{aligned} \left|B_1\right\rangle &= p\left|B_d\right\rangle + q\left|\overline{B}_d\right\rangle \\ \left|B_2\right\rangle &= p\left|B_d\right\rangle - q\left|\overline{B}_d\right\rangle \end{aligned},$$

where CPT invariance is assumed and p and q are complex numbers in general. Therefore a state prepared as $\left|B_d\right\rangle$ or $\left|\overline{B}_d\right\rangle$ will oscillate between $\left|B_d\right\rangle$ and $\left|\overline{B}_d\right\rangle$.

When we consider the decay of B_d, we can express the decay amplitude as a superposition of the direct decay and the decay from $\overline{B}_d$ through the mixing. Accordingly, the decay probability also oscillates with time, in general. A typical example is the decay, $B_d\left(\overline{B}_d\right) \to J/\psi + K_S$. In this case, the oscillating component of the asymmetry between the states prepared as $\left|B_d\right\rangle$ and $\left|\overline{B}_d\right\rangle$ can be expressed as

$$\sin 2\phi_1 \sin \Delta m t$$

where Δm is the mass difference of B_1 and B_2. ϕ_1 (or β) is given by

$$e^{2i\phi_1} = \frac{p}{q}\frac{A}{\overline{A}} = \frac{1-\rho+i\eta}{1-\rho-i\eta}$$

where $A\left(\overline{A}\right)$ is the decay amplitude of $B_d\left(\overline{B}_d\right)$. The most important fact here is that the observable asymmetry is expressed in terms of the mixing parameters only.

The above example is ideal from the theoretical point of view, but it requires measurement of the time dependence of the decay in the range of a few picoseconds. To accomplish this, an asymmetric B-factory was invented. The asymmetry of the colliding energies boosts the produced particles and makes it possible to measure the decay time through the decay position. Asymmetric B-factories were built at SLAC and KEK. Their performance is excellent. Details are left to a separate report of the present conference.

CP violation in the B-meson system was discovered at the asymmetric B-factory, almost forty years after the discovery of CP violation. During this period, CP violation was observed only in the neutral K-meson system. A couple of recent physics results are shown below. From the measurement of time dependent CP violation of $B_d\left(\overline{B}_d\right) \to J/\psi + K_S$ and related modes, the angle ϕ_1 (or β) is determined as

$$\sin \phi_1 = 0.726 \pm 0.037 .$$

This is shown in Fig.1 together with other constraints obtained from various experiments. The results are quite consistent with the standard model.

In a certain class of the decay processes, however, a hint for a new physics is observed. Figure 2 shows the results of the time dependent CP violation for the processes including b to s transition through the Penguin diagram. The plotted quantities are expected to coincide with $\sin \phi_1$ in the standard model. While data for each process still include large errors, the average of them shows a deviation from the expectation in the standard model.

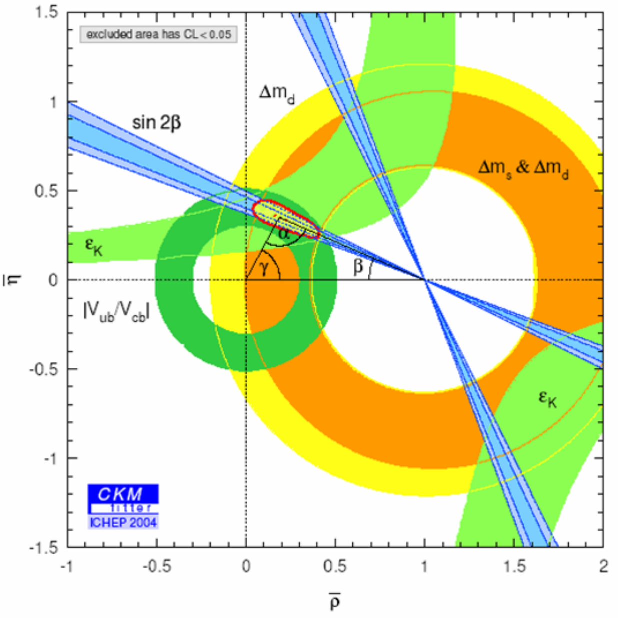

Figure 1: Constraints on mixing parameters[1]. The angle ϕ_1 in the text is denoted as β.

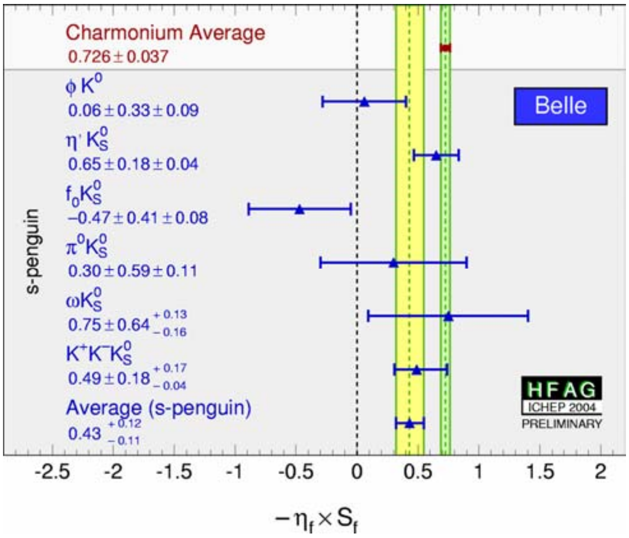

Figure 2: CP asymmetry for the processes including the b to s Penguin diagram[2].

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