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SEARCH FOR TIME-REVERSAL VIOLATION IN CHARGED- KAON DECAYS

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This report is on experiments which have been performed at the Japanese National Laboratory KEK, Tsukuba, Japan, using stopped positive kaons. The Standard Model (SM) of particle physics has been extremely successful in the description of a broad range of phenomena, sometimes with extreme accuracy. However, we are not completely satisfied with the SM, for several reasons. And we are hoping to observe some “physics beyond the Standard Model”. An attractive possibility is to search for observables which have null values (or are negligibly small) in the SM. An example is the transverse polarization of the muon in the decays $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \gamma\mu^+\nu$, the first one being particularly attractive because it is practically exempt from final-state interactions. The experimental method and experimental set-up will be described and the upper limits obtained will be presented.

1. Introduction

The Standard Model of particle physics has accumulated remarkable successes in the explanation of a large number of experimental facts. This gives us confidence that the Higgs boson, an essential ingredient of the model, will be discovered soon, when the Large Hadron Collider (LHC) starts operating at CERN, and that other very important predictions of the Standard Model will be verified.

However, we are not completely satisfied with the Standard Model, for several reasons:

The Standard Model contains too many arbitrary parameters, arbitrary assumptions, and one is looking for a more unified and complete theory. The final goal is a theory which will also include gravitation.

There are some disturbing features in the Standard Model. For instance, the matter-antimatter asymmetry of the universe does not seem to be correctly explained in the Standard Model. It is generally accepted that the amount of CP violation is not sufficient in the Standard Model.

It is therefore important to search for experimental manifestations of “new physics” or “physics beyond the Standard Model”. In this report I am especially interested in manifestations of CP violation beyond the Standard Model.

There are, essentially, two possibilities:

Search for deviations of certain observables from their Standard Model predictions. These deviations are in general expected to be small.

Search for observables which have zero values in the Standard Model (or have so small values that they could not be measured experimentally).

In the second category, there are observables which are essentially zero in the Standard Model, but which can reach measurable values in several extensions of the Standard Model. In the following I will discuss the transverse polarization P_T of the muon in the decays $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \gamma\mu^+\nu$.

These decays are produced by the weak interaction and they have a T-odd character. Therefore, they violate time-reversal symmetry [1]. Assuming the CPT theorem, a violation of time-reversal is equivalent to a violation of CP.

The interesting feature is that these observables violate time reversal symmetry in a non-standard way: the transverse polarizations P_T have extremely small values in the Standard Model.

I will report on experiments which have been performed at the Japanese National Laboratory KEK, Tsukuba, Japan, by a group of 30 scientists from Japan, Russia, Canada, Korea and the U.S.A.

The kaon beam was produced by the 12 GeV proton synchrotron. In contrast to previous experiments, where the kaons were allowed to decay in flight, our kaons were stopped in a target, where they decayed from rest. We believe that the systematics of the experiment are better controlled in this way.

An extensive description of the detector and experimental method can be found in a published paper [2].

2. Time-reversal violation in kaon decays

A measurement of the transverse polarization P_T of the muon in the $K^+ \to \pi^0\mu^+\nu$ decay has been proposed long ago by Sakurai [3] as a search for new physics. The Standard Model prediction for this

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transverse polarization is extremely small, $\sim 10^{-7}$ [4]. Another advantageous feature is the smallness of final-state effects which could mimic time reversal violation. There is no strong interaction between particles in the final state. And, since there is only one charged particle in the final state, the electromagnetic final-state interaction is very small [5, 6]: $\sim 10^{-5}$. This provided an interesting window to search for "New Physics" since the best available experimental values of P_T in the $K^+ \to \pi^0 \mu^+ \nu$ decay were of the order of a few times 10^{-3} when our experiment was started.

The measurement of the transverse polarization P_T of the muon in the $K^+ \to \gamma\mu^+\nu$ decay has been proposed by Kobayashi et al. [7]. By combining the two decays $K^+ \to \pi^0 \mu^+ \nu$ and $K^+ \to \gamma\mu^+\nu$ it should be possible to obtain very stringent constraints on some extensions of the Standard Model (for example three-Higgs models). But, in this decay,the electromagnetic interaction is not so small: $\sim 10^{-4}$. Therefore, the sensitivity of this decay to new physics is not as good, being limited to a smaller range of P_T values. There is also another difficulty: the branching ratio of the $K^+ \to \gamma\mu^+\nu$ is only $(5.50 \pm 0.28)\cdot 10^{-3}$. In comparison, the branching ratio of the $K^+ \to \pi^0 \mu^+ \nu$ decay is $(3.18 \pm 0.08)\cdot 10^{-2}$. Nevertheless, our group has established the first experimental upper limit on P_T in the $K^+ \to \gamma\mu^+\nu$ decay.

3. What is to be measured?

Let us start with the matrix element of the kaon decay $K^+ \to \pi^0 \mu^+ \nu$.

In the Standard Model, the matrix element has the following $V - A$ form:

$$M = \frac{G_F}{2} \sin\theta_C [f_+(q^2)(p_K + p_\pi)^\alpha + f_-(q^2)(p_K - p_\pi)^\alpha] \cdot [\bar{u}_\mu \gamma_\alpha (1-\gamma_5) u_\nu],$$

where p_K and p_π are the energy-momentum four-vectors of the kaon and pion, respectively. The $f_+(q^2)$ and $f_-(q^2)$ are two form factors, functions of the momentum transfer squared $(p_K - p_\pi)^2 = (p_\mu + p_\nu)^2$. Using the Dirac equation for the leptons, it is possible, after some calculations, to obtain the expression:

$$M = \frac{G_F}{2} \sin\theta_C \; f_+(q^2)[2 p_K^\alpha \cdot \bar{u}_\mu \gamma_\alpha (1-\gamma_5) v_\nu + (\xi(q^2) - 1) m_\mu \bar{u}_\mu (1-\gamma_5) v_\nu]$$

with the definition:

$$\xi(q^2) = \frac{f_-(q^2)}{f_+(q^2)}.$$

These form factors have been the object of many experimental studies. They are momentum-dependent:

$$f_\pm(q^2) = f_\pm(0)[1 + \lambda_\pm (\frac{q}{m_\pi})^2].$$

The currently adopted values are [8]:

$$\lambda_+ = 0.0284 \lambda_- = 0$$

and

$$\xi(0) = -0.14 \pm 0.05.$$

In the Standard Model the form factor $\xi(q^2)$ arises from the strong interaction, which is T-invariant; it is therefore real. But, in extensions of the Standard Model, additional contributions coming from new scalar interactions can contribute an imaginary part $Im\xi(q^2)$. Therefore, a measurement of a non-zeo $Im\xi(q^2)$ will be a manifestation of new physics.

According to Kobayashi et al. [7] an exotic scalar interaction ΔS would induce an imaginary part $Im\xi$:

$$Im\xi \approx Im\Delta S = \frac{\sqrt{2}(m_K^2 - m_\pi^2) ImG_S^*}{(m_s - m_u) m_\mu G_F \sin\theta_C},$$

where G_S is the exotic scalar coupling constant and m_K, m_π, m_s and m_u are the masses of the kaon, pion, s-quark and u-quark, respectively. Therefore, according to their theory, an upper limit on P_T would put a constraint on ImG_S.

It can be shown that the transverse polarization of the muon is proportional to $Im\xi(q^2)$ [9]:

$$P_T = Im\xi \frac{m_\mu}{m_K} \frac{|\vec{p}_\mu|}{[E_\mu + |\vec{p}_\mu|(\vec{n}_\mu \cdot \vec{n}_\nu) - m_\mu^2/m_K]}.$$

This polarisation P_T is proportional to the lepton mass. This represents a definite advantage over a β decay, like the pion β decay, $\pi^+ \to \pi^0 e^+ \nu$.

4. The principle of the experiment

As it is always the case in experimental physics, a compromise has to be made between the quantity and the quality of the recorded events.

The purpose of the experiment is the measurement of a transverse polarization P_T of the muon. If the kaon decays from rest the decay plane is completely defined for the $K^+ \to \pi^0 \mu^+ \nu$ by the momenta of the muon and the neutral pion, and for the $K^+ \to \gamma \mu^+ \nu$ by the momenta of the muon and the photon (there is no way to detect the neutrino).

For the $K^+ \to \pi^0 \mu^+ \nu$ the transverse polarization P_T is that component of the polarization vector P_μ which is perpendicular to the decay plane:

$$P_T = \frac{P_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{|\vec{p}_\pi \times \vec{p}_\mu|}.$$

The other two components are the “longitudinal” one, P_L, along the muon momentum:

$$P_L = \frac{P_\mu \cdot \vec{p}_\mu}{|\vec{p}_\mu|}$$

and the “normal” one, P_N perpendicular to the momentum and lying in the decay plane:

$$P_N = \frac{P_\mu \cdot [\vec{p}_\mu \times (\vec{p}_\pi \times \vec{p}_\mu)]}{|\vec{p}_\mu \times (\vec{p}_\pi \times \vec{p}_\mu|}.$$

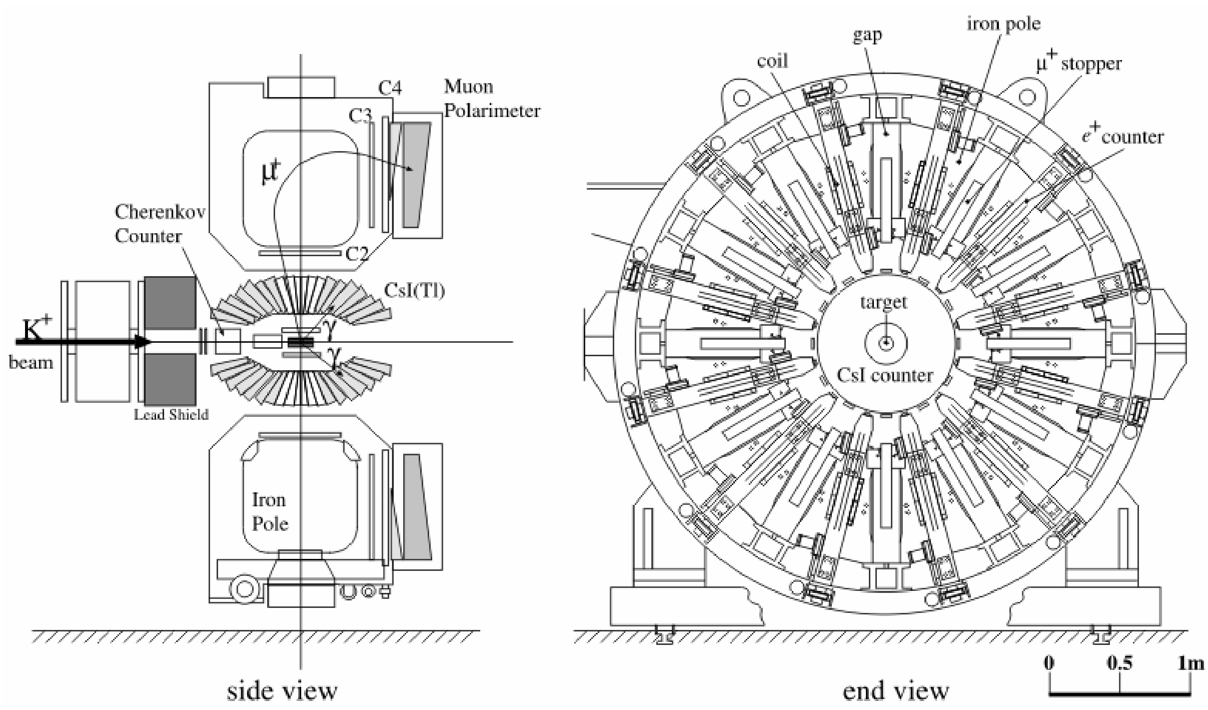
We have similar definitions for the polarization vector of the muon in the $K^+ \to \gamma \mu^+ \nu$ decay.

The two components P_L and P_N, which are not forbidden by fundamental symmetries, are much larger than the transverse component P_T. This is the major problem of the experiment.

The elimination of the spurious effects produced by these two components P_L and P_N can be achieved by exploiting the symmetries of the detector. The detector consists of twelve azimutal sectors (see figure). The muons are deflected by a magnetic field into twelve gaps where their polarization is analysed.

4.1. Definition of the decay plane

The incident kaon is tracked through a position sensitive target made of 256 scintillation rods, where it comes to rest. This establishes the point of kaon decay.



Superconducting Toroidal Magnet

The muon goes through a magnetic field and is tracked in a system of several scintillation counters and drift chambers. It is, therefore, momentum-analysed. The acceptance of the magnetic field is such that the muons from some other decays of the kaon are rejected.

The neutral pion decays rapidly ($\sim 10^{-16}$ sec.) into two photons and can be identified in two ways:

1) If the two photons share the total energy of the neutral pion almost equally, they are emitted at forward angles, and both detected in an array of 768 CsI(Tl) crystals. The momentum of the neutral pion can be reconstructed. The corresponding event is called a two-photon event.

2) If the energy sharing between the two photons is very asymmetric, one photon carries most of the neutral pion energy and is emitted at a small angle with respect to the neutral pion. It is detected by the scintillation counter array. The corresponding event is called a one-photon event.

The two sets of events are collected and analysed separately.

4.2. Measurement of the muon polarization

One makes use of the positive muon decay:

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

Due to parity violation in the weak interaction, the decay positron is emitted preferentially in the direction of the polarization vector of the muon. The angular correlation is given by:

$$W(\theta) \sim 1 + \alpha(E) P_\mu \cos\theta ,$$

where E is the positron energy, $\alpha(E)$ is given by the theory of weak interactions, P_μ is the degree of polarization of the muon, and θ is the angle between the direction of the polarization vector of the muon P_μ and the positron momentum. The principle of the measurement is to detect the positrons in two opposite directions, $\theta = 0$ and $\theta = \pi$ and obtain the asymmetry:

$$A = \frac{W(0) - W(\pi)}{W(0) + W(\pi)}$$

Since one is interested in the transverse component P_T , the experimental set-up must be designed in such a way that it is insensitive to the other components P_L and P_N . This can be realized (as much as possible) by exploiting the symmetries of the detector.

The muon loses its kinetic energy in an absorber and stops in a polarimeter made of aluminum plates, which is placed between two positron counters. In a perfect geometry these counters would be sensitive to P_T only. The other components P_L and P_N would give no effect, due to the symmetries.

The transverse polarization P_T is proportional to the counting asymmetry A, defined above, and between the two counters (one on the right, one on the left). As can be seen on the figure, one particular positron counter is the "right" counter for a muon stopping in a definite gap and the "left" counter for a muon stopping in the neighbouring gap. Such an arrangement reduces systematic effects due to the imperfections of the geometry and to the slightly different detection efficiencies of the positron counters. This is achieved by summing the asymmetries over the twelve gaps.

In a polarization experiment it is usual to exploit another symmetry, using a reversal of the polarization. How to reverse the transverse polarization P_T of the muon in this experiment?

It can be done by keeping the direction of the muon and reversing the direction of the neutral pion. The photon detector determines the direction of the neutral pion. By selecting the neutral pions which are emitted "forward" (in the inital kaon beam direction) and "backward" (in the opposite direction) one selects two ensembles of muons which have opposite transverse polarization P_T. The direction of P_T in the different sectors switches from a "clockwise" configuration to a "counter-clockwise" configuration. By combining the two sets of events, one doubles the effect. And the method also provides a possibility to check for the absence of spurious asymmetries.

The elimination of spurious effects can be tested by Monte Carlo calculations, based on accurate measurements of the geometry and the magnetic field, as well as tests on the detected events.

4.3. Efficiency of the polarimeter

According to the Standard Model, the angular distribution of the decay positrons of the muon decay $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ is asymmetric:

$$W(\theta) \sim 1 + \alpha P_\mu \cos\theta ,$$

where θ is the angle between the polarization of the muon and the momentum of the positron. The quantity α is given by the Standard Model.

As it has been said before, the direction of the neutral pion is selected either forward or backward (with respect to the initial kaon beam direction) so that the polarimeter is sensitive to the "transverse" component P_T. Another configuration can be used, where the direction of the neutral pion is perpendicular to the initial kaon beam direction, either to the left or to the right. In this configuration the polarimeter is sensitive to the "normal" component P_N, which is quite large and can be calculated from theory. This provides a way to calibrate the polarimeter. Of course this calibration method rests on a good knowledge of the P_N component. This can be calculated from theory. But the value of this component depends on the real part $Re\xi$. Another possibility is to use a Monte Carlo calculation.

There are, of course, a number of considerations which can not be discussed here. All the details on the experimental apparatus, experimental method and data analysis can be found in our final paper [10].

5. Results

Data have been taken in three periods (1996 - 1997), (1998) and (1999 - 2000). They have been analysed by two groups working independently. The results of the two analyses have been combined.

Upper limits on P_T and $Im\xi$ in the $K^+ \to \pi^0 \mu^+ \nu$ decay have been obtained [10]:

$$P_T = -0.0017 \pm 0.0023(\text{stat.}) \pm 0.0011(\text{syst.}) ,$$

$$Im\xi = -0.0053 \pm 0.0071(\text{stat.}) \pm 0.0036(\text{syst.}) .$$

By adding the statistical and systematic errors quadratically one obtains:

$$P_T = -0.0017 \pm 0.0026 ,$$

$$Im\xi = -0.0053 \pm 0.0080 ,$$

which can be converted to 90 % confidence limits:

$$|P_T| < 0.0050\,,$$

$$|Im\xi| < 0.016\,.$$

This result is an improvement, by a factor of 3, on the previous Brookhaven experiment [11]. Let us note that the precision of the above KEK result is limited by statistics.

A result has been obtained, for the first time, on the $K^+ \to \gamma\mu^+\nu$ decay [12]:

$$P_T = -0.0064 \pm 0.0185(\text{stat.}) \pm 0.0010(\text{syst.})\,.$$

Future experiments

There are plans to pursue this experimental programme at the new facility JPARC which will be operating in Japan in a near future [13]. Due to the higher energy of the accelerator (50 GeV) there will be more kaons available and the beam qualities will be much better (in particular the pion contamination will be lower). In a first step, an improved version of the present detector will be used. A new detector concept, allowing better performances, is presently under study.

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ПОИСК НАРУШЕНИЯ ОБРАЩЕНИЯ ВРЕМЕНИ В РАСПАДАХ ЗАРЯЖЕННЫХ КАОНОВ

П. Депомьер

Этот доклад об экспериментах, выполненных в Национальной лаборатории КЕК (Цукуба, Япония) с использованием остановленных положительных каонов. Стандартная Модель (СМ) физики частиц достигла значительных успехов в описании широкого круга явлений, иногда с очень большой точностью. Однако, мы не вполне удовлетворены СМ по нескольким причинам. И мы надеемся увидеть некую “физику за пределами Стандартной Модели”. Интересной возможностью является исследование в СМ наблюдаемых, имеющих нулевые значения (или являющиеся пренебрежимо малыми). Примером является поперечная поляризация мюона в распадах $K^+ \to \pi^0\mu^+\nu$ и $K^+ \to \gamma\mu^+\nu$. Первый случай особенно интересен, поскольку он является практически чистым взаимодействием в конечном состоянии. Будут описаны экспериментальный метод и методика и представлены полученные верхние пределы.

ПОШУК ПОРУШЕННЯ ОБЕРНЕННЯ ЧАСУ В РОЗПАДАХ ЗАРЯДЖЕНИХ КАОНІВ

П. Депомьєр

Ця доповідь про експерименти, виконані в Національній лабораторії КЕК (Цукуба, Японія) із використанням зупинених позитивних каонів. Стандартна Модель (СМ) фізики частинок досягла значних успіхів в описі широкого кола явищ, інколи з дуже великою точністю. Однак, ми не повністю задоволені СМ з декількох причин. І ми сподіваємось спостерігати певну “фізику поза межами Стандартної Моделі”. Цікавою можливістю є дослідження в СМ спостережуваних величин, що мають нульові значення (або тих, що є надзвичайно малими). Прикладом є поперечна поляризація мюона в розпадах $K^+ \to \pi^0 \mu^+ \nu$ та $K^+ \to \gamma \mu^+ \nu$. Перший випадок є особливо цікавим, оскільки він є практично чистою взаємодією у кінцевому стані. Буде описано експериментальний метод і методика та представлено отримані верхні границі.