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PARTIAL RATE DIFFERENCES FROM CP VIOLATION AT LEAR

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1. INTRODUCTION

The discovery of the quark families and the development of the standard model, with the recent discovery of the intermediate bosons, have truly enlightened our understanding of the electroweak and the strong interactions. Therefore, it is important to ask what new physics can be learned by studying phenomena which are not foreseen by and have no direct relation to the standard model. Besides the decay of the proton, the neutrino masses, and the neutrino oscillations, the breakdown of the CP invariance in nature has an impact on problems beyond the standard model, such as the baryon asymmetry and the grand unification.

From our present knowledge of the production and decay of c and b quark states in known and planned accelerators and storage rings, it will be extremely difficult to determine the source of CP violation in heavy-quark decays. Consequently, the neutral-kaon system and the hyperon decays still represent the most promising means of investigating the breakdown of the CP invariance.

In a properly chosen convention there are two parameters describing the CP non-conservation in the neutral-kaon system: a small complex number ϵ specifying the CP impurity of the observed

eigenstates K_S^0 and K_L^0 , which is a measure of the CP violation in the mass matrix, and the amplitude ϵ' measuring the violation of the CP symmetry in the decay matrix. Although the ratio $|\epsilon'/\epsilon|$ is required in order to quantify the source of CP violation, its magnitude is suppressed, mainly because of the $\Delta I = \frac{1}{2}$ rule. Therefore, any attempts to look for other CP-violating phenomena are very welcome. In this context two main arguments have been discussed:

- i) The partial rate difference between particles and antiparticles introduced and worked out by Chau¹⁻³.
- ii) The measurement of CP violation in decay channels other than into two pions, namely the 3π , $\pi^+\pi^-\gamma$, and 2γ mode.

In order to study experimentally both of these new attempts, it is necessary to have a high-yield clean source of particles and antiparticles, which can be achieved at the Low-Energy Antiproton Ring (LEAR) at CERN⁴. This machine is particularly suited for precise measurements, as required by experiments looking for CP violation, owing to its high performances, i.e. 10^6 antiprotons per second in the momentum range of 50 MeV/c to 2 GeV/c with a momentum spread of better than 10^{-3} . In the middle of 1987 the intensity of LEAR will increase by a factor of 10, reaching 10^7 antiprotons per second, owing to the construction of the Antiproton Collector (ACOL). By using the high-intensity antiproton source at LEAR, it is possible to produce a well-defined source of K^0 and $\bar{K}^0$ mesons through the reactions

In these reactions K^0 and $\bar{K}^0$ can be uniquely identified through the detection of the companion K^+ and K^- , respectively. Hence the total rate of tagged K^0 's and $\bar{K}^0$'s is $\sim 2 \times 10^8$ per day, assuming a stop rate of 10^6 antiprotons per second ($\sim 10^{11}$ antiprotons per day). The possibility of tagging K^0 's and $\bar{K}^0$'s separately, with a flux such as the one provided by LEAR, is unique and is almost inconceivable at external beams.

2. DIFFERENCE IN THE PARTIAL DECAY RATES BETWEEN PARTICLES AND ANTIPARTICLES

Recent theoretical ideas¹⁻³ have given rise to the possibility of a new effect in the difference of the partial decay rates between particles and antiparticles. It has been argued that besides contributing CP-violation effects in the mass matrix, the complexity in the mixing matrix can also give rise to CP-violation effects in the partial decay rates due to interference between the weak interaction amplitudes and the strong interaction amplitudes. These possible new CP-violating effects are measured by the asymmetry

$$D_K = \frac{|A(K^0 \rightarrow 2\pi)|^2 - |A(\bar{K}^0 \rightarrow 2\pi)|^2}{|A(K^0 \rightarrow 2\pi)|^2 + |A(\bar{K}^0 \rightarrow 2\pi)|^2} = 4[\text{Re } \Delta_K + \text{Re } \varepsilon'] \quad (2a)$$

or

$$D_\Lambda = \frac{|A(\Lambda \rightarrow N\pi)|^2 - |A(\bar{\Lambda} \rightarrow \bar{N}\pi)|^2}{|A(\Lambda \rightarrow N\pi)|^2 + |A(\bar{\Lambda} \rightarrow \bar{N}\pi)|^2} = \text{Re } \Delta_\Lambda + \text{Re } \varepsilon'_\Lambda, \quad (2b)$$

where the quantity Δ_K (Δ_Λ) appears because of the simultaneous complexity of the coupling constants and the complexity of the amplitudes arising from a possible absorptive part. It is important to notice that Δ_K (Δ_Λ) arises from possible interference in the dominant isospin amplitude and thus it is not suppressed by the $\Delta I = \frac{1}{2}$ rule, whereas the quantity $\text{Re } \varepsilon'$ arises from the interference of the different isospin amplitudes and thus it is suppressed by the $\Delta I = \frac{1}{2}$ rule. However, as is shown elsewhere⁵, the quantity Δ_K (Δ_Λ) is a CPT-violating parameter and thus CPT invariance implies striking limitations to Δ_K (Δ_Λ), resulting in a difference in the partial decay rates of the order of ε' :

$$D_K = 4 \text{Re } \varepsilon', \quad D_\Lambda = \text{Re } \varepsilon'$$

with

$$\frac{\varepsilon'}{10} < \varepsilon_\Lambda \leq \varepsilon'. \quad (3)$$

It is interesting that comparison of the measurements of the asymmetry D_K (D_Λ) with the measurements of $|\varepsilon'/\varepsilon|$ from other methods will provide a very sensitive test for the CPT invariance in the $\Delta S = \pm 1$ current^{6,7}.

2.1 The neutral-kaon decays

In order to study CP-violation effects in the neutral-kaon system with this novel experimental method with initially pure K^0 and $\bar{K}^0$ states, we consider a detector⁷ consisting of a magnetic spectrometer and a gamma-ray calorimeter, suitable for measuring the asymmetry of intensities in different K^0 and $\bar{K}^0$ decay channels (Fig. 1). The magnetic field has to be parallel to the beam in order to stop the $\bar{p}$'s in a "point-like" hydrogen target at the centre of the spectrometer. The initial atomic $p\bar{p}$ state has a precisely defined energy; hence the neutral-kaon direction and momentum are defined through the $K^\pm\pi^\mp$ kinematics, whilst the strangeness of the K^0 and $\bar{K}^0$ is determined by the sign of the charged kaon, which is determined in the magnetic spectrometer. This procedure results in the absolute and independent determination of the flux of K^0 's and $\bar{K}^0$'s. The identification of the charged kaons in the relevant momentum range (≤ 750 MeV/c) can be done using time-of-flight (TOF) and conventional Cherenkov detectors, e.g. FC72 or H_2O , at the outer radius of the detector. In order to achieve a high Cherenkov efficiency it is important to extend the photomultiplier sensitivity in the ultraviolet region. The main source of background arises from pions being misidentified as kaons from the reactions $\pi^+\pi^-\pi^0\pi^0$ [10% of all annihilations] and $\pi^+\pi^-\pi^0\pi^0\pi^0$ [23% of all annihilations]⁸. In addition to the Cherenkov detector, kinematical constraints will help to isolate the $K^\pm\pi^\mp K^0$ channel. Kaonic channels⁹ involving more particles, such as $K^\pm\pi K^0\pi^0$, can be suppressed by a factor of more than 100 by these kinematical selections. However, pion events, which will be misidentified as kaons because of inefficiencies, will introduce a continuous background in the $K^\pm\pi^\mp$ missing-mass spectrum.

Fig. 1. A schematic view of the experimental set-up.

This small background contribution can by no means create any systematic asymmetry and can be used in monitoring the overall trigger efficiency.

We are aware that in the physical apparatus $K^+\pi^-$ and $K^-\pi^+$ behave differently; total cross-sections, absorption, small-angle scattering, etc., are different, and the detector itself with $\vec{E} \times \vec{B}$ effects cannot be completely charge-symmetric. However, all observables are normalized independently for K^0 and $\bar{K}^0$, and any inefficiency in the K^0 and $\bar{K}^0$ trigger will not create a systematic asymmetry in the partial decay rates. But systematic errors can be introduced by the different interactions of the K^0 's and $\bar{K}^0$'s with the target surroundings. Nevertheless, such systematic errors can be eliminated if interactions in the first four decay lengths (~ 25 cm) around the target are minimized, because, independently of the initial state, the neutral kaon contains, after an eigenlifetime of $\sim 4 \tau_S$, the same amount of K^0 's and $\bar{K}^0$'s (Fig. 2). Target self-absorption and

Fig. 2. The $\bar{K}^0$ contents of a neutral kaon as a function of the distance from the production vertex.

Fig. 3. The difference in the interactions between K^0 and $\bar{K}^0$ as a function of the target radius for a cooled hydrogen gas (27 K, 1 atm) target. The main difference in the interactions comes from the 1 mm thick mylar target window.

interactions with materials around the target -- which are unavoidable -- result in a systematic error of less than 10^{-7} per millibarn in the difference between the tagged K^0 's and $\bar{K}^0$'s for the case of a cooled hydrogen-gas target at 1 atm (Fig. 3).

It can be seen that any measurement of the neutral-kaon decay rates should cover the time interval out to $\sim 20 \tau_S$ (80 cm), in order to cover the region of maximum interference at $14 \tau_S$. The magnetic spectrometer, with a momentum resolution of a few per cent ($\sigma \sim 4\%$), will enable us to define the neutral-kaon four-momentum and detect the decays over a distance of ~ 80 cm path length. The knowledge of

the neutral-kaon momentum vector allows, by a 2C-fit, the determination of the vertex with a resolution of better than 1 cm, without the magnetic analysis of the charged decay pions.

Starting from K^0 and $\bar{K}^0$ states it is possible to define a time-dependent asymmetry factor between K^0 and $\bar{K}^0$ rates given by

$$A(t) = \frac{R[K^0 \rightarrow 2\pi^\pm](t) - R[\bar{K}^0 \rightarrow 2\pi^\pm](t)}{R[K^0 \rightarrow 2\pi^\pm](t) + R[\bar{K}^0 \rightarrow 2\pi^\pm](t)}$$

$$= 2 \left[\frac{|\eta_{+-}| e^{(\gamma_S/2)t} \cos(\Delta m t - \theta_{+-})}{1 + |\eta_{+-}|^2 e^{\gamma_S t}} - \text{Re } \epsilon \right] \quad (4)$$

In first order, systematic errors, such as detector efficiencies, solid angles, resolutions, and small contributions from other neutral-kaon decays cancel out, and thus the asymmetry $A(t)$ is free from systematic errors. The time-dependent rate $A(t)$ is illustrated in Fig. 4 from which it is possible to extract $|\eta_{+-}|$ and θ_{+-} since they respectively determine the amplitude and position of the interference effect. Assuming⁷ a geometrical acceptance of 60% and an overall trigger efficiency of better than 50%, a resolution of less than 1 cm in defining the decay vertex results in a definition of $|\eta_{+-}|$ with an accuracy of 5×10^{-3} for a 10 day run at LEAR (2×10^9 K^0 's and $\bar{K}^0$'s). The measurement of the asymmetry $A(t)$, correcting for the time dependence, is sensitive to the difference between $|\eta_{+-}|$ and $|\epsilon|$, which is the parameter $|\epsilon'|$.

The asymmetry $A(t=0)$ is related to the parameter D_K [Eqs. (2a) and (4)] by the expression

$$A(t=0) = D_K = 4(\text{Re } \Delta_K + \text{Re } \epsilon') \quad (5)$$

A limit on the asymmetry $A(t=0)$ will give a limit on the magnitude of the CPT-violating parameter⁵ Δ_K . The asymmetry $A(t=0)$ can be measured to an accuracy of 7×10^{-5} at LEAR and would provide a very sensitive test for the CPT invariance in the $\Delta S = \pm 1$ current⁵. This

Fig. 4. The asymmetry factor $A(t)$ [Eq. (4)]. The statistical errors correspond to 2×10^9 K^0 's and $\bar{K}^0$'s.

measurement will improve the actual limit by roughly one order of magnitude.

In order to determine the partial decay difference in the two neutral-pion decays, we abandon the time-dependent measurement of the neutral decays -- hence we have the cumbersome vertex reconstruction from the gamma-rays -- and use only the integral rates in a time interval, i.e. $t=0$ to $t_0 \approx 20 \tau_S$, given by

$$I^{00} = \frac{\int_0^{t_0} R(K^0 \rightarrow \pi^0 \pi^0) dt - \int_0^{t_0} R(\bar{K}^0 \rightarrow \pi^0 \pi^0) dt}{\int_0^{t_0} R(K^0 \rightarrow \pi^0 \pi^0) dt + \int_0^{t_0} R(\bar{K}^0 \rightarrow \pi^0 \pi^0) dt} \approx 4 \operatorname{Re} \eta_{00} - 2 \operatorname{Re} \varepsilon. \quad (6)$$

The detection of the neutral-decay products over a distance of 80 cm will require a photon detector of large solid angle (70-80%), and of relatively good energy resolution and modularity, which can detect photons down to low energies (~ 10 MeV). The decays into three neutral pions result only from the K_L component; thus these decays represent only $\sim 5\%$ of the decays into two neutral pions inside the decay volume considered. We would like to emphasize that, to the order of the achievable statistical accuracy, the integral asymmetry I^{00} , similar to the asymmetry $A(t)$, is free from systematic errors. In a run of 10 days (2×10^9 K^0 's and $\bar{K}^0$'s) the neutral asymmetry I^{00} can be defined to an accuracy of $\sim 2\%$.

By measuring the particle (K^0) - antiparticle ($\bar{K}^0$) difference in the partial decays into two charged pions and into two neutral pions we can extract the ratio $|\varepsilon'/\varepsilon|^{10}$. The ratio $|\varepsilon'/\varepsilon|$ as a function of $|\eta_{+-}|$ and I^{00} is given by the expression

$$10|\varepsilon'/\varepsilon| = \left[2 - \frac{I^{00}}{\operatorname{Re} \eta_{+-}} \right]. \quad (7)$$

Consequently, after ten days of running at LEAR we will be able to measure $|\varepsilon'/\varepsilon|$ to an accuracy of 2×10^{-3} (Fig. 5).

To summarize, we can say that this approach with initially pure K^0 and $\bar{K}^0$ states represents a novel experimental method of looking at the CP-violating phenomena. The advantage, as opposed to the standard experimental configuration with K_S and K_L , is mainly the extremely reduced systematic errors. This approach is limited mainly by the statistics and not by systematics. In conclusion, we would like to emphasize that irrespective of the theoretical estimates on

Fig. 5. The experimental sensitivity in defining the CP-violation parameter $|\epsilon'/\epsilon|$ for the two-pion decays.

the magnitude of $|\epsilon'/\epsilon|$, measuring $|\epsilon'/\epsilon|$ from the partial-decay difference between particles and antiparticles gives an independent measurement¹⁻³ from those existing experiments measuring ϵ' .

2.2 The hyperon decays

Now we turn to the difference in the partial hadronic decays between hyperons and antihyperons. Above 1.43 GeV/c there are the thresholds for strangeness 1 hyperon-antihyperon pairs $\bar{p}p \rightarrow \bar{Y}Y$. Up to the highest LEAR momentum $\bar{Y}$ and Y are kinematically confined in a narrow forward cone. Therefore a rather small forward detector, as used in experiment PS185¹¹, is sufficient to study these reactions

Fig. 6. A schematic view of the set-up of the experiment PS185. 1: target, 2: proportional wire chambers, 3: drift chambers, 4: hodoscope, 5: baryon number identifier. An example of a "perfect track event" is indicated. The target region is given in a magnified view with T: target, S1-4: scintillation counters.

with full efficiency (Fig. 6). The experiment PS185 seems to be a good approach to measure the parameter D_{Λ} of Eqs. (2b) and (3). A difference in the rates for $p\bar{p} \rightarrow \Lambda\bar{\Lambda} \rightarrow \bar{p}n\pi^+\pi^0$ and $p\bar{p} \rightarrow \Lambda\bar{\Lambda} \rightarrow \bar{n}p\pi^0\pi^-$ would be the signal for CP violation.

The normalized difference

$$\Delta = \frac{\{\bar{p}n\pi^-\pi^0\} - \{\bar{n}p\pi^0\pi^-\}}{\{\bar{p}n\pi^+\pi^0\} + \{\bar{n}p\pi^0\pi^-\}}$$

can be determined to $\sim 10^{-3}$ statistical precision in PS185 within 5 to 10 days with 10^6 $\bar{p}/s$ ¹².

The problem will be to control *systematic errors*. They occur mainly (besides "wrong" triggers) owing to unsymmetries in the behaviour of $\bar{\Lambda}$ and Λ and their decay products. There are two principal

experimental differences between the neutral kaons and the hyperons in measuring partial-decay rates. Firstly, the hyperons cannot be tagged and therefore it is not possible to have independent normalization for Λ 's and $\bar{\Lambda}$'s. Secondly, the decay products of the hyperons have very different behaviour as compared to the neutral kaons, where the decay products are identical for K^0 's and $\bar{K}^0$'s.

a) In the laboratory system $\bar{\Lambda}$ particles are produced preferentially with larger momenta and smaller angles than the Λ particles (forward peaked differential cross-section), except very close to threshold where however cross-sections are unknown and small. The different $\bar{\Lambda}$ and Λ momentum distributions lead to different distributions for the decays in space. The differential production cross-sections will be determined in PS185.

b) Rescattering and absorption of the produced $\bar{\Lambda}$ and Λ in the target and detectors will differ. The short target (~ 2.5 mm polyethylene) and the thin detectors will help to reduce such effects.

c) Also the rescattering and absorption of the decay products ($\bar{p}$ and p , π^+ and π^-) is unsymmetric and needs corrections.

One can control the knowledge of systematic errors by performing the experiment at different $\bar{p}$ beam momenta. With some modifications a similar check of CP violation can be done for $\bar{p}p \rightarrow \bar{\Sigma}^+ \Sigma^+$.

Another good test for CP-violation effects should be a comparison of the decay asymmetries $\bar{\alpha}$ and α for $\bar{\Lambda}$ and Λ . Here $\bar{\alpha} + \alpha = 0$ has to be checked and one can reach a statistical precision of $\sim 5 \times 10^{-3}$ within 5 to 10 d with 10^6 antiprotons per second in experiment PS185. (If $\bar{\alpha} + \alpha \neq 0$ this would simulate an apparent difference in $\bar{\Lambda}$ and Λ polarization¹².)

3. CP VIOLATION IN OTHER THAN THE TWO-PION DECAY MODE

The decay of the long-lived K^0 meson, K_L , into two pions is so far the only clear evidence of CP violation; no other process has yet been uncovered. When studying CP violation in decays of neutral kaons other than into two pions, we cannot look for a simple violation of a

selection rule, since both K_L and K_S are allowed to decay into such final states as $\pi^+\pi^-\gamma$ and $\gamma\gamma$, and the branching ratio of $K_S \rightarrow 3\pi$ is extremely small ($\lesssim 10^{-9}$). The following theorem¹³ of Sehgal and Wolfenstein forms the basis for identifying CP violation in these channels: "For any possible non-leptonic decay mode of the neutral kaon the observation of an interference effect between K_L and K_S decays in the partial decay rate in this mode is evidence of CP violation". The most feasible way of detecting interference effects seems to be to measure the asymmetry of the decay intensities using a beam of K^0 particles as well as a beam of $\bar{K}^0$ particles. Consequently, our experimental philosophy of starting with pure K^0 and $\bar{K}^0$ states is ideally suited for measuring CP violation in these channels.

3.1 The quantity $|\eta_{000}|$

The actual limit of $|\eta_{000}|^2$ is 0.28, i.e. $|\eta_{000}| < 0.53$, whereas the parameter $|\eta_{+-0}|^2$ is less than 0.12, i.e. $|\eta_{+-0}| < 0.35$. There is a general argument about the major importance of $|\eta_{000}|$ relative to $|\eta_{+-0}|$. If CP were an exact symmetry, $K_S \rightarrow 3\pi^0$ would be forbidden (π^0 are C eigenstates), but $K_S \rightarrow \pi^+\pi^-\pi^0$ would be allowed. However, the $K_S \rightarrow \pi^+\pi^-\pi^0$ would be inhibited by an angular momentum barrier factor of the order of $(Q/m_K)^2 \approx 1/200$, not so much different from the expected CP-violation effects. Thus the cleanest test for CP violation in the 3π decays is the $3\pi^0$ mode.

We intend to measure⁷ the asymmetry of the partial decay rates between $K^0 \rightarrow 3\pi^0$ and $\bar{K}^0 \rightarrow 3\pi^0$

$$I^{000} = \frac{\int_0^{t_0} R(K^0 \rightarrow 3\pi^0) dt - \int_0^{t_0} R(\bar{K}^0 \rightarrow 3\pi^0) dt}{\int_0^{t_0} R(K^0 \rightarrow 3\pi^0) dt + \int_0^{t_0} R(\bar{K}^0 \rightarrow 3\pi^0) dt} . \quad (8)$$

The partial width of K^0 's into $3\pi^0$ is

$$\begin{aligned}
R(K^0 \rightarrow 3\pi^0) &= \frac{R(K_S \rightarrow 3\pi^0)}{4|p|^2} e^{-t/\tau_S} + \frac{R(K_L \rightarrow 3\pi^0)}{4|p|^2} e^{-t/\tau_L} + \\
&+ \frac{2|\eta_{000}|}{4|p|^2} R(K_L \rightarrow 3\pi^0) \exp \left[-t(\tau_S + \tau_L)/2\tau_S\tau_L \right] \times \\
&\times \cos(\Delta m t - \phi_{000})
\end{aligned} \tag{9}$$

with $|p|^2 = (1 + 2 \operatorname{Re} \epsilon)/2$, and the partial width of $\bar{K}^0$'s into $3\pi^0$ is

$$\begin{aligned}
R(\bar{K}^0 \rightarrow 3\pi^0) &= \frac{R(K_S \rightarrow 3\pi^0)}{4|q|^2} e^{-t/\tau_S} + \frac{R(K_L \rightarrow 3\pi^0)}{4|q|^2} e^{-t/\tau_L} - \\
&- \frac{2|\eta_{000}|}{4|q|^2} R(K_L \rightarrow 3\pi^0) \exp \left[-t(\tau_S + \tau_L)/2\tau_S\tau_L \right] \times \\
&\times \cos(\Delta m t - \phi_{000})
\end{aligned} \tag{10}$$

with $|q|^2 = (1 - 2 \operatorname{Re} \epsilon)/2$.

Similarly to the $2\pi^0$ case the integral asymmetry I^{000} is given by

$$I^{000} = \left[\left(\frac{\tau_S}{\tau_L} \right) \frac{4 \operatorname{Re} |\eta_{000}|}{(1 - e^{-\gamma_L t_0})} - 2 \operatorname{Re} \epsilon \right] / \left[1 - \frac{8 \operatorname{Re} \epsilon \operatorname{Re} \eta_{000}}{(1 - e^{-\gamma_L t_0})} \left(\frac{\tau_S}{\tau_L} \right) \right]$$

or for $t_0 \ll \tau_L$

$$I^{000} = \left(\frac{\tau_S}{t_0} \right) 4 \operatorname{Re} |\eta_{000}| - 2 \operatorname{Re} \epsilon. \tag{11}$$

The sensitivity of the measurement of I^{000} is shown in Fig. 7 as a function of the magnitude of $|\eta_{000}|$. For this particular measurement we expect to have an additional systematic error of 10%, coming mainly from the uncertainty in the definition of the integration interval $t_0 \approx 20 \tau_S$.

To conclude, we would like to emphasize that the only possible place to measure in such a direct way and with such an accuracy the quantity $|\eta_{000}|$ is at LEAR, where one exploits features not accessible from the standard configuration with K_S and K_L beams.

Fig. 7. The experimental sensitivity in defining the CP-violation parameter $|\eta_{000}|$ for the three-pion decays. The parameter ε is here assumed to be independent of the η_{000} magnitude and is equal to 2.3×10^{-3} .

3.2 The two-photon decay

The two-photon decay of the neutral kaon may be of particular interest because, firstly, by involving electromagnetism it does not obey isospin invariance and, secondly, the measurement of the $K_S \rightarrow 2\gamma$ branching ratio, which is presently unknown, will check our understanding on neutral-kaon decays^{15,16}.

The asymmetry between the K^0 and $\bar{K}^0$ decays has the following time dependence in vacuum^{17,18}:

$$A(t) = \frac{Y(t) - 2 \operatorname{Re} \varepsilon X(t)}{X(t) - 2 \operatorname{Re} \varepsilon Y(t)}, \quad (12)$$

where

$$X(t) = \left\{ R(K_L \rightarrow \gamma\gamma) e^{-t/\tau_L} + R(K_S \rightarrow \gamma\gamma) e^{-t/\tau_S} \right\}$$

and

$$Y(t) = 2 \{ |\varepsilon_1| R(K_S \rightarrow \gamma\gamma) \cos(\theta_1 - \Delta mt) + |\varepsilon_2| R(K_L \rightarrow \gamma\gamma) \cos(\theta_2 + \Delta mt) \} \times \exp \left[\frac{t(\tau_S + \tau_L)}{2\tau_S\tau_L} \right]$$

where t is the proper time and θ_1 and θ_2 are the phases of the complex amplitudes¹⁷

$$\varepsilon_1 = \frac{r_1 - q/p}{r_1 + q/p} \quad \text{and} \quad \varepsilon = \frac{r_2 - q/p}{r_2 + q/p}$$

with

$$|r_1| e^{i\phi_1} = -A[K^0 \rightarrow \gamma\gamma \text{ (CP = +1)}] / A[\bar{K}^0 \rightarrow \gamma\gamma \text{ (CP = +1)}]$$

$$|r_2| e^{i\phi_2} = A[K^0 \rightarrow \gamma\gamma \text{ (CP = -1)}] / A[\bar{K}^0 \rightarrow \gamma\gamma \text{ (CP = -1)}]$$

$$p = \frac{1 + \varepsilon}{\sqrt{2(1 + |\varepsilon|^2)}} \quad \text{and} \quad q = \frac{1 - \varepsilon}{\sqrt{2(1 + |\varepsilon|^2)}} .$$

The sensitivity in measuring the integral asymmetry

$$I^{\gamma\gamma} = \frac{\int_0^{t_0} R(K_0 \rightarrow \gamma\gamma) dt - \int_0^{t_0} R(\bar{K}^0 \rightarrow \gamma\gamma) dt}{\int_0^{t_0} R(K^0 \rightarrow \gamma\gamma) dt + \int_0^{t_0} R(\bar{K}^0 \rightarrow \gamma\gamma) dt} \quad (13)$$

at LEAR is presented in Fig. 8 as a function of the phases ϕ_1 and ϕ_2 . As was shown a long time ago¹⁷, the asymmetry $I^{\gamma\gamma}$ is always non-vanishing and of order ε because of CP violation in the K^0 - $\bar{K}^0$ mass matrix. As is shown in Ref. 18, the effects of the CP violation in the decay matrix modify the superweak predictions, as follows:

$$|r_1| = |r_2| \quad \text{and} \quad \phi_1 = 0 ; \phi_2 = \xi \approx 0(10^{-3}) .$$

Fig. 8. The dependence of the asymmetry [Eq. (13)] on the relative phase of the amplitudes $A(K^0 \rightarrow \gamma\gamma)$ and $A(\bar{K}^0 \rightarrow \gamma\gamma)$. The magnitudes of these amplitudes were taken to be equal.

Although in the two-photon decay mode we have, for the first time, a milliweak prediction of the order of ϵ , which is not suppressed by the $\Delta I = \frac{1}{2}$ rule, our experiment is completely insensitive to this effect. Only if the 3π intermediate state has a contribution comparable to the short distance and if, in contradiction to the theoretical predictions¹⁴, η_{000} is very different from ϵ , then a measurable effect could be seen in $I^{\gamma\gamma}$.

By measuring K^0 ($\bar{K}^0$) $\rightarrow 2\gamma$ one will verify that CP is indeed violated in this channel and one will measure the branching ratio of the $K_S \rightarrow 2\gamma$.

4. SUMMARY

It is our contention that by using LEAR it is possible to study CP-violating phenomena through the asymmetry of intensities in the partial-decay rates of K^0 's and $\bar{K}^0$'s. This experiment is sensitive to the interference terms, as opposed to the standard experiments with K_L beams, which are sensitive to the CP impurities of the observed K_S and K_L states. The detection of such asymmetries will allow the determination, firstly, of the parameter $|\epsilon'/\epsilon|$ from a measurement independent from those existing experiments measuring ϵ' and, secondly, of the violation of the CP invariance in decays other than into two pions. The intensity of stopped $\bar{p}$'s at LEAR and the symmetry of the annihilation at rest provide us with a unique way of studying such processes with reduced systematic errors, using a modest-sized detector with a magnetic-field volume and an electromagnetic calorimeter.

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REFERENCES

1. L. L. Chau Wang, Phenomenology of CP violation from the Kobayashi-Maskawa Model, in "AIP Conf. Proc. No. 72, Particles and Fields", Subseries No. 23, G. B. Collins, L. N. Chang and J. R. Ficenec, eds, AIP, New York (1980)
2. L. L. Chau, Status of electroweak gauge theories, in "Proc. 6th European Symposium on NN, QQ Interactions", Santiago de Compostela, Spain, 1982, Anales de Fisica, Series A, 79:297 (1983)
3. L. L. Chau, Quark mixing in weak interactions, Phys. Rep. 5:1 (1983)
4. P. Lefèvre, D. Möhl and G. Plass, in "Proc. 11th Int. Conf. on High-Energy Accelerators", Geneva, 1980 (Birkhäuser, Basle, 1980), p. 819
5. C. Kounnas, A. B. Lahanas and P. Pavlopoulos, Phys. Lett. 127B:381 (1983)
6. L. Wolfenstein, Nuovo Cimento 63:269 (1969)
7. Basle-Stockholm-Thessaloniki Collaboration, Letter of Intent, Tests of symmetries with K^0 and $\bar{K}^0$ beams, CERN/PSCC/83-28/PSCC/I65
8. Table XI of R. Armenteros and B. French, in "High-Energy Physics", E. H. S. Burhop, ed., Academic Press, New York (1969), Vol. 4
9. Table XIV of R. Armenteros and B. French, in "High Energy Physics", E. H. S. Burhop, ed., Academic Press, New York (1969), Vol. 4
10. E. Gabathuler and P. Pavlopoulos, Strong and weak CP violation at LEAR, to be published in "Proc. Workshop on Physics at LEAR with Cooled Low Energy Antiprotons", Erice, 1982
11. CERN-Erlangen-Freiburg-Los Alamos- Carnegie Mellon-Saclay-Uppsala Collaboration, Proposal of the experiment PS185, Study of threshold production of $\bar{p}p \rightarrow Y\bar{Y}$ at LEAR. CERN/PSCC/81-69/PSCC/P49 and extension CERN/PSCC/81-6/PSCC M152
12. K. Kilian, private communication
13. L. M. Sehgal and L. Wolfenstein, Phys. Rev. 162:1362 (1967)
14. L. F. Li and L. Wolfenstein, Phys. Rev. D 21:178 (1980)
15. M. K. Gaillard and B. W. Lee, Phys. Rev. D 10:897 (1974)
16. J. Ellis, M. K. Gaillard and D. V. Nanopoulos, Nucl. Phys. B 109:213 (1976)
17. B. R. Martin and E. de Rafael, Nucl. Phys. B 8:131 (1968)
18. R. Decker, P. Pavlopoulos and G. Zoupanos, CP violation in $K^0(\bar{K}^0) \rightarrow 2\gamma$ decays, submitted to Phys. Lett. B