SEARCHING FOR \( CP \) VIOLATION IN PION DECAY\(^a\)

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Abstract
Surprisingly, until recently \( CP \) violation in pion decay was not ruled out experimentally even at the percent level. I have derived the first experimental limit, \(-0.01 < A_{\text{CP}} < 0.02\), from old data on the anomalous magnetic moment \( g - 2 \) of the muon. New data from the Brookhaven \( g - 2 \) experiment might extend the search by a few orders of magnitude, but probably will not probe the theoretically-interesting sub-\(10^{-7}\) regime.

1 Introduction
While the main topic of this Workshop is \( CP \) violation in heavy-quark systems (\( s, c, b \), and even \( t \) have been discussed), it is perhaps surprising to realize that we don’t even know whether pion decay conserves \( CP \)! If we consider this question, we are likely to assume that the answer is yes, but an experimental test would be desirable.

2 A Possible \( CP \)-Violation Signature
A conceptually-straightforward test is to measure the angular distribution of the electrons from the \( \pi \to \mu \to e \) decay chain. This distribution is nonuniform due to parity violation in the weak interaction. \( CP \) symmetry implies that the nonuniformity will be the same for electrons from \( \pi^- \) as for positrons from \( \pi^+ \). This approach has the added benefit of being sensitive to \( CP \) violation whether it occurs in pion decay or in muon decay.

The original observation of parity violation in this decay chain was carried out using positive pions stopping in carbon. A complementary experiment using \( \pi^- \) would in principle allow a \( CP \) test but is not feasible due to the bias introduced by negative-pion and muon capture in matter. It follows that pions decaying in flight in vacuum are required for such a \( CP \) test.

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3 Muon $g - 2$ Experiments

An opportunity for such a measurement is afforded by the muon $g - 2$ experiment. The anomalous magnetic moment $g - 2$ of the muon has been measured with extreme precision using a muon storage ring at the CERN PS, and an improved version of that apparatus is now in operation at the Brookhaven AGS.

In a typical experiment, charged pions are injected into the ring, and muons from pion decay are captured in stable orbits. Electrons from the decay of the stored muons are detected, and, due to the muon polarization arising from parity violation, their rate in a given direction oscillates in time (see Fig. 1) as the muon spin precesses about the magnetic-field direction in the storage ring. The amplitude $A$ of this oscillation is proportional to both the degree of polarization of the muons and the analyzing power of the $\mu \rightarrow e$ decay. In principle both of these could be affected by phases arising from physics beyond the Standard Model, resulting in a detectable difference in oscillation amplitude between electrons from $\pi^- \rightarrow \mu^-$ and positrons from $\pi^+ \rightarrow \mu^+$:

$$A_{CP} \equiv \frac{A_{\pi^+} - A_{\pi^-}}{A_{\pi^+} + A_{\pi^-}}. \quad (1)$$

4 The First Experimental Limit

While the CERN $g - 2$ group never published such a $CP$ limit, one has recently been derived from a figure in their “Final Report on the CERN Muon Storage Ring,” in which measurements are given of $A_{\pi^+}$ and $A_{\pi^-}$ for four electron energy thresholds. The resulting limit is

$$-0.01 < A_{CP} < 0.02 \quad (2)$$

at 90% confidence. Given the higher statistics, one might expect $O(10^{-5})$ sensitivity to be possible in the Brookhaven experiment. However, the CERN limit is dominated by systematic effects. It remains to be seen whether these would dominate also at Brookhaven, and at what level they can be controlled.

5 Theoretical Upper Limit

It is also of interest to estimate how large a $CP$ asymmetry is possible theoretically. Discussions at this Workshop suggest that the effect is limited to $O(10^{-7})$ or less, since the final-state phase difference necessary for an observable interference effect must here come from a weak interaction involving a neutrino. Thus one has little expectation of an observable effect at present levels of statistics.
Figure 1: Example of data from the Brookhaven $g - 2$ experiment showing oscillations as described in text.

Positron Energies > 2 GeV
3 x $10^5$ events
$\tau_n = 64.4$ $\mu$s
$\Lambda = 0.49$
$\omega_n = 1.44 \times 10^6$ rad/s
6 Conclusions

Given the availability of pions in enormous numbers, the possibility of extremely precise experiments in the future is not ruled out. It is also worth searching for alternative signatures to which new-physics contributions might be larger, for example $T$-odd correlations or measurements involving suppressed decay modes of the pion.

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