USING K^+ DECAYS AS A SOURCE OF TAGGED π^0's

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Summary

The rare decays $\pi^0 \to e^+e^-$, $\pi^0 \to \nu\bar{\nu}$, and $\pi^0 \to \tilde{\gamma}\tilde{\gamma}$ are discussed. Better measurements are called for because the physics interests in these decays are high. The process $K^+ \to \pi^+\pi^0$ provides an appropriate source of tagged π^0's in vacuum for these measurements. Experimental possibilities are examined.

Several rare π^0 decay modes are of interest because either they are not present in the standard model so their occurrence would indicate the need to extend that model, or the decay rate through conventional electromagnetic contributions is calculable so any deviation from this rate would indicate the presence of additional, unexpected mechanisms.

As an example, the imaginary part of the amplitude for the decay $\pi^0 \to e^+e^-$ is dominated by a two-photon intermediate state and implies a lower bound[1,2] of

$$B_{ee} = \frac{\Gamma(\pi^0 \to e^+e^-)}{\Gamma(\pi^0 \to \gamma\gamma)} > 0.48 \times 10^{-7} \quad . \qquad (1)$$

The calculation of the real part of the amplitude is model dependent. These calculations[2] do not tend to increase B_{ee} substantially above this lower bound. The effects of weak neutral currents[3] and Higgs bosons[4] are also expected to be small. On the other hand, unconventional effects, such as direct quark-lepton couplings[5] or pseudoscalar currents,[3] could lead to large enhancements. Experimentally, there are two published measurements[6,7] of B_{ee}, yielding

$$B_{ee} = (1.7 \pm 0.6) \times 10^{-7} \quad ,$$

which is (3.5 ± 1.3) times the unitarity limit. Another result[8] should become available within the next year, but the experimental error probably will not be significantly smaller. Should this additional result also indicate a large value for B_{ee}, some exciting new physics may very well be indicated; a more accurate experiment with smaller errors certainly would be called for.

The present experiments are limited not by statistics (~60 events have been observed) but rather by the presence of substantial backgrounds. The predominant background comes from $\pi^0 \to \gamma\gamma$ with the photons converting asymmetrically into e^+e^- pairs (either internally or externally) or Compton scattering; most of these processes take place in the target used to produce the π^0's and therefore cannot be eliminated. A source of π^0's that would eliminate this problem is the decay $K^+ \to \pi^+\pi^0$ (BR = 21%), as the π^0's are produced in vacuum. The limitation here is the number of π^0's that are available. As an example, consider the apparatus of Bloch et al.[6,9] Using a 2.8-GeV/c separated K^+ beam at the CERN Proton Synchrotron, they detected 41 events from $K^+ \to \pi^+e^+e^-$ with a branching ratio of $(2.7 \pm 0.5) \times 10^{-7}$. They also detected ~4 events from $\pi^0 \to e^+e^-$. These numbers indicate that they were sensitive to $\sim 10^8$ K^+ decays (or $\sim 2 \times 10^7$ π^0 decays). One could conceive of an apparatus with a slightly higher acceptance and a somewhat higher incident kaon flux. An experiment at the Alternating Gradient Synchrotron (AGS)[10] hopes to be sensitive to $\approx 10^{11}$ K^+ decays (in particular $K^+ \to \pi^+\mu^+e^-$) by using a short unseparated K^+ beam. If this experiment is successful, it would indicate that the $\pi^0 \to e^+e^-$ experiment could be performed with present accelerators. Some compromises might be needed in beam purity and beam quality to improve the e^+e^- invariant mass resolution and to reduce the background from $\pi^0 \to e^+e^-\gamma$ (Dalitz decays). This may imply that higher proton currents are needed. A side benefit of the $\pi^0 \to e^+e^-$ experiment could be an improved measurement of the π^0 electromagnetic form factor from Dalitz decays; the current measurement of the form factor[11] slope is somewhat larger than expected.

Another rare-decay process is $\pi^0 \to \nu\bar{\nu}$. Observations of this decay mode would indicate either the existence of neutrino states of both chiralities or lepton-number violation (or both).[12] In the framework of lepton-number conservation, this would indicate the presence of neutrino masses or scalar and/or pseudoscalar couplings. These couplings could, for example, be mediated by Higgs bosons. In Ref. 12 an experimental limit of

$$B_{\nu\nu} = \Gamma(\pi^0 \to \nu\bar{\nu})/\Gamma(\pi^0 \to \text{all}) < 2.4 \times 10^{-5} \qquad (2)$$

was derived. It clearly would be exciting if evidence for this decay were found.

Another possible mechanism for π^0 decaying into "nothing" is the process $\pi^0 \to \tilde{\gamma}\tilde{\gamma}$, where $\tilde{\gamma}$ is a photino, the supersymmetric partner of the photon. Assuming the photino mass is less than $m_{\pi^0}/2$, the expected branching ratio is given by[13]

$$B_{\tilde{\gamma}\tilde{\gamma}} = \frac{\Gamma(\pi^0 \to \tilde{\gamma}\tilde{\gamma})}{\Gamma(\pi^0 \to \text{all})} \approx 5 \times 10^{-8} \times \left(\frac{50\ \text{GeV}}{M_{\tilde{u}}}\right)^4 \times \left(\frac{M_{\tilde{\gamma}}}{M_\pi}\right)^2 \times \left(1 - \frac{4M_{\tilde{\gamma}}^2}{M_\pi^2}\right)^{1/2} \quad ,$$

where $M_{\tilde{u}}$ is the mass of the supersymmetric partner of the up quark. Thus, such a light photino might well be "observable."

To improve these limits, one must have a source of tagged π^0's and establish the absence of any e^+, e^-, or γ's resulting from their decay. A suitable source is $K^+ \rightarrow \pi^+\pi^0$, either at rest or in flight. The detection of the π^+ with the right kinematics to indicate a missing π^0 mass tags the π^0. Highly efficient γ vetoes completely cover the region where photons from π^0 decay could emerge. The ultimate sensitivity would depend on the veto inefficiency, which can be measured using the tagged π^0's; measuring the energy and conversion point of one γ implies that the energy and direction of the other γ can be determined. Thus, we have a tagged γ source with which to measure the detection efficiency for γ's. This experiment might be limited less by the raw number of available K^+'s than by the need to have an extremely clean source of tagged π^0's (few π^+'s in the beam, for example) and low singles rates in the γ detectors.

Such a clean environment certainly is not present in Ref. 10. An experiment at rest with a sensitivity to $B_{\nu\nu} \sim 10^{-9}$ (this appears to be the most interesting region[12]) would require $\sim 10^{11}$ stopping K^+ (assuming $\Omega/4\pi \sim 0.1$ for detection of the π^+). This is more K^+ than could be stopped in a thin target at present accelerator intensities; higher proton fluxes and cleaner K^+ beams would be required. The same experiment could also search for $K^+ \rightarrow \pi^+\nu\bar{\nu}$. This process can be used to measure the number of (light) neutrinos, to search for $\tilde{\gamma}$, and to provide a sensitive test of the GIM mechanism.

An interesting detector, which may be ideally suited to the detection of these processes, was recently proposed by Ferro-Luzzi.[14] The detector is basically a vat of liquid argon covered with photomultiplers. The K^+ stops in the middle of the argon. The range of the π^+ (and the decays $\pi^+ \rightarrow \mu^+ \rightarrow e^+$) is measured using the scintillation light from the argon, while the argon also serves as a shower counter (using Cherenkov light) to veto γ's. The detector has $\Omega/4\pi$ of nearly 1. These experimenters hope to stop 75000 K^+/ps pulse (along with $\approx$300000 π^+); these rates may be too high. If the detector works as advertised, it could be sensitive to a kaon branching ratio as low as 10^{-10}. Clearly, the experiment would be better off with a lower π contamination and a higher duty factor.

Other rare π^0 decays appear to be less interesting; $\pi^0 \rightarrow 3\gamma$ violates C conservation, but it can be tested down to a branching ratio of 10^{-9} at LAMPF.[15] The fundamental limitation appears to be the background from $\pi^0 \rightarrow e^+e^-\gamma$. This limitation might be helped by producing the π^0's in vacuum ($K^+ \rightarrow \pi^+\pi^0$ in flight), but the γ detectors would have to be very large. The lepton-flavor-violating decay $\pi^0 \rightarrow \mu^{\pm}e^{\mp}$ is expected to be quite small[16] and probably would not be a fruitful avenue of investigation.

In summary, it appears that using $K^{\pm} \rightarrow \pi^+\pi^0$ is a useful source of tagged π^0's to investigate the rare decays $\pi^0 \rightarrow e^+e^-$, $\pi^0 \rightarrow \tilde{\gamma}\tilde{\gamma}$, and $\pi^0 \rightarrow \nu\bar{\nu}$. Present accelerator intensities may be sufficient to study the first process, although a detailed experimental design may show that higher intensities are needed. Higher flux beams clearly are needed to achieve the best sensitivity to $\pi^0 \rightarrow \nu\bar{\nu}$ and $\pi^0 \rightarrow \tilde{\gamma}\tilde{\gamma}$.

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