CP Violation in η decays

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CP are the product of discrete symmetries:

- P or parity transformation left $\longleftrightarrow$ right

- C or charge conjugation particle $\longleftrightarrow$ anti $-$ particle

- CP violation means a physical process is ODD under combined C and P transformation

- Due to general CPT theorem in field thery

$$CP \longleftrightarrow T$$

  where T is time reversal $t \to -t$

Origin of CP violation is one of the deepest question in particle physics. Its study involves

- Particle Physics – full range of techniques from precision atomic physics to high energy colliders

- Cosmology and astrophysics

Current Experimental Staus

- Observed in
  - K decays $K_{0L} \longrightarrow \pi^+\pi^-(2\pi^0)$ First observation made in 1967 and recently direct CP violation is estabished in measurements of $\frac{\epsilon'}{\epsilon}$ at CERN and FNAL
  - B decays $B \longrightarrow \psi K_s$ at KEK and SLAC (2001). This is an asymmetry mesurement

    $$A(t) = \frac{\Gamma(\bar{B}^0 \rightarrow f_{CP}) - \Gamma(B^0 \rightarrow f_{CP})}{\Gamma(\bar{B}^0 \rightarrow f_{CP}) + \Gamma(B^0 \rightarrow f_{CP})}$$

    Oscillation in time is seen.First observation of CP violation outside the K meson system

- Indirectly in the Baryon asymmetry of the universe (BAU)

Fermion content of the SM $(SU(3)_c \times SU(2)_L \times U(1)_Y)$

- **QUARKS**
  There are six quarks (3 colors each)

$$\left(\begin{array}{c} u \\ d \end{array}\right)_L, \left(\begin{array}{c} c \\ s \end{array}\right)_L, \left(\begin{array}{c} t \\ b \end{array}\right)_L ; u_R, c_R, t_R, d_R, s_R, b_R$$

- **Leptons**
  The leptons (color singlets) arranged similarly :

$$\left(\begin{array}{c} \nu_e \\ e \end{array}\right)_L, \left(\begin{array}{c} \nu_\mu \\ \mu \end{array}\right)_L, \left(\begin{array}{c} \nu_\tau \\ \tau \end{array}\right)_L ; e_R, \mu_R, \tau_R; \nu_R(?)$$

  The number of ν_R needed for neutrino masses is not yet clear. It is model dependent.

The weak interactions are transitions bet u-type and d-type quark doublets and the lepton doublets

In the Standard model the weak eigenstates are not the same as the mass eigenstates.

- There is a unitary transformation U relating the two bases.

- For the minimal six quarks model U is a 3×3 matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & a\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- This contains one unique phase : CKM phase η

- $A = .85 \pm .06$, $\lambda = \sin\theta_c = .22$ and $(\rho^2 + \eta^2)^{\frac{1}{2}} = .41 \pm .11$

$$\boxed{\text{CP violation is due to } \eta \neq 0}$$

In the SM, CP violation is a second order weak interaction involving flavor changing neutral current processes such as the decays of K or B mesons

- Main goal of B-factories to pin down value of η and test unitarity of the CKM matrix
- B-Tev measurements of B_s mixing is important
- The rare decay mode $K_{0L} \longrightarrow \pi^0 \nu \bar{\nu}$

The CKM paradigm is consistent with experiments.

But

- Origin is a mystery
- Vaguely connected to generation of fermion masses and the flavor problem
- Does not explain BAU
- Many models beyond the SM have more CP violating phases

Crucial to explore other sources of CP violation

CP Violation in flavor conserving processes

- Extensive searches in electric dipole moments (EDM) of
  1. the electron $d_e < 1.8\times10^{-27}$e.cm (SM $\lesssim 10^{-40}$e.cm)
  2. the neutron $d_n < 6.3\times10^{-26}$e.cm (SM $\lesssim 10^{-31}$e.cm) with large theoretical uncertainties.
  3. atoms such as ^{199}Hg. $|d_{\mathrm{Hg}})| < 2.1 \times 10^{-28}$e.cm Atomic physics uncertainties and interpretation in terms of light quark chromo-EDM and θ_{QCD} become intertwined.

- CP-odd mixing of opposite parity nuclear levels. Limits not as good

$$\boxed{\text{If found} \longrightarrow \text{NEW PHYSICS}}$$

CP violation in η decays

- They are also a flavor conserving processes

- Involving mainly the strange quark in a less ambiguous way

$$\begin{aligned}\eta &\sim \frac{\cos\theta}{\sqrt{6}}\left(u\bar{u}+d\bar{d}-2s\bar{s}\right)-\frac{\sin\theta}{\sqrt{3}}\left(u\bar{u}+d\bar{d}+s\bar{s}\right)\\ &\simeq .58(u\bar{u}+d\bar{d})-.57s\bar{s}\end{aligned}$$

  Depends on the details of $\eta-\eta\prime$ mixing (i.e. value of θ)

- Very complementary to the d_n searches. The hadronic physics involved is different.

- SM predictions are all small as in the EDM

- If found will be signature of physics beyond the SM

- Caveat ::the experiments are hard and theory is still in its infancy

What do we know about CP violation in η decays?

Quantum numbers of the η

$$I^G(J^{PC}) = 0^+(0^{-+})$$

The studies done are

- Limit on the decay rate of

$$\eta \longrightarrow \pi\pi$$

- Longitudinal polarization of muon in

$$\eta \longrightarrow \mu\bar{\mu}$$

- Photon polarization in

$$\eta \longrightarrow \pi^+\pi^-\gamma$$

$$\boxed{\eta \longrightarrow 2\pi}$$

$$\begin{aligned} CP|\pi^+\pi^-\rangle &= C(\pi^+\pi^-)P(\pi^+\pi^-) \\ &= (-1)^{2l} \end{aligned}$$

where l is the orbital angular momentum of the $\pi^+\pi^-$ system and $l = 0$.
Similarly CP of 2 π^0 is also even.

For spin-0 mesons

$$\boxed{\text{Only CP even state can decay into 2 } \pi \text{ 's}}$$

η is CP ODD

- If the decay is observed it must be CP violating.

- Experimentally

$$\begin{aligned} Br(\eta \rightarrow \pi^+\pi^-) &< 3.3 \times 10^{-4} \\ Br(\eta \rightarrow \pi^0\pi^0) &< 4.3 \times 10^{-4} \end{aligned}$$

Expectation from the SM

In the SM there is no flavor conservating neutral current at the tree level. Hence $\eta \to \pi\pi$ must go thru intermediate states invloving kaons

$$\begin{aligned} \eta &\to K^0\bar{K}^0 \to \pi\pi \\ \eta &\to K\pi \to \pi\pi \end{aligned}$$

It must be suppressed *c.f.* to $K_{0L} \to \pi\pi$ by a factor of

$$G_F m_\eta^2 \sin\theta_c$$

Nore accurate estimate by Jarlskog and Shabalin gives

$$\begin{aligned} \Gamma(\eta \to \pi\pi) &= \frac{|g_{\eta\pi\pi}|^2}{16\pi m_\eta}\left(1 - \frac{4m_\pi^2}{m_\eta^2}\right)^{1/2} \\ g_{\eta\pi\pi} &\leq 2 \times 10^{-16} \sin\delta \end{aligned}$$

This gives a branching ratio of $\leq 10^{-27} \sin^2\delta$. Too small to be observed any time soon

Muon Polarization in $\eta \to \mu\bar{\mu}$

- The CP of a $f\bar{f}$ pair is given by

$$\begin{aligned} CP(f\bar{f}) &= (-1)^{l+s}(-1)^{l+1} \\ &= (-1)^{s+1} \end{aligned}$$

  - $\mu\bar{\mu}$ in a $^1S_0$ state $\to CP = -1$ and $P = -1$

    $\boxed{\text{Amplitude: Parity } \surd \text{ if CP } \surd}$

  - $\mu\bar{\mu}$ in a $^3P_0$ state $\to CP = 1$ and $P = 1$

    $\boxed{\text{Amplitude: Parity } \times \text{ if CP } \times}$

- If one measures a longitudinal polarization of the muon define by

$$\mathcal{P}_l \equiv \frac{N_R - N_L}{N_R + N_L}$$

where $N_R(N_L)$ is the number of muon with right(left)-handed helicity it will be a signature of CP violation

A little more formalism

- The general form of the matrix element for the decay is

$$M = a\bar{u}i\gamma_5 v + b\bar{u}v$$

where $a$and$b$ are complex numbers.

- The polarization is

$$\mathcal{P}_l = \frac{m_\eta \beta^2 Im(ba^*)}{4\pi\Gamma}$$

where Γ is the width and $\beta^2 = (1 - 4m_\mu^2/m_\eta^2)$

- To get non-vanishing $\mathcal{P}_l$ we must have effective scalar and pseudoscalar interference plus a non-trivial relative phase bet a and b.

- The dominant contribution to $Im\ a$ comes from the two photon intermediate state. b will be induced by weak interactions (possibily new physics).

- For the SM it is very small since there is no psuedoscalar. Need 2-loops or higher order effect

$\boxed{\text{Some new physics that can give rise } \mathcal{P}_l}$

- Mulitple Higgs
- Some version of Supersymmetric SM
- R parity violating SUSY models
- Leptoquark models

$$\boxed{\eta(p) \longrightarrow \pi^{+}(p_{+})\, \pi^{-}(p_{-})\, \gamma(k,\epsilon)}$$

work done with
C.Q. Geng and T.H. Wu

This decay is interesting to study because

- Relatively large branching ratio of 4.75×10^{-2}
- Final states are relatively easy to detect
- Needs to measure photon polarization to discern T-odd effect
- New way of studying flavor conserving CP violation

The general amplitude is given by

$$\mathcal{M} = \frac{i}{m_\eta^3}\left(-M\epsilon_{\mu\nu\rho\lambda}p_+^\mu p_-^\nu k^\rho \epsilon^\lambda + E[(\epsilon\cdot p_+)(k\cdot p_-) - (\epsilon\cdot p_-)(k\cdot p_+)]\right)$$

where M, E denote magnetic and electric transitions.
In the η rest frame choose the decay to be in the $x - z$ plane, then

$$\mathcal{M} = \frac{i}{m_\eta^2}E_\gamma\left[M\vec{k}\cdot(\vec{\epsilon}\times\vec{p}_+) - E(\vec{\epsilon}\cdot\vec{p}_+)\right]$$

	C	P	CP
M	+	-	-
E	+	+	+

Keep only order (momentum)^3 terms

$$
\begin{aligned}
|\mathcal{M}|^2 &= m_\eta^{-4} E_\gamma^2 \left\{ |M|^2 |\hat{k}\cdot(\vec{\epsilon}\times\vec{p}_+)|^2 + |E|^2 |\vec{\epsilon}\cdot\vec{p}_+|^2 + \right. \\
&\left. E^* M [\hat{k}\cdot(\vec{p}_+\times\vec{\epsilon})]\,(\vec{\epsilon}\cdot\vec{p}_+)^* + M^* E [\hat{k}\cdot(\vec{p}_+\times\vec{\epsilon})]^*\,(\vec{\epsilon}\cdot\vec{p}_+) \right\}
\end{aligned}
$$

Notice

- The triple correlation $\hat{k}\cdot(\vec{p}_+\times\vec{\epsilon})$ is odd under **T**(time reversal)

- Requires interference of M and E relatively complex.

- Requires measuring ϵ

Integrating over the photon gives

$$
\frac{d\Gamma}{dE_+ dE_-} = \frac{1}{256\pi^3 m_\eta} \sum_{\text{spin}} |\mathcal{M}|^2 \propto |M|^2 + |E|^2
$$

Information on CP violation is loss with ϵ summed over.

The rate is dominated by M

$\boxed{M \text{ is well described by resonance + box anomaly}}$

For chiralperturbation models M is given by *

$$M = M^{+}(s) \;\simeq\; -\frac{e m_\eta^3}{4\pi^2 f_\pi^3} \times \frac{\sqrt{3}}{6}\left(1 - \frac{3m_\rho^2}{m_\rho^2 - s}\right)$$

where $f_\pi = 93\ MeV$ and $m_\rho = 770\ MeV$.

*See review B.Holstein hepph/0112150

Theoretical Expectations of E

- It can first go thru $\pi^+\pi^-$ and the photon is emitted from one the pions.
  If so this contribution is very small
  - From experimental limit
  $$|g_{\eta\pi\pi}| \leq 5 \times 10^{-11}\text{GeV}$$

- The photon can be directly emitted from the $\eta\pi\pi$ vertex i.e. structure dependent part

$$\boxed{\textbf{Not Constrained by } \eta \to \pi\pi}$$

- One such structure is
  $$\mathcal{O} = \frac{G}{m_\eta^2}[\bar{s}i\sigma^{\mu\nu}\gamma_5(p-k)^\nu s\bar{u}\gamma^\mu u]$$
  where G is unknown constant given by new physics.

- To calculate the contributio of $\mathcal{O}$ need model of hadron physics.
  Use factorization,i.e.

  $$< \eta|\mathcal{O}|\pi^+\pi^-\gamma > \sim \frac{1}{m_\eta^3} G < \eta|\bar{s}i\sigma_{\mu\nu}\gamma_5(p-k)^\nu s|\gamma >< 0|\bar{u}\gamma^\mu u|\pi^+\pi^- >$$

  and define the $\eta \to \gamma$ transition form factor F via

  $$< \eta|\bar{s}i\sigma_{\mu\nu}\gamma_5(p-k)^\nu s|\gamma >= ie\left[\epsilon_\mu(k\cdot p) - (\epsilon_\mu \cdot p)k_\mu\right]\frac{F(s)}{m_\eta}$$

- F can be estimated by QCD models. We use light-front quark model and get $F(0) \sim 0.19$

$$E \sim 2eF(s)G$$

$\boxed{\text{Any model independent constraints on G?}}$

Basically None

- Does not contribute to $\eta \to \pi\pi$
- Does not contribute to d_n
  although is looks similar to strange quark dipole moment.

In principle $G \sim O(1)$ is allowed.

Conclusions

CP violation exp in η decays is very a unique probe of new physics

- It probes flavor conserving sector which to date only one limit is provided by d_n
- Very complementary to d_n as shown by photon polarization studies in $\eta \to \pi\pi\gamma$
- The study of four-quark operators is very interesting in hadron physics
- New physics models for $\mathcal{O}$ is needed. Similarly for $\eta \to \pi\pi$ and $\eta \to \mu\bar{\mu}$
- New intense sources of $\eta \longrightarrow$ a new tool to unravel the deep mystery of CP violation