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TAU DECAYS INVOLVING THE ETA MESON*

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ABSTRACT

The decays of the tau lepton which involve the eta meson are examined within the standard model. Such modes are prime candidates to comprise the approximately 7% of tau decays (with a one-prong topology) that are not assignable to known exclusive channels. It is shown that the combination of existing electron-positron annihilation data and measurements of five-prong tau decays prevents modes involving the eta from contributing more than 2% to one-prong tau decays.

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As now known, the properties of the tau lepton and the tau neutrino are generally in excellent accord with those expected in the standard model for the third generation charged and neutral leptons, respectively. The decays $\tau \rightarrow \nu_\tau e \bar{\nu}_e$, $\tau \rightarrow \nu_\tau \mu \bar{\nu}_\mu$, $\tau \rightarrow \nu_\tau \pi$, $\tau \rightarrow \nu_\tau 2\pi$, $\tau \rightarrow \nu_\tau 3\pi$, and $\tau \rightarrow \nu_\tau 4\pi$, occur[1] at the expected rates and account for almost 90% of tau decays.

However, there is a nagging problem in accounting for all tau decays.[2] It shows up in doing the bookkeeping for the sum of the exclusive modes that result in one charged prong and comparing the result with the corresponding inclusive topological branching ratio[1] of $86.3 \pm 0.3\%$. Taking all the modes listed above plus Cabibbo-suppressed modes into account, there remains about 7% of tau decays that are not assignable to known exclusive channels.

The least disturbing explanation for this discrepancy, that the measurements of the major one-prong exclusive channels needed to be scaled up, became less likely as new and more accurate measurements became available.[3] By the time of the Kyoto Conference in 1985, the World-average branching ratios had significantly reduced errors and the discrepancy remained.[4]

However, data published in the past year seemed to point toward a resolution of the problem in a still relatively conventional manner through decays of the tau involving eta mesons. The MarkII[5] and TPC[6] collaborations each used slightly different tagging techniques and, constraining the sum of all the branching fractions to be unity, found that tau decays into a neutrino, charged pion, and two or more neutral hadrons were well in excess of the theoretical expectations[2] for the sum of just $\tau^- \rightarrow \nu_\tau \pi^- 2\pi^0$ and $\tau^- \rightarrow \nu_\tau \pi^- 3\pi^0$. As other modes involving only pions and kaons had been shown to make very small contributions to the one-prong plus multi-neutrals topology,[2] by process of elimination decays involving the eta meson in the "multi-neutrals" became prime suspects.[7]

The finger was put more directly on the eta by the Crystal Ball[8] and the HRS[9] collaborations, who both claimed evidence for an eta signal in tau decays, with HRS reporting a branching fraction for $\tau^- \rightarrow \nu_\tau \pi^- \eta ...$ of $5.0 \pm 1.0 \pm 1.5\%$.

Thus, by the Berkeley Conference the discrepancy seemed to be moving toward a resolution in terms of tau decays to an eta meson.[1][10]

Even though no one expected such large branching ratios involving the eta, everything seemed to be quieting down to a quite conventional result. Now, the situation has come alive again with the HRS collaboration claiming that the decays involving the eta occur in exactly the mode, $\tau^- \rightarrow \nu_\tau \pi^- \eta$, that is not expected in the standard model.[11] It seems likely that several other experiments should be able to substantiate or refute this claim in the near future.

With this in mind, we ask and answer here a related question which antedates the HRS result: Could we have in fact solved the missing one-prong problem with decay modes including etas, *i.e.*, how big could tau decays that result in an eta be within the standard model?

We examine the situation mode by mode.

- $\tau \rightarrow \nu_\tau \eta \pi$

As the eta and pi are pseudoscalars, this decay must proceed through the hadronic vector current. This is characterized by even G-parity (like the ρ meson) while the $\eta\pi$ system is G odd, so we have by definition a process that involves a second class current. Within the standard model this should happen at a level of roughly α^2 in the rate when compared to processes arising through the usual first class currents. Thus, in the standard model such a decay is completely negligible.[12]

- $\tau \rightarrow \nu_\tau \eta 2\pi$

By comparison with the previous case we have added another pion, making the hadronic final state G even and perfectly allowed to occur through the action of the vector current. The only question is the rate. Here we may use the fact that the vector current in strangeness non-changing weak processes is an isospin rotation of the isovector part of the (vector) current of electromagnetism (*i.e.*, CVC). There is consequentially a relation between the tau decay rate and an integral over electron-positron annihilation cross sections for production of the corresponding hadronic final states. In this case the relation is:

$$\frac{\Gamma(\tau^- \to \nu_\tau \eta \pi^- \pi^0)}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} =$$

$$\cos^2\theta_c \, \frac{3}{2\pi\alpha^2 m_\tau^8} \int_0^{m_\tau^2} dQ^2 Q^2 (m_\tau^2 - Q^2)^2 (m_\tau^2 + 2Q^2) \sigma_{e^+e^- \to \eta\pi^+\pi^-}(Q^2), \tag{1}$$

or

$$\frac{\Gamma(\tau^- \to \nu_\tau \eta \pi^- \pi^0)}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = 2\cos^2\theta_c \int_0^1 dx (1-x)^2 (1+2x) \frac{\sigma_{e^+e^- \to \eta\pi^+\pi^-}}{\sigma_{pt}}, \tag{2}$$

in terms of the scaled variable $x = Q^2/m_\tau^2$ and the point cross section, $\sigma_{pt}(Q^2) = 4\pi\alpha^2/3Q^2$.

Only within the past year have data for $\sigma_{e^+e^- \to \eta\pi^+\pi^-}$ been published which cover the full energy region[13] needed for performing the integral in Eq. (1). The data from Novosibirsk[14] for center-of-mass energies of 1.05 to 1.4 GeV show a cross section consistent with zero (and an upper bound of ~ 0.5 nb) up to 1.35 GeV; they join on to the data from DCI[15] which indicate a broad maximum of the cross section[16] in the 1.5 to 1.6 GeV region of a few nanobarns. Carrying out the integral in Eq. (1) gives a branching ratio for $\tau^- \to \nu_\tau \eta \pi^- \pi^0$ of 0.15%. Even taking 5 nb as a generous upper limit on the $e^+e^- \to \eta\pi^+\pi^-$ cross section above 1.4 GeV produces an upper limit of 0.24%. This is not the place to find several percent of tau decays if the electron-positron cross sections are right.

- $\tau \to \nu_\tau \eta 3\pi$

Although this mode proceeds through the axial-vector current and we can no longer relate it to electron-positron annihilation, we can bound such modes in a different manner by using the paucity of five-prong tau decays.[17] From the fact that the final hadrons are in a state with I = 1, we have:

$$\Gamma(\tau^- \rightarrow \nu_\tau \eta 2\pi^- \pi^+) \geq \Gamma(\tau \rightarrow \nu_\tau \eta \pi^- 2\pi^0). \quad (3)$$

The process on the left-hand side leads to five prong tau decays through the 29% of η decays that yield two charged pions plus neutrals. Using 8×10^{-4} as an upper limit on five-prong tau decays with additional neutrals,[1] the upper limit on the branching ratio for the one-prong mode $\tau \rightarrow \nu_\tau \eta \pi^- 2\pi^0$ is 0.3%.

- $\tau \rightarrow \nu_\tau \eta\eta\pi$ and $\tau \rightarrow \eta\eta\pi\pi$

We can similarly bound these branching ratios, but have to rely on the case where both η decays involve charged particles to produce a five-prong tau decay. The upper bound on their combined branching ratio of 1.0% to produce one-prong decays is correspondingly weaker.[18]

Conclusion

We have essentially run out of phase space for tau decays with the above modes. Their sum is less than 2%. Within the standard model, the "missing" exclusive modes have to come from somewhere else.

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13. I thank Jim Smith for calling my attention to the most recent data.

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16. Strictly speaking this is the cross section with a ρ mass cut, but since the $\pi^+\pi^-\eta$ final state has to be isovector, the two pions must have total I = 1 and odd relative angular momentum, making the ρ mass region a likely place for the dipion invariant mass to be found.

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18. As in Ref. 10, we have taken a factor of two drop in relative efficiency for the five-prong topology coming from $\eta\eta\ \pi^-(\pi^0)$. Only $(0.71)^2$ of all $\tau \rightarrow \nu_\tau\eta\eta\pi$ and $\tau \rightarrow \nu_\tau\eta\eta\pi\pi$ decays give the one-prong topology.