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Decay $\eta \rightarrow \pi l \nu$ reexamined

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Limits on the branching ratio for the decay $\eta \rightarrow \pi l \nu$ are interpreted as a tool for the search for second-class vector currents.

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As long as 27 years ago, Singer [1] published a paper on weak-interaction decays of the η meson in which he pointed out "that the *primitive* weak interaction responsible for $\eta \rightarrow \pi l \nu$ is *purely of second class* with a *vector-type* coupling". (For a definition of second-class currents, see, for example, Ref. [2].) Thus this decay is of fundamental interest, for it provides a "possible unambiguous test for this type of current."

However, the branching ratio for this decay would be of the order of 10^{-9} or less even for a (unknown) weak process similar to K_{l3} decay. A process mediated by a second-class vector current is, in addition, suppressed by a factor of $(m_l/M_\eta)^2$ due to helicity conservation. Therefore, the case was soon closed and forgotten. It was remembered and reopened as a possible solution to the small but persistent discrepancy [3] of the sum of exclusive versus inclusive one-charged-prong decay modes of the τ lepton [4]. But two of the present authors pointed out that this does not provide good limits for second-class current couplings either [5].

Interest in rare η decays was revived when a facility dedicated to the production of η mesons was installed at the Saturne synchrotron at Saclay [6]. Apart from improving the measurement of $\eta \rightarrow \mu^+\mu^-$ [7], this facility could observe the decay

$$\eta \rightarrow \pi^+ + e^- + \overset{(-)}{\nu}_l , \quad l = e, \mu \tag{1}$$

down to a level [8] of 10^{-10} to 10^{-11}. Since the neutrino is unobserved, it can be either a $\bar{\nu}_e$ (corresponding to a second-class vector current) or any other kind of ν or $\bar{\nu}$, i.e., μ or τ like (corresponding to a flavor-changing lepton current). The latter gives a limit on mass/(coupling constant) for leptoquarks and/or horizontal Higgs bosons [9].

From the point of view of gauge theories (or even the standard theory), second-class vector currents are admittedly quite horrible. However, it is a matter of taste whether they are considered more exotic than leptoquarks or horizontal Higgs bosons. Therefore we shall give limits for the coupling of second-class vector currents related to the above-mentioned possible experimental limits. The model we choose for this purpose is the static quark model, which has proven to be a good tool in phenomenology despite its rather crude approximation [10].

In obvious notation, the relevant second-class vector current j^μ on the quark level is

$$j^\mu = \partial^\mu (\bar{u} d) . \tag{2}$$

Assuming equal (constituent) quark masses $m_u = m_d = m$ and parametrizing the hadronic matrix element of the current j^μ between η and π states in terms of a (single) form factor $f(q^2)$,

$$\langle \pi^+(\mathbf{Q}) | j^\mu(x) | \eta(\mathbf{P}) \rangle = \frac{1}{(2\pi)^3} i q^\mu f(q^2) e^{iqx} , \tag{3}$$

where q denotes the four-momentum transfer $q \equiv Q - P$, the form factor $f(q^2)$ is given in terms of the Schrödinger wave functions in momentum space of η and π mesons, f_η and f_π, respectively, by

$$\begin{aligned} f(q^2) = \frac{1}{\sqrt{2}} \int d^3p\, f_\pi^*(\tfrac{1}{2}\mathbf{Q} + \mathbf{p} - \mathbf{P}) f_\eta(\mathbf{p} - \tfrac{1}{2}\mathbf{P}) \\ \times \left[\frac{(E_\mathbf{p} + m)(E_\mathbf{K} + m)}{E_\mathbf{p} E_\mathbf{K}} \right]^{1/2} \\ \times \left[1 - \frac{\mathbf{p} \cdot \mathbf{K}}{(E_\mathbf{p} + m)(E_\mathbf{K} + m)} \right] , \end{aligned} \tag{4}$$

with the shorthand notation

$$E_\mathbf{p} \equiv \sqrt{\mathbf{p}^2 + m^2}, \quad \mathbf{K} \equiv \mathbf{Q} + \mathbf{p} - \mathbf{P} .$$

If the current (2) is coupled to the usual leptonic current l_μ with strength G_2,

TABLE I. Limits for the second-class vector current coupling G_2 versus the Fermi coupling G for various precisions in the (measured) branching ratio of process (1).

$B(\eta \rightarrow \pi^+ l^- \bar{\nu}_l)$	$G_2 M_\eta / G$ $l = e$	$l = \mu$
10^{-9}	5×10^4	2.9×10^2
10^{-10}	1.6×10^4	91
10^{-11}	5×10^3	29
10^{-12}	1.6×10^3	9.1

$$\mathcal{L}_{\text{int}}^{\text{SC}}=iG_2 j^{\mu} l_{\mu}+\text{H.c.} \ , \tag{5}$$

the decay widths for the processes $\eta \rightarrow \pi^+ + l^- + \bar{\nu}_l$, with $l = e$ or μ, are given by

$$\Gamma(\eta \rightarrow \pi^+ + e^- + \bar{\nu}_e) = 2.77\times 10^{-4} G_2^2 M_{\eta}^4 M_{\pi} m_e^2 \ , \tag{6}$$

$$\Gamma(\eta \rightarrow \pi^+ + \mu^- + \bar{\nu}_\mu) = 2.00\times 10^{-4} G_2^2 M_{\eta}^4 M_{\pi} m_\mu^2 \ . \tag{7}$$

Accordingly, by measuring process (1), the coupling G_2 can be limited as is shown in Table I.

It should be restressed that the decay (1) provides a unique opportunity to look at (and rule out empirically) second-class vector currents. Within the standard model, such a process can be induced by higher-order interactions; since it must contain the mass difference $m_u - m_d$ in the amplitude in addition to all other suppression factors around, it is beyond reach of present experiments. Therefore, observation of process (1) at the level of 10^{-11} would uniquely point at new physics.

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