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ABSTRACT

After briefly reviewing the status of recent experiments looking for the fifth force in ordinary matter, we discuss two classes of experiments sensitive to the presence of a coupling of kaons to the fifth force. These are attempts to detect hyperphotons (γ_Y) in the decay $K_L \to \pi^+\pi^-\gamma_Y$, and searches for an energy-dependence of the $K^0 - \overline{K}^0$ parameters.

The original suggestion of a possible fifth force in Nature[1] focussed attention on apparent experimental anomalies in three systems: *i*) The geophysical data of Stacey, *et al.*,[2] *ii*) the original Eötvös experiment,[3] and *iii*) the $K^0 - \overline{K}^0$ system.[4] Subsequent experimental work has concentrated most heavily on geophysical searches for non-Newtonian gravity,[5–8] and on variants of the Eötvös experiment.[9–16] However, kaon experiments currently underway may open new possibilities to search for manifestations of the fifth force. In what follows we summarize some recent work in two areas: 1) The possibility of detecting hyperphotons in the decays $K_L \to \pi\pi\gamma_Y$, where the hyperphoton (γ_Y) is the presumed quantum of the fifth force field, and 2) effects of an external fifth force field on the fundamental parameters of the $K^0 - \overline{K}^0$ system.

To place the ongoing kaon work in context we briefly review the conventional description of the fifth force. Let $V(r)$ denote the potential energy for two masses m_1 and m_2 separated by a distance r:

$$V(r) = -G_\infty \frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right) \equiv V_N(r) + V_5(r). \tag{1}$$

Here $V_N(r)$ is the usual Newtonian potential, $V_5(r)$ is the fifth force contribution, α is the strength of the fifth force coupling relative to gravity, and λ is its range. When $r/\lambda \gg 1$, the Newtonian potential is recovered, with G_∞ being the Newtonian gravitational constant. For $r/\lambda \ll 1$ (which for $\lambda \cong 100\,\mathrm{m}$ would describe laboratory experiments), the Newtonian potential is again recovered, but with a different gravitational constant $G_\infty(1+\alpha) \equiv G_0$. Observing a difference between G_∞ and G_0, or a variation of the strength of the gravitational coupling for intermediate values of r, would be evidence for the presence of $V_5(r)$ in (1).

Another manifestation of V_5 arises from the circumstance that α in (1) is not a universal constant, but depends weakly on the compositions of objects 1 and 2. For example, if V_5 arises from a coupling to baryon number B then

$$\alpha \longrightarrow \alpha_{12} = -\left(\frac{B_1}{\mu_1}\right)\left(\frac{B_2}{\mu_2}\right)\frac{f^2}{G_\infty m_{\rm H}^2} \equiv -\left(\frac{B_1}{\mu_1}\right)\left(\frac{B_2}{\mu_2}\right)\xi, \qquad (2)$$

where $\mu_{1,2}$ are the masses of objects 1 and 2 in units of $m_{\rm H} = m({}_1H^1)$, and f is the analog for the fifth force of the electric charge e. From the data of Stacey, *et al.*,[2] we can infer that $f^2/e^2 \cong 8 \times 10^{-39}$, and $\xi \cong 10^{-2}$. Since α_{12} is in general different for different pairs of materials, the accelerations of two objects towards a common source (*e.g.*, the Earth) will depend on their compositions. The original Eötvös experiment was designed to look for just such an effect, and the indication[1] of a nonzero signal in the Eötvös data has sparked renewed interest in the related questions of non-Newtonian gravity and new forces. To date a number of experiments have reported deviations from the predictions of Newtonian gravity which would be consistent with a variation of the gravitational constant with r. Some experiments have also reported evidence for a composition-dependence of the acceleration, although other similar experiments see no such effect. It is not clear at present what the origin is of the apparent differences in results obtained by seemingly similar experiments. A detailed review of the present experimental situation is given in Ref. 17.

We turn next to the question of whether the fifth force quantum γ_Y can be detected experimentally. Following an argument due to Weinberg,[18] it was noted in Ref. 1 that γ_Y could show up in the decays $K^0 \rightarrow \pi\pi\gamma_Y$ at an experimentally interesting level, provided that γ_Y were a *vector* particle which coupled to the nonconserved hypercharge current. The hypercharge Y is given by $Y = B + S$ where S is strangeness, and hence for ordinary matter (for which $S = 0$) a coupling to Y is the same as a coupling to B. However, a coupling to Y (or to some other linear combination of B and S) allows the fifth force to also interact with kaons, as will any interaction which couples differently to d and s quarks. Evidently a coupling of this sort must be assumed if we are to attribute the apparent anomalies in the $\mathrm{K}^0 - \overline{\mathrm{K}}^0$ parameters[4] to the fifth force. It should be emphasized that if γ_Y is a *scalar* field, then even if it couples to hypercharge, the decay rate into γ_Y will be too small to be detected. The suggestion in Ref. 1 that $\Gamma(K^0 \rightarrow \pi\pi\gamma_Y)$ could be large enough to be seen experimentally was followed by a number of papers[19-22] which considered the decay modes $K^\pm \rightarrow \pi^\pm\gamma_Y$ and also[20] $K^0_{L,S} \rightarrow \pi^0\gamma_Y$. It was noted by the authors of Refs. 19-22 that in $K \rightarrow \pi\gamma_Y$ the analogous decays $K \rightarrow \pi\gamma$ are strictly forbidden by gauge invariance or angular momentum conservation, which thus eliminates an important background from electromagnetic decays. Moreover, existing experimental limits[23] from $K^+ \rightarrow \pi^+ +$ *missing neutrals* implied limits on the γ_Y coupling strength and mass, when combined with theoretical models of the weak decay amplitude.

Although $K^+ \rightarrow \pi^+\gamma_Y$ is an ideal channel in which to look for γ_Y experimentally, it may not be ideal from the point of view of extracting information on γ_Y. This is reflected by the wide range of values quoted for f^2/m_Y^2 by various authors, all of whom start from the same experimental result of Asano, *et* *al.*[23] In a recent summary of the existing calculations, Aronson, *et al.*,[24] note that the values of f^2/m_Y^2 inferred by different authors differ by roughly a factor of 70. The differences among the various calculations arise from two sources: a) The off-shell mass extrapolations used to relate the weak amplitude $\langle \pi^+ | H_W | K^+ \rangle$ to $\Gamma(K_S \to \pi^+\pi^-)$, and b) non-pole contributions to the $K^+ \to \pi^+\gamma_Y$ amplitude. We will discuss elsewhere the problem of bringing the calculations of $\Gamma(K^+ \to \pi^+\gamma_Y)$ into agreement, and confine the present discussion to a demonstration that by an appropriate choice of decay modes, both of these theoretical uncertainties can be substantially reduced.

Consider, for example, the decays $K_L \to \pi^+\pi^-\gamma_Y$ and $K_S \to \pi^+\pi^-\gamma_Y$, which are closely related to the decay $\bar{K}^0 \to \pi^+\pi^-\gamma_Y$ considered in Refs. 1 and 18. We show in more detail elsewhere[25] that $\Gamma(K_L \to \pi^+\pi^-\gamma_Y)$ depends on the weak amplitude $W(K_S(\ell) \to \pi^+(p_1)\pi^-(p_2); z) \equiv W(z)$, where $z = -\ell^2/m_K^2$, and this is closely tied to $\Gamma(K_S \to \pi^+\pi^-)$. As a result $\Gamma(K_L \to \pi^+\pi^-\gamma_Y)$ is relatively insensitive to models for $W(z)$ and this is reflected by the expression for the dominant pole contribution to the decay rate:

$$\Gamma(K_L \to \pi^+\pi^-\gamma_Y) = \frac{\Gamma(K_S \to \pi^+\pi^-)}{32\pi^2(1 - z_{\rm min})^{1/2}} \left(\frac{\bar{f}^2 m_K^2}{m_Y^2} \right) \times \int_{z_{\rm min}}^{1} dz \left(1 - \frac{z_{\rm min}}{z} \right)^{1/2} (1 - z) \frac{|W(z)|^2}{|W(1)|^2}, \qquad (3)$$

where $\bar{f}^2 = 4\pi f^2$, and $z_{\rm min} = 4m_\pi^2/m_K^2 \cong 0.3146$. We have examined a number of models of $W(z)$ and shown that for these models $\int dz$ varies by less than 30%. Even the extreme (and unrealistic) model in which $W(z)$ is a constant, leads to a value for Γ which differs from more realistic models by only a factor of ~ 4. This compares with a factor of ~ 70 for $\Gamma(K^+ \to \pi^+\gamma_Y)$, and clearly underscores the advantage of studying $K_L \to \pi\pi\gamma_Y$.

It might be thought that the theoretical advantage in studying the $\pi\pi\gamma_Y$ decay mode would be offset from an experimental point of view by the disadvantage of having to deal with the background arising from $K_L \to \pi\pi\gamma$. Happily this may turn out not to be the case: It can be shown that the pole contributions to $K_S \to \pi^+\pi^-\gamma_Y$ and $K_L \to \pi^+\pi^-\gamma$ are CP-suppressed, whereas $K_L \to \pi^+\pi^-\gamma_Y$ is not. It follows that the branching ratio $\Gamma(K_L \to \pi^+\pi^-\gamma_Y)/\Gamma(K_L \to \pi^+\pi^-\gamma)$ can be quite large, and in fact is of order unity for the nominal values of the fifth force parameters in Ref. 20. Using the values[20]

$$\bar{f}^2/\bar{e}^2 \approx 8 \times 10^{-39}, \qquad \frac{\bar{e}^2}{4\pi} \cong \frac{1}{137}, \qquad m_Y \approx \frac{1}{200\,\mathrm{m}} = 0.985 \times 10^{-9}\,\mathrm{eV}, \qquad (4)$$

and a simple model[25] for $W(z)$ we find from Eq. (3),

$$\frac{\Gamma(K_L \to \pi^+\pi^-\gamma_Y)}{\Gamma(K_L \to \pi^+\pi^-\gamma)} = 0.59, \qquad (5)$$

and

$$\frac{\Gamma(K_L \to \pi^+\pi^-\gamma_Y)}{\Gamma(K_L \to all)} = 2.6 \times 10^{-5}. \qquad (6)$$

In arriving at the results in (5) and (6) we have included only contributions from pole diagrams in the γ_Y amplitude. However, we will show elsewhere[25] that our results are not substantially changed when non-pole contributions are included.

From an experimental point of view, the branching ratio in (6) is sufficiently large that we would expect substantial numbers of γ_Y events in ongoing experiments, assuming the values of the γ_Y parameters as given in (4). For example, experiment E-731 at Fermilab[26] has several thousand candidates for $K_L \to \pi^+\pi^-\gamma$, and hence we could anticipate setting a stringent limit on f^2/m_Y^2 from this decay. Since γ_Y cannot be directly observed in a detector,[20] these decays would show up as $K_L \to \pi^+\pi^-$ events, where the effective mass of the $\pi^+\pi^-$ system would be less than m_K. Evidently such events can be confused with backgrounds from $K_L \to \pi^+\pi^-\gamma$ (where the γ is not detected), and $K_L \to \pi^\mp\ell^\pm\nu$ (where the $\ell^\pm$ is misidentified as $\pi^\pm$). However these and other similar backgrounds are well understood, and prospects for obtaining new and useful limits on f^2/m_Y^2 from these decays seem quite promising.[25]

Finally we briefly review recent work[27] aimed at understanding how an external field which couples to kaons can produce an energy-dependence of the $\mathrm{K}^0 - \overline{\mathrm{K}}^0$ parameters. Although the effects reported in Ref. 4 have not been confirmed by subsequent experiments,[28,29] the latter results are not necessarily in conflict with the previous one, as we discuss in Ref. 24. We also show in Ref. 24 that irrespective of the details of the experiment, the phase $\phi_\pm$ of the CP-violating parameter $\eta_\pm$ should be a decreasing function of laboratory energy at sufficiently high energies. The same is not true for the other parameters of the $\mathrm{K}^0 - \overline{\mathrm{K}}^0$ system, such as $|\eta_\pm|$, the K_S lifetime τ_S, and the $K_L - K_S$ mass difference Δm. For these parameters any energy-dependence can look quite different in different experiments. These and other related questions will be discussed in more detail elsewhere.

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