Experimental Signals for Hyperphotons

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We discuss experiments for detecting hyperphotons (γ_Y), which are the real quanta of a hypercharge field whose existence has been suggested by a recent reanalysis of the Eötvös experiment. It is shown that γ_Y is best detected as an unobserved neutral in the decays $K^\pm \to \pi^\pm \gamma_Y$ and $K_S^0 \to \pi^0 \gamma_Y$, and that existing experimental limits provide nontrivial constraints on the strength and range of possible hypercharge couplings.

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A recent reanalysis[1] of the Eötvös experiment[2] has uncovered evidence for the existence of a new intermediate-range force coupling to baryon number or hypercharge. The work in Ref. 1 was motivated by earlier work on the K^0-$\bar{K}^0$ system,[3] and by persistent discrepancies between the laboratory value of the Newtonian gravitational constant (G_0) and that obtained from geophysical measurements.[4] Similarities in the strength of the forces needed to account for the K^0-$\bar{K}^0$, geophysical, and Eötvös data suggest that these effects could have a common origin in some new intermediate-range interaction. If this is in fact the case, then a direct observation of the quantum mediating this interaction, the hyperphoton (γ_Y), would be of great importance. The object of the present paper is to describe how hyperphotons might be observed experimentally, and to point out that existing limits on the production of unobserved neutrals in $\Delta S = 1$ decays place stringent constraints on possible hypercharge couplings.

The analysis of methods for detecting hyperphotons depends crucially on the assumption that they are massive vector particles. A vector interaction is the natural choice to account for the geophysical evidence that the new interaction is *repulsive,* as demanded by the observation that G_0 is *smaller* than the geophysical value G_1. The γ_Y mass m_Y is then given by $m_Y = \lambda^{-1}$, where λ can be determined from the geophysical data. The value of λ quoted in Ref. 1 was 200 ± 50 m, which corresponds to $m_Y \cong 1 \times 10^{-9}$ eV. However, a subsequent reexamination of the geophysical data by Stacey[5] indicates that the uncertainty in λ is probably much greater than the quoted error would imply, and hence for present purposes we will simply assume that m_Y is small. By contrast, the strength of the postulated new interaction is more firmly established: If we write the potential energy for two masses $m_{1,2}$ separated by a distance r in the form[1]

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

where $V_N(r)$ is the usual Newtonian contribution and G_∞ is the gravitational constant for $r \to \infty$, then α is given by[4,5]

$$\alpha \cong -(1.0 \pm 0.4) \times 10^{-2}. \tag{2}$$

α is related to the hypercharge coupling f by

$$f^2/G_0 m_p^2 \cong -\alpha/(1+\alpha), \tag{3}$$

where m_p is the proton mass. From (2) and (3) it follows that the hypercharge coupling is even weaker than gravity. In terms of the electric charge e, where $e^2 \cong \hbar c/137$, f^2 is given by

$$f^2/e^2 \cong (8 \pm 3) \times 10^{-39}, \tag{4}$$

a result that will be useful in the ensuing discussion.

Despite the weakness of the hypercharge coupling, branching ratios for decays into hyperphotons can become quite large, as was first noted by Weinberg[6] for $K^0 \to \pi\pi\gamma_Y$. The practical difficulty with looking for this particular decay is that it can easily be confused with the competing and much stronger mode $K^0 \to \pi\pi\gamma$, unless the detection efficiency for photons is near 100%. To avoid the problem of distinguishing between γ_Y and an unobserved γ we consider the modes

$$K^\pm \to \pi^\pm \gamma_Y, \quad K_S^0 \to \pi^0 \gamma_Y. \tag{5}$$

The corresponding decays into ordinary photons are strictly forbidden by angular momentum conservation,[7] since the spin of a massless photon is necessarily perpendicular to the γ-π orbital angular momentum. By contrast, the γ_Y, because it is massive, has an additional ($S_z=0$) spin degree of freedom through which the $K\to\pi\gamma_Y$ decays can proceed. To calculate the branching ratio for these modes we consider the diagrams in Fig. 1. The coupling constant f is given by (4), and $a(K^0-\pi^0)$ can be obtained via current algebra from the decay $K_S^0\to\pi^0\pi^0$. If we define

$$\langle\pi^0(p_1)|H_w|K^0(k)\rangle=(2\pi)^{-3}(4p_{10}k_0)^{-1/2}a(K^0-\pi^0), \tag{6}$$

$$\langle\pi^0(p_1)\pi^0(p_2)|H_w|K_S^0(k)\rangle=i(2\pi)^{-9/2}(8p_{10}p_{20}k_0)^{-1/2}a(K_S^0\to\pi^0\pi^0), \tag{7}$$

then[8]

$$a(K^0-\pi^0)=-\sqrt{2}f_\pi[2(m_K^2-m_\pi^2)/\kappa^2]^{-1}a(K_S\to\pi^0\pi^0), \tag{8}$$

where $f_\pi=130$ MeV is the pion decay constant. κ denotes the common four-momentum of the K and π, which we take to be the pion momentum p. $a(K_S\to\pi^0\pi^0)$ is related in turn to $\Gamma(K_S\to\pi^0\pi^0)$ via

$$\Gamma(K_S\to\pi^0\pi^0)=(|\mathbf{p}|/8\pi m_K^2)|a(K_S\to\pi^0\pi^0)|^2, \tag{9}$$

where $\mathbf{p}$ is the three-momentum of either of the outgoing pions in the rest frame of the kaon. Combining the previous results, and using the transversality condition $q\cdot\epsilon(q)=0$ for the polarization vector $\epsilon_\mu(q)$ of γ_Y, we can write the amplitude $T(K\to\pi\gamma_Y)$ in the form $[\bar{f}\equiv(4\pi)^{1/2}f]$

$$T=\bar{f}\epsilon_\mu(q)\mathcal{M}_\mu=\bar{f}\epsilon_\mu(q)\left[2k_\mu\frac{a(K^0-\pi^0)}{(k-q)^2+m_K^2}\right]. \tag{10}$$

Note that $q_\mu\mathcal{M}_\mu\neq 0$, which can be traced to the circumstance that hypercharge nonconservation in the weak interaction leads to amplitudes in which only one hadron can radiate a hyperphoton. This in turn has the consequence that in computing $|T|^2$,

$$|T|^2-\bar{f}^2\sum_{\text{polarizations}}(\epsilon_\mu\mathcal{M}_\mu)(\epsilon_\nu\mathcal{M}_\nu)^*=\bar{f}^2(\delta_{\mu\nu}+q_\mu q_\nu/m_Y^2)\mathcal{M}_\mu\mathcal{M}_\nu^*, \tag{11}$$

the term proportional to m_Y^{-2} survives, and leads to a large enhancement of the decay into γ_Y. For kaon decays this enhancement is such that the ratio of decay rates into γ_Y and γ is characteristically of order

$$\frac{f^2}{e^2}\frac{m_K^2-m_\pi^2}{2m_Y^2}\cong 7\times10^{-4}, \tag{12}$$

with use of the values of the various parameters given in Ref. 1. On the other hand, the cross sections for *absorbing* γ_Y are generally *not* enhanced, and hence are exceedingly small: Common processes by which γ_Y can be absorbed satisfy $q_\mu\mathcal{M}_\mu=0$ (since they do not involve the weak interaction), and hence act as if they were hypercharge conserving. We return to this point below.

Returning to (11), the contribution proportional to $\delta_{\mu\nu}$ is negligible, and the remaining term yields

$$\Gamma(K^\pm\to\pi^\pm\gamma_Y)=\frac{|\mathbf{p}|}{2m_K^2}|a(K^\pm-\pi^\pm)|^2\frac{f^w}{m_Y^2}=(3.4\times10^9\ \text{eV}^3)\frac{f^2}{m_Y^2}. \tag{13}$$

In arriving at (13) we have combined (8) and (9) and used the $|\Delta\mathbf{I}|=\frac{1}{2}$ relation $|a(K^\pm-\pi^\pm)|=\sqrt{2}|a(K^0-\pi^0)|$ to give $|a(K^\pm-\pi^\pm)|/\sqrt{2}=1.05\times10^{-7}\kappa^2$. From (13) we then find

$$\frac{\Gamma(K^\pm\to\pi^\pm\gamma_Y)}{\Gamma(K^\pm\to\text{all})}=(4.7\times10^{14}\ \text{eV}^2)\frac{f^2/e^2}{m_Y^2}, \tag{14}$$

and similarly

$$\frac{\Gamma(K_S^0\to\pi^0\gamma_Y)}{\Gamma(K_S^0\to\text{all})}=(3.3\times10^{12}\ \text{eV}^2)\frac{f^2/e^2}{m_Y^2}. \tag{15}$$

Given an experimental limit on any of the $K\to\pi\gamma_Y$ branching ratios we can extract from (14) or (15) a constraint on $\lambda^2(f^2/e^2)$. As we now discuss, existing experimental searches for various rare kaon decay

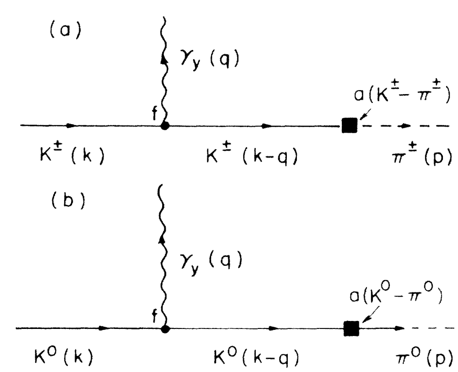

FIG. 1. Pole-model diagrams for $K\to\pi\gamma$. The momenta of various particles are given in parentheses.

modes do in fact set stringent limits on the branching ratios in (14) and (15).

By the argument made above one expects γ_Y to interact very weakly with ordinary matter. In addition, it should have a very small decay rate; although a hyperphoton can decay via $\gamma_Y \rightarrow 3\gamma$, this decay is highly suppressed.[9] It follows that the most straightforward way to detect hyperphotons is by their *absence:* The signature for the decay $K \rightarrow \pi\gamma_Y$ would be a pion of fixed energy in the kaon center-of-mass system and nothing else detected.

A number of experiments have been performed in stopping K^+ beams to search for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K^+ \rightarrow \pi^+ a^0$, where a^0 is a light, noninteracting neutral such as the axion.[10,11] The latest of these, by Asano *et al.*,[11] quotes at 90% confidence level $B(K^+ \rightarrow \pi^+ a^0) < 4.6\times 10^{-8}$. We take this limit to apply to the branching ratio for the hyperphoton decay mode as well.

In the neutral-kaon case, there are no experimental limits of comparable strength. An experiment using the technique of Banner *et al.*[12] to study the spectrum of the π^0 from K_L^0 decay in flight could in principle search for the hyperphoton decay mode, again signaled by a peak in the π^0 center-of-mass energy (or transverse momentum) spectrum. From the data of Ref. 12 one can infer a limit of 10^{-4}–10^{-5} for the hyperphoton decay of K_L^0. We expect the branching ratio for $K_L^0 \rightarrow \pi^0\gamma_Y$ to have a value about 3×10^{-3} that given in (15), because the K_L^0 decay is CP nonconserving. Hence, the neutral-kaon limit is about 6 orders of magnitude less stringent than that obtained from K^+ decays.

If we combine (3) and (14) with the limits of Asano *et al.*[11] for $K^+ \rightarrow \pi^+\gamma_Y$ we deduce the constraint

$$\left|\frac{\alpha}{1+\alpha}\right|\left(\frac{\lambda}{1\ \text{m}}\right)^2 \leqslant 4.7. \tag{16}$$

We now consider the implications of this limit. In principle a vector field A_λ for which the Earth is a source could couple to baryon number (B), hypercharge (Y), isospin (I_z), or lepton number (L). Because of the large variations in the ratios I_z/μ or L/μ [μ is the mass in units of $m({}_1\text{H}^1)$] in the samples studied by Eötvös, a coupling to I_z or L would have to be very weak.[13] By contrast, the Eötvös data are consistent with a coupling to any linear combination of B and Y, and hence, additional constraints are needed from other experiments. Let us consider then the possibility that A_λ couples not to the conventional hypercharge $Y = B + S$, but rather to a generalized hypercharge,

$$Y_\theta = \sqrt{2}\cos\theta_Y B + \sqrt{2}\sin\theta_Y S. \tag{17}$$

The Eötvös and geophysical experiments test couplings proportional to $\cos^2\theta_Y$, the anomalies in the K^0-$\bar{K}^0$ parameters are proportional to $\cos\theta_Y \sin\theta_Y$, and $\Gamma(K \rightarrow \pi\gamma_Y)$ is proportional to $\sin^2\theta_Y$. In particular (16) and (17) lead to

$$\tan^2\theta_Y\left(\frac{\lambda}{1\ \text{m}}\right)^2\left|\frac{\alpha}{1+\alpha}\right| \leqslant 4.7. \tag{18}$$

We see from (18) that the greater the range of the hypercharge interaction the more severely the coupling to S is constrained. Holding and co-workers[4] find $\alpha = -0.0075$ for $\lambda \leqslant 200$ m, and hence for $\lambda = 200$ m, $|\tan\theta_Y| \leqslant 0.13$. A coupling to the standard hypercharge ($\tan\theta_Y = 1$) is permissible for $\lambda \cong 15$ m. Although the geophysical and Eötvös results would be consistent with $\theta_Y = 0$, the apparent energy dependence[3] of the K^0-$\bar{K}^0$ parameters suggests a nonvanishing coupling to strangeness.[1] We note that a current Brookhaven National Laboratory experiment[14] will be sensitive to a branching ratio for $K^+ \rightarrow \pi^+\gamma_Y$ as low as 10^{-10}–10^{-11}. A null result in this experiment would severely constrain any coupling to S, and may force us to conclude that the apparent effects in the K^0-$\bar{K}^0$ system have some other origin. For $\theta_Y = 0$ the current to which γ_Y couples could be conserved, and this has an obvious theoretical appeal. We should, of course, emphasize that the limits inferred from $\Gamma(K \rightarrow \pi\gamma_Y)$ are subject to the usual current-algebra uncertainties that arise in nonleptonic amplitudes.[8] We believe, for instance, that the choice $\kappa = p$ in Eq. (8) is correct. However, if one were to choose instead $\kappa = k$, the constraints implied by (16) and (18) would be much more stringent.

In conclusion, it is worth noting that m_Y is as far removed from the ordinary hadron energy scale as the latter is from the presumed grand unification scale. It would thus not be surprising to find a rich structure at this level, just as we do at the familiar electroweak scale. In particular, if hyperphotons are detected, it would be interesting to explore whether their production modes exhibit the familiar symmetries of the electroweak interactions. To consider but one example, the decay $K_L^0 \rightarrow \pi^0\gamma_Y$ is suppressed by CP conservation if γ_Y is CP odd, as we have assumed. Should it turn out, however, that $\Gamma(K_L^0 \rightarrow \pi^0\gamma_Y)$ and $\Gamma(K_S^0 \rightarrow \pi^0\gamma_Y)$ are in fact comparable, then we could infer that CP conservation is violated to a greater extent in γ_Y interactions than is the case for known kaon decays. Similar remarks apply to other symmetries, and suggest that decays into γ_Y may provide a powerful tool for exploring possible intermediate-range couplings to hypercharge.

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