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THE COMPATIBILITY OF GRAVITY AND KAON RESULTS IN THE SEARCH FOR NEW FORCES

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ABSTRACT

The existing data on energy-dependences of the fundamental parameters of the K^0-$\bar{K}^0$ system, and the limits on the decay $K^+ \to \pi^+$ + (invisible neutrals), are used in conjunction with geophysical data to explore the coupling of the putative fifth force to quantities other than baryon number.

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I. INTRODUCTION

Evidence for a new weak intermediate-range force (the so-called "fifth force") has been found in several recent experiments[1] employing macroscopic devices to measure deviations from ordinary gravity. Several years ago hints of a new force were also reported[2] in high-energy determinations of the fundamental parameters of the neutral kaon system. It has been hypothesized[3] that these diverse phenomena are linked through a single new interaction which couples to hypercharge

$$Y = B + S, \tag{1.1}$$

where B and S are baryon number and strangeness, or to some generalization thereof. In this note we comment briefly on the presently available data, and explore the question of compatibility with the hypercharge hypothesis. We emphasize that neither the kaon nor gravity effects have been convincingly established. Even among the gravity-related experiments, the present data are not completely accommodated by a simple coupling to baryon number. What we are addressing here is the question of how to generalize the analysis of such effects in ordinary matter to a system where other quantum numbers are involved. This exercise is intended to illustrate the potential value of particle physics experiments in the search for new forces.

In Section II we summarize the expected effects of intermediate-range forces on the neutral kaon system, and compare these with existing data. In Section III we review the prospects for observing the decay of kaons into hyperphotons, which are the quanta of the presumed new field. We combine these two types of results to produce a limit on the strength of the new interaction in Section IV, and also confront this limit with the existing results in the gravity sector.

II. K^0-$\bar{K}^0$ SYSTEM IN AN INTERMEDIATE-RANGE FIELD

The present understanding of the putative fifth force is that if the observed effects are real, they are probably due to an interaction weaker than gravity and of intermediate range: $10 < \lambda < 10^4$ m. We have recently reviewed and refined the analysis of the neutral kaon system to include the case of finite range, and the details are presented elsewhere.[4] The effect of an external field on neutral kaons moving with respect to the source is to induce an energy-dependence in the fundamental parameters of the K^0-$\bar{K}^0$ system. In terms of the (approximate) CP-eigenstates K_S and K_L, these parameters include the mass difference

$$\Delta m = m_{K_L} - m_{K_S}, \tag{2.1}$$

the CP-violation parameter η_{+-}

$$\eta_{+-} = |\eta_{+-}|e^{i\phi_{+-}} = A(K_L \to \pi^+\pi^-)/A(K_S \to \pi^+\pi^-), \tag{2.2}$$

the decay rates Γ_S and Γ_L, and the K_L semileptonic charge asymmetry

$$\delta_\ell = \frac{\Gamma(K_L\to\pi^-\ell^+\nu)-\Gamma(K_L\to\pi^+\ell^-\bar{\nu})}{\Gamma(K_L\to\pi^-\ell^+\nu)+\Gamma(K_L\to\pi^+\ell^-\bar{\nu})}. \tag{2.3}$$

We parameterize the energy-dependence of a parameter x as

$$x(\gamma) = x_0(1 + b_x^{[n]}\gamma^n),\ \gamma = E_K/m_K. \tag{2.4}$$

Because of the finite range of the force the b_x's depend in principle on the detailed geometry of the experiment. We considered[4] circumstances in which the kaons are moving toward or away from an infinite-plane source, as well as the case of a constant potential. This latter configuration describes kaons travelling parallel to the surface of the source (e.g., the Earth), and so is the operative case for existing neutral kaon experiments. If A_o is the strength of the potential and f is the coupling constant, we find[4]

$$\begin{aligned} b_{\Delta m} &= b_{\Gamma_S} = b_{\Gamma_L} = 0, \\ b_\eta^{[2]} &= \frac{f^2 A_o^2}{4\Delta m^2 |\eta_{+-}|^2}, \\ b_\phi^{[1]} &= \frac{-\sqrt{2}\, f A_o}{\Delta m |\eta_{+-}|}, \\ b_\delta^{[1]} &\simeq -b_\phi^{[1]}/2. \end{aligned} \tag{2.5}$$

In Eq. (2.5) b_ϕ refers to the energy-dependence of $\tan\phi_{+-}$ rather than ϕ_{+-}.

We note here that only b_ϕ and b_δ are linear in the field strength; the other parameters have weaker energy-dependence or none at all. Computing A_o in terms of the density of the Earth and the range of the force, we get[4]

$$b_\phi^{[1]} \simeq -2.13 \times 10^{-8}\ \xi\left(\frac{\lambda}{1\text{m}}\right)^2, \tag{2.6}$$

where $\xi = f^2/G_\infty m_H^2$.

In the high-energy results reported in Ref. 2, b_ϕ was the most consistent signal of energy-dependence, being non-zero in all analyses. Using only the Fermilab data[5] and determining b_ϕ independent of the energy-dependences of all parameters other than $\tan\phi_{+-}$,

$$b_{\phi}^{[1]} = -(2.88 \pm 1.33) \times 10^{-3}. \qquad (2.7)$$

Other new experiments[6] can in principle determine b_{ϕ} and b_{δ} in the near future. We return to make use of (2.6) and (2.7) below in Section IV.

III. DETECTION OF HYPERPHOTONS

A number of authors[7-12] have considered the possibility of directly observing the vector boson associated with the fifth force. This particle, called the hyperphoton (γ_Y), could be detected in the process

$$K^{\pm} \rightarrow \pi^{\pm} + \gamma_Y, \qquad (3.1)$$

provided that γ_Y is indeed a <u>vector</u> particle, and in addition couples to the nonconserved hypercharge current. Under these circumstances the decay amplitude describing (3.1) is enhanced by a factor of order $(m_K^2 - m_\pi^2)/2m_Y^2$ which is extremely large.[7,9] For example, if the decays $a \rightarrow b + \gamma_Y$ and $a \rightarrow b + \gamma$ are both kinematically allowed, then the ratio of the corresponding amplitudes is of order[9]

$$\frac{T(a \rightarrow b + \gamma_Y)}{T(a \rightarrow b + \gamma)} \sim \frac{f^2}{e^2} \frac{m_K^2 - m_\pi^2}{2\,m_Y^2} \simeq 7 \times 10^{-4}. \qquad (3.2)$$

However, if the fifth force existed but was mediated by a <u>scalar</u> field, then the ratio in (3.2) would be of order $f^2/e^2 \simeq 8 \times 10^{-39}$. Thus the detection of the decay (3.1) is one means of clearly determining the spin of the component of the fifth force which couples to $K^{\pm}$.

Even though the amplitudes for decays which <u>produce</u> γ_Y can be enhanced by the Weinberg mechanism,[7] the amplitudes for <u>absorbing</u> γ_Y are not.[9] This means that in practice the hyperphoton will not be seen in detectors, so the signal is

$$K^{\pm} \rightarrow \pi^{\pm} + \text{"nothing"}. \qquad (3.3)$$

This signal has been searched for in stopping K^+ experiments. The best existing limit is[13]

$$\text{B.R.}(K^+ \rightarrow \pi^+ \gamma_Y) < 4.6 \times 10^{-8} \;\; (90\% \text{ C.L.}) \qquad (3.4)$$

A new experiment[14] should be able to push this limit down to the range 10^{-9} to 10^{-10} within the next year or so.

The branching ratio limit in (3.4) can be compared to various theoretical predictions to infer a limit on the product $f^2/m_Y^2 = f^2\lambda^2$. Using Eq. (6.5) of Ref. 15 we can write

$$\mathrm{B.R.}(K^\pm \to \pi^\pm \gamma_Y) = 7.7 \times 10^{15}\ \mathrm{eV}^2 \left| \frac{a(K^\pm - \pi^\pm)}{1\times 10^9\ \mathrm{eV}^2} \right|^2 f^2\lambda^2, \qquad (3.5)$$

where our notation is the same as Ref. 15. The nonleptonic amplitude $a(K^\pm - \pi^\pm)$ has been calculated by a number of authors,[8-12] and the results for B.R.$(K^\pm \to \pi^\pm \gamma_Y)$ are summarized in Table I.

TABLE I. THEORETICAL VALUES OF B.R.$(K^\pm \to \pi^\pm \gamma_Y)$.

Authors	B.R. in units of 10^{16} eV^2 $f^2\lambda^2$
Aronson, Cheng, Fischbach and Haxton[9]	6
Suzuki[8]	
(r = 1.5)	56
(r = 12)	444
Bouchiat and Iliopoulos[10]	403
Lusignoli and Pugliese[11]	380
Galić[12]	
model A (n = 5)	320
model B (n = 5)	23

With the exception of Galić's results, which are new, the details of the other calculations can be found in the corresponding references. Galić assumes[12] that a key to understanding kaons and pions, which are large systems, lies in long distance physics rather than in short distance corrections. He constructs several sets of pion and kaon wavefunctions, all of which describe K-decays fairly well, including the $|\Delta \vec{I}| = 1/2$ enhancement. These wavefunctions are then used in an analysis of $K^+ \to \pi^+ \gamma_Y$. The decay amplitude is dominated by diagrams in which a weak s→d transition takes place within a single quark line. Two typical values for B.R.$(K^\pm \to \pi^\pm \gamma_Y)$ are shown in Table I. From the difference in these results we see that the branching ratio is sensitive to the choice of wavefunction, which confirms the importance of long distance phenomena.

We see from the results of Table I that the theoretical estimates for B.R.$(K^\pm \to \pi^\pm \gamma_Y)$ vary widely, as is particularly evident from Galić's values. Using the experimental limit[13] on the branching ratio, we derive limits on $\xi\lambda^2$ and tabulate them in Table II.

TABLE II. LIMITS ON $\xi\lambda^2$ implied by B.R.$(K^+\to\pi^+\gamma_Y)$.

These are obtained by combining the experimental limit in (3.4) with the theoretical results in Table I, using the relation $\xi = f^2/G_\infty m_H^2$.

Authors	Upper limit on $\xi(\lambda/1\mathrm{m})^2$
Aronson, Cheng, Fischbach and Haxton[9]	4.7
Suzuki[8]	
(r = 1.5)	0.54
(r = 12)	0.07
Bouchiat and Iliopoulos[10]	0.08
Lusignoli and Pugliese[11]	0.08
Galić[12]	
model A	0.09
model B	1.3

IV. COMPATIBILITY OF EXISTING RESULTS

We begin by comparing the two sets of kaon results to one another. Assuming the fifth force couples equally to kaons and baryons, as implied by Eq. (1.1), is clearly inconsistent with these data: Combining Eqs. (2.6) and (2.7) gives $\xi\lambda^2 > 1000$ while from Table II $\xi\lambda^2 < 4.7$. We therefore introduce a more general charge:

$$V_5(r) = \frac{Q_1 Q_2 e^{-r/\lambda}}{r}, \tag{4.1a}$$

where for nuclei,

$$Q_i = Q_i^N = f\mu_i[1+c_B(B/\mu)_i + c_I(I_z/\mu)_i]. \tag{4.1b}$$

The sign in Eq. (4.1a) corresponds to a repulsive (vector) interaction.[16] A scalar interaction may also be present, although we expect the energy-dependences and γ_Y decays in the kaon sector to be dominated by the vector piece.[15]

Kaons might manifest fifth force effects via a coupling either to isospin or strangeness. For definiteness we write for mesons

$$Q_i = Q_i^M = \pm f\mu_i[c_S(S/\mu)_i + \ldots]. \tag{4.2}$$

The "fifth force" charge of a kaon is therefore given by $Q_K^M = \pm fc_S$. We should thus make the replacement $f \to fc_S$ in those equations derived under the assumption that the fifth force couples with equal strength to kaons and to baryons. For the process $K^+ \to \pi^+ \gamma_Y$,

$$c_S^2 \, \xi \left(\frac{\lambda}{1\text{m}}\right)^2 \lesssim 1, \tag{4.3}$$

where we choose the right-hand side as representative of the range of values in Table II.

Similarly, we replace Eq. (2.6) by (assuming $c_{B,I} \ll 1$)

$$b_\phi^{[1]} \simeq -2.13 \times 10^{-6} \, c_S \, \xi \left(\frac{\lambda}{1\text{m}}\right)^2. \tag{4.4}$$

Comparing Eqs. (2.7) and (4.4) gives

$$c_S \xi \left(\frac{\lambda}{1\text{m}}\right)^2 \simeq 1350 \pm 620. \tag{4.5}$$

Combining Eqs. (4.3) and (4.5), we find at the 1σ level:

$$\begin{aligned} c_S &\lesssim 7.4 \times 10^{-4}, \\ \xi \left(\frac{\lambda}{1\text{m}}\right)^2 &\gtrsim 1.8 \times 10^{6}. \end{aligned} \tag{4.6}$$

This value of c_S, though small, is comparable to coefficients found in reconciling various composition-dependent experiments.[1,17]

It is interesting to compare Eq. (4.5) with calculations based on the available data for the energy-dependence of $|\eta_{+-}|$. The analog of Eq. (2.6) for b_η is[4]

$$b_\eta^{[2]} \simeq 5.6 \times 10^{-13} \left[c_S \xi \left(\frac{\lambda}{1\text{m}}\right)^2\right]^2. \tag{4.7}$$

The ABCF 1σ limit on $b_\eta^{[2]}$, based on the Fermilab data is

$$b_\eta^{[2]} \lesssim 1.0 \times 10^{-6} \text{ (ABCF)}. \tag{4.8}$$

Also, from the measurement of $|\eta_{+-}|$ by Coupal et al.,[18]

$$|\eta_{+-}| = (2.28 \pm 0.06) \times 10^{-3} \text{ at } \langle E_K \rangle = 65 \text{ GeV} \tag{4.9}$$

we can infer

$$b_\eta^{[2]} \lesssim 1.8 \times 10^{-6} \text{ (Coupal et al.)}, \tag{4.10}$$

where we used the low-energy value $|\eta_{+-}| = (2.274 \pm 0.022)\times 10^{-3}$ at 5 GeV. Combining Eqs. (4.7), (4.8), and (4.10) gives

$$c_S\, \xi \left(\frac{\lambda}{1\text{m}}\right)^2 \le 1330 \text{ (ABCF)}$$

$$\le 1790 \text{ (Coupal et al.)}. \qquad (4.11)$$

We note that the limits in Eq. (4.11) are consistent with Eq. (4.5).[19]

Turning to the geophysical data we see that the nominal geophysical values,[20]

$$\xi \simeq 10^{-2},\ 10\text{m} \le \lambda \le 10^3\text{m} \qquad (4.12)$$

are not compatible with Eq. (4.6). More recent results from the tower experiment of Eckhardt, et al.,[21] when taken together with the data of Stacey, et al.,[20] open up interesting new possibilities in the geophysical sector. As discussed in Refs. 1 and 21, these data require the existence of at least two Yukawa components whose couplings obey

$$\xi_0 - \xi_1 \simeq -0.01,$$

$$\xi_0 \left(\frac{\lambda_0}{1\text{m}}\right) - \xi_1 \left(\frac{\lambda_1}{1\text{m}}\right) \simeq 5. \qquad (4.13)$$

The vector coupling proportional to ξ_1 can be larger than the value 10^{-2} we have assumed in Eq. (4.12). Solutions which imply $\xi_1 \left(\frac{\lambda_1}{1\text{m}}\right)^2 \ge 10^4$ are thus accommodated by the existing geophysical data. As mentioned above, we naturally identify the vector coupling with that component of the fifth force which gives rise to the kaon energy-dependences. It is encouraging that these considerations lead in the direction of reducing the discrepancies noted in comparing $b_\phi^{[1]}$ and the hyperphoton limits to the geophysical data.

In summary, kaons provide a means for studying the coupling of possible new forces to quantum numbers other than baryon number and lepton number, which presumably describe couplings to ordinary matter. Limits on the strength of a coupling to hypercharge (or strangeness or isospin) can be inferred from B.R.$(K^+ \to \pi^+ \gamma_Y)$, albeit with large theoretical uncertainties. Most interesting, perhaps, are the constraints implied by the energy-dependence of the K^0-$\bar{K}^0$ parameters, as embodied, for example, in $b_\phi^{[1]}$, since these depend on the coupling of the fifth force to both kaons and to ordinary matter. The possibility that a consistent picture of these couplings could emerge strongly argues for new and more precise kaon experiments. Finally, the considerations that apply to the K^0-$\bar{K}^0$ system apply <u>mutatis mutandis</u> to other systems such as

D^0-$\bar{D}^0$ and B^0-$\bar{B}^0$. Attention must also be given to the possibility of looking for couplings of new weak forces to charm, beauty,...etc.

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