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A possible model for fifth force

RAMANAND JHA and K P SINHA
Department of Physics, Indian Institute of Science, Bangalore 560012, India

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Abstract. Recent reanalysis of the data of the Eötvös experiment suggested the existence of a new force. We show that a negative energy massive scalar field minimally coupled to gravity in a background Schwarzschild metric naturally leads to a potential which can explain the small anomalous effect in the Eötvös experiment.

Keywords. Fifth force; negative energy scalar field; baryon number; Eötvös experiment.

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1. Introduction

Recent re-analysis of the data of the Eötvös experiment (Fischbach *et al* 1986) suggested a possible existence of a new force. This re-analysis revealed that two objects 1 and 2 with masses $m_{1,2}$ and baryon numbers (or hypercharges) $B_{1,2}$ have accelerations $a_{1,2}$ towards the earth, which will no longer have the universal Newtonian value g, but will differ by an amount $\Delta a = a_1 - a_2$, given by

$$\frac{\Delta a}{g} = \frac{\eta}{Gm_\mu^2}\left(\frac{B_\oplus}{\mu_\oplus}\right)\left(\frac{B_1}{\mu_1} - \frac{B_2}{\mu_2}\right). \tag{1}$$

Here μ_1 denotes the masses m_i in the units of atomic hydrogen (m_μ), $B_\oplus$ and $\mu_\oplus$ are baryon number (or hypercharge) and the mass of the earth respectively; the value of the constant η in SI units is

$$\eta = (1{\cdot}06 \pm 0{\cdot}13) \times 10^{-69}\,\text{N–m}^2,$$

which has been determined from the re-analysis of the data of the Eötvös experiment.

Fishbach *et al* assumed a coupling of the form

$$V(r) = -G_\omega(m_1 m_2/r)\{1 - \alpha\exp(-r/\lambda)\} \tag{2}$$

and deduced the values

$$\alpha = (7{\cdot}2 \pm 3{\cdot}6) \times 10^{-3} \quad \text{and} \quad \lambda = 200 \pm 50\,\text{m}.$$

Several papers, some criticizing the validity of this work and others suggesting vectorial interaction as a source of the anomalous force, have appeared since then (Keyser *et al* 1986; Thieberger 1986; Neufeld 1986; Nussianov 1986). Chu and Dicke (1986) claim that systematic effects due to thermal gradient can account for the experimental data.

Hayashi and Shirafuji (1986) invoke a vector gauge field universally coupled to the fermion number.

We have shown that the 'fifth force', if it exists, can be explained by a scalar interaction (previous theoretical explanations have been based on vector theories). Of course, the existence of the force is still controversial because of experimental difficulties.

Many delicate experiments have been performed (Thieberger's differential accelerometer, Eötvös-type experiment by Stubbs *et al* etc, Iacopini 1987) but the results are contradictory. It is also difficult to say whether the deviation from standard Newtonian gravity is due to a fifth force or from something more conventional.

However, "all of the geophysical evidence, from different geological environments in different parts of the world suggest that there is a real short-range repulsive fifth force at work on the scale of laboratory measurements" (see *New Scientist* 15 October 1987).

It is too early to draw any conclusion, but in a few years there will be many experimental results, and we will know if there really is another force besides the four known fundamental forces.

2. A negative energy massive scalar field model

In the present paper we consider a non-vectorial interaction and show that a negative energy massive scalar field minimally coupled to gravity in a background Schwarzschild metric naturally leads to a potential which is capable of explaining the result.

We consider an action given by

$$A = -\int \frac{R\sqrt{-g}}{2K_E}\mathrm{d}^4x - \frac{1}{g_F}\int\left(\frac{1}{2}\phi_\mu\phi^\mu - \frac{1}{2\lambda}\phi^2\right)\sqrt{-g}\,\mathrm{d}^4x - \sum_p\int m_p c^2\,\mathrm{d}s_p - \sum_p \theta b_N B_p\int\phi\,\mathrm{d}s_p. \tag{3}$$

The first term is the action for the gravitational field, the second term is the action for negative energy massive scalar field (ϕ) and g_F is the coupling constant, the third term is the inertial term and the last term represents the interaction of the p-th particle having baryon number B_p (b_N is the baryon charge of a nucleon) with the scalar field ϕ. The constant θ can be either $+1$ or -1 and $\phi_\mu = \phi_{,\mu} = \partial\phi/\partial x^\mu$.

In our model, although the scalar field has a negative energy, it differs considerably from the C-field of Narlikar and Padmanabhan (1985). ϕ is a negative energy massive scalar field and its source is the baryon or hypercharge which affects the world-line of a particle having a baryon charge even during its existence and it does not give rise to particle production. However, the negative energy massless scalar field, C-field, arises only whenever a baryon (and its accompanying lepton) is created or destroyed i.e. it has a source in the beginning or end of a world-line and it does not affect the world-line of a particle during its existence but only at ends of the world-lines.

The action given by (3) leads to the following field equations:

Metric equations

$$G_{\mu\nu} = K_E(T_{\mu\nu} - 1/g_F X_{\mu\nu}) + \theta\phi\rho_B u_\mu u_\nu, \tag{4}$$

Scalar field equation

$$\Box^2\phi + 1/\lambda^2\phi = +\theta g_F\rho_B. \tag{5}$$

Geodesic equations

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\{(mc^2 + \theta b_N B\phi)u^\mu\} = \theta b_N B\phi^\mu c^2, \tag{6}$$

where

$$T_{\mu\nu} = \rho u_\mu u_\nu, \tag{7}$$

$$X_{\mu\nu} = \phi_\mu\phi_\nu - 1/2g_{\mu\nu}(\phi_\alpha\phi^\alpha - 1/\lambda\phi^2), \tag{8}$$

and ρ_B = baryon number density. Here $\Box^2$ denotes the d'Alembertian operator in a curved space-time and ρ is the mass density.

Let us assume that the presence of the scalar field does not affect the background geometry, which is tantamount to saying that the scalar field energy-momentum tensor is negligible and also exterior to the earth and $T_{\mu\nu}$ and ρ_B are zero. Then the metric field equations (4) give approximately flat space-time for an object like the earth.

For a flat space-time metric a solution of (5) is

$$\phi = +\theta[(g_F b_N B_1)/4\pi][\exp(-r/\lambda)/r] \tag{9}$$

for a point source (B_1) at the origin of the coordinate system.

The time component of (6) for a stationary test particle, B_2, in a static scalar field $\phi(r)$ turns out to be

$$(mc^2 + \theta b_N B_2\phi)u^\circ = \text{constant (say, } E\ c). \tag{10}$$

Here the constant of integration is identified with the total energy (E) multiplied by the velocity of light (c). Now (10) can be written as

$$E = mc^2 + \theta^2\{[g_F(b_N^2 B_1 B_2)]/4\pi\}\{[\exp(-r/\lambda)]/r\}. \tag{11}$$

Here the energy of a test particle increases due to the interaction (which is independent of the sign of θ). This implies that the force is repulsive. The origin of such a repulsive force mediated by a scalar field lies in the fact that the kinetic term of the scalar field in the action has the "wrong sign".

The scalar field (9) for a spherically distributed extended source of radius $R_\oplus$ and total baryon number $B_\oplus$ becomes (we have taken $\theta = 1$)

$$\phi = [(3g_F b_N B_\oplus)/x_\oplus^3]\{[\exp(-x)/r]f(x_\oplus)\}, \tag{12}$$

where

$$x = r/\lambda, \quad x_\oplus = R_\oplus/\lambda, \quad r \geqslant R_\oplus$$

and

$$f(x_\oplus) = x_\oplus \cosh x_\oplus - \sinh x_\oplus. \tag{13}$$

Now the force between an extended spherically symmetric source with baryon number $B_\oplus$ and a point particle with baryon number B will be

$$F = (3g_F b_N^2 B_\oplus B)\{[(x+1)f(x_\oplus)\exp(-x)]/x_\oplus^3 r^2\}. \tag{14}$$

The acceleration of a particle of mass μ_1 and baryon number B_1 due to the earth's gravity and the scalar field will be g and a respectively where

$$g = Gm_\mu \mu_\oplus / r^2 \tag{15}$$

and

$$a = \frac{3g_F b_N^2 B_\oplus B_1}{m_\mu \mu_1} \frac{(x+1) f(x_\oplus) \exp(-x)}{x_\oplus r^2}. \tag{16}$$

The relative acceleration between two particles of masses $\mu_{1,2}$ and baryon numbers $B_{1,2}$ towards the earth at $r = R_\oplus$ will be

$$\frac{\Delta a}{g} = \frac{3g_F b_N^2}{Gm_\mu^2} \left(\frac{B_\oplus}{\mu_\oplus}\right) \Delta\left(\frac{B}{\mu}\right) \frac{(x_\oplus + 1) f(x_\oplus) \exp(-x_\oplus)}{x_\oplus}, \tag{17}$$

where

$$\Delta(B/\mu) = (B_1/\mu_1) - (B_2/\mu_2)$$

since $R_\oplus \gg \lambda$ i.e. $x_\oplus \gg 1$
and

$$\operatorname*{Lt}_{x_\oplus \gg 1} (x_\oplus + 1) f(x_\oplus) \exp(-x_\oplus) = \tfrac{1}{2} x_\oplus^2. \tag{18}$$

Substituting (18) in (17) we get

$$\frac{\Delta a}{g} = \frac{3}{2} \left(\frac{g_F b_N^2}{Gm_\mu^2}\right) \left(\frac{B_\oplus}{\mu_\oplus}\right) \left(\frac{\lambda}{R_\oplus}\right) \Delta\left(\frac{B}{\mu}\right). \tag{19}$$

Comparing (19) and (1) gives

$$\tfrac{3}{2}(g_F b_N^2)\left(\frac{\lambda}{R_\oplus}\right) = (1{\cdot}06 \pm 0{\cdot}13) \times 10^{-69} N - m^2$$

which implies

$$g_F b_N^2 = 2 \times 10^{-66} N - m^2, \tag{20}$$

where we have used $\lambda = 200\,\text{m}$ and $R_\oplus = 6370\,\text{km}$.

The values of λ and $g_F b_N^2$ have been determined from the data taken from $k - k^\circ$ (Aronson *et al* 1982, 1983), geophysical (Stacey and Tuck 1981; Holding and Tuck 1984; Stacey 1984; Holding *et al* 1986; Stacey *et al* 1986) and Eötvös measurements (Fischbach *et al* 1986).

The expression for the potential between two point particles of baryon numbers B_1 and B_2 is approximately

$$V(r) = g_F b_N^2 \{[B_1 B_2 \exp(-r/\lambda)]/r\}, \tag{21}$$

where

$$g_F b_N^2/\hbar c = 6{\cdot}3 \times 10^{-41}$$

and

$$\lambda = 200\,\text{m (corresponding to mass } 10^{-9}\,\text{eV).} \tag{22}$$

3. Conclusion

The coupling constant of the new force is approximately 100 times weaker than the force due to gravity. The new force is of short range owing to the presence of the exponential term and hence it will not have any observable influence on the precession of orbital perihelion and deflection of light near the sun.

The occurrence of a repulsive Yukawa-type interaction between two point sources through a scalar field implies that we are dealing with a situation involving an indefinite metric for the scalar field. This point and the question of energy boundedness have been lucidly discussed by Sudarshan (1961) and Nelson and Sudarshan (1972).

The negative energy scalar field is generally associated with the problem of unitarity and such problems are not necessarily solved for this model by the work of Nelson and Sudarshan (1972).

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