The Search for New Macroscopic Forces: Past, Present, and Future

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Outline

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    - Solar System Tests
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The Past
Conservation of Heavy Particles and Generalized Gauge Transformations

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The possibility of a new macroscopic force is discussed.

This conservation law of nature, which has two distinct categories: those that are related to invariance under space-time displacements and rotations, and those that are not. In the former category, there are the conservation laws of momentum, energy, and angular momentum. In the latter category, we find the conservation laws of electric charge, of heavy particles, and the approximate conservation laws of baryonic charge. We wonder that one has known within the second category; the conservation of electric charge is related to invariance under gauge transformations which express the non-triviality of the phase of the complex wave function of a charged particle.

We are asked whether similar gauge invariances should be related to all conservation laws of the second category. Up to now, this question has been discussed in connection with the conservation of baryonic charge by Yang and Mills. We still have to understand the position in connection with the conservation of heavy particles.

If we take the conservation of heavy particles to mean invariance under the transformation

$$\psi \to e^{-i\theta} \psi,$$

for the wave function of the heavy particles (e.g., nucleons and protons), a general gauge transformation (heavy-particle gauge transformation) is a transformation (1) with the phase-constant phase function $\theta$.

Invariance under such a transformation means that the relative phase of the wave functions of a heavy particle at two different space-time points is not measurable.

Such a gauge transformation is formally completely identical with the electroweak gauge transformation. However, under such a transformation, invariance means the existence of a neutral vector meson field coupled to all heavy particles. A nucleus would have a "heavy-particle charge" of $e^{-i\theta}$ in each field, and an atom would have a "heavy-particle charge" of $e^{-i\theta}$. The force between two nucleus heliums therefore would contain a contribution from the Coulomb attraction between such "heavy-particle charges." The usual force, including the gravitational attraction, is

$$F = -G M_1 M_2 / r^2.$$

Here $M_1$, $M_2$, and $M_3$ are the baryon masses and $r$ is the distance between the two nuclei. These should also be a non-trivial constant interaction between individual nuclei because the masses are in constant motion in a nucleus. But in a macroscopic object, the medium spins average out so that (2) in vector under the two nuclei can remain unchanged in high speeds.

Next the probability function of various strange differ so that (2) varies functionally from solution to solution by $e^{-i\theta}$. This means that the observed gravitational masses (which consists of a contribution from the atom in 4) divided by the heaviest mass would vary functionally from solution to solution by $e^{-i\theta}$, where $\theta = \psi$ is the phase of the product. Very careful measurements by Bohr and co-workers have shown this variation to be $< 10^{-4}$. Therefore

$$\psi e^{-i\theta} < 10^{-4}.$$
A model is proposed which allows a dilaton to show up in a possible non-Newtonian part of the gravitational force. By examining the available observational facts it can be shown that the range of the additional force, if it exists, will be either between 10 m and 1 km or smaller than ~1 cm.

A dilaton—a Nambu-Goldstone boson of dilatation invariance—is a scalar particle which is not a genuine spin-2 particle because of its masslessness. As a consequence the dilaton may affect the gravitational force between two masses.

If the dilaton mass is of the order of hadronic masses, any modifications will occur only within the distances of the order of fm. The dilaton mass could be, on the other hand, of the order of \( \kappa \sim (G \eta^{-2})^{1/4} \) which is a typical combination of two fundamental constants in the gravitational and strong inter-

We have an order of magnitude estimate of the constant \( F_2 \)

\[ F_2 \sim a^{-1} \]  

(1)

The 8-graviton mixing problem is then resolved to give a gravity potential

\[ V(r) = -\frac{3}{4} G \frac{1}{r} \left[ 1 + \frac{1}{3} \right] \left( \cos \kappa r - \frac{1 - t_0/2\kappa^2}{\sqrt{-D}} \sin \kappa r \right) e^{-\kappa \sqrt{-D} r} \]  

(2)

where \( \kappa^2 = (3/8)G_0 \), and \( -D = t_0/\kappa^2 - 1 \) with the restriction \( t_0 > \kappa^2 \). From (1), with \( G = 6.67 \times 10^{-11} \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-2} \), we obtain \( \kappa \sim 10^{-20} \text{ m}^{-1} \) or \( \kappa^{-1} \sim 10^3 \text{ cm} \).

If the "bare" dilaton mass squared \( (t_0) \) vanishes, that is, dilatation invariance is strict, there is no change in the gravitational interaction. If \( t_0 \) is of the order of a hadronic mass squared, then \( \kappa \sqrt{-D} \sim \sqrt{t_0} \) in the exponent in (2), because \( t_0 \gg \kappa^2 \). The finite-range part vanishes for any macroscopic distance. On the other hand, \( t_0 \) may be of the same order of, but still larger than, \( \kappa^2 \). We obtain \( \kappa \sqrt{-D} \sim \kappa \), because \( -D \sim 1 \). The force-range is of the order of \( \kappa^{-1} \sim \text{ km} \). We have then an entirely new situation.

Consider the Cavendish experiment with the distance \( r \sim 10 \text{ cm} \). The potential (2) becomes
Newtonian gravity measurements impose constraints on unification theories

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Theories which attempt to unify gravity with the other forces of nature can be coarsely classified according to the mass scale of the new particles they introduce or equivalently the length scale at which new phenomena occur. This mass scale can be expressed as \( m_{\mu}(m_{\mu}/m_{\pi})^{n} \), where \( m_{\mu} \) is a typical hadron mass and \( m_{\pi} \) is the Planck mass. In most current theories \( n \) is 0 or 1. However, in some theories \( n = 2 \), which offers the possibility of experimental consequences at kilometre scales. Here using satellite and geophysical data we place constraints on such theories and find that they are not viable unless \( m_{\mu} > 10^{8} \) GeV.

geodesy measurements\(^{21,22}\) together with the results of a recent mine experiment\(^{23}\) and those in refs 18, 24 place stringent limits on the parameters appearing in theories of the Fujii or Scherk types.

If gravitation is due to the exchange of particles of Compton wavelength \( \lambda_{\alpha} \) and coupling \( \alpha_{\mu} \) the potential energy of two masses \( m \) and \( m' \) at a separation \( r \) is:

\[
V = -G_{m} \frac{mm'}{r} \left( 1 + \sum_{i=1}^{N} \alpha_i \exp(-r/\lambda_i) \right) \quad (1)
\]
The Search for New Macroscopic Forces: The Past

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Reanalysis of the Eötvös Experiment

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We have carefully reexamined the results of the experiments of Eötvös, Pekár, and Fekete, which compared the accelerations of various materials to the Earth. We find that the Eötvös-Pekiá- Fekete data are sensitive to the composition of the materials used, and that their results support the existence of an intermediate-range coupling in baryon number or hypercharge.

PACS numbers: 04.50. +e

Recent geophysical determinations of the Newtonian constant of gravitation $G$ have reported values which are consistently higher than the laboratory value $G_0$. With the assumption that the discrepancy between these two sets of values is a real effect, one interpretation of these results is that they are the manifestation of a non-Newtonian coupling of the form

$$V(r) = -G_0 \frac{m_1 m_2}{r} (1 + \alpha e^{-\lambda r})$$

$$-V_N(r) + \Delta V(r) .$$

(1)

Here $V_N(r)$ is the usual Newtonian potential energy for two masses $m_1, m_2$ separated by a distance $r$, and $G_0$ is the Newtonian constant of gravitation for $r \to \infty$. The geophysical data can then be accounted for quantitatively if $\alpha$ and $\lambda$ have the values

$$\alpha = -(7.2 \pm 3.6) \times 10^{-11}, \quad \lambda = 200 \pm 50 \text{ cm}.$$  

(2)

If $\Delta V(r)$ actually describes the effects of a new force, and if not just a parametrization of some other systematic effects, then its presence would be expected to manifest itself elsewhere as well. Recently, we have undertaken an exhaustive search for the presence of such a force in other systems. Our analysis, to be presented elsewhere,\(^1\) leads to the conclusion that if such a force existed it would show up at present sensitivity levels only in three additional places: (i) the $K^0 \bar{K}^0$ system at high laboratory energies, where in fact anomalous effects have previously been reported;\(^4\) (ii) a comparison of satellite and terrestrial determinations\(^3\) of the local gravitational acceleration $g$; and (iii) the original Eötvös experiment\(^5\) which compared the acceleration of various materials to the Earth. We note that the subsequent repetitions of the Eötvös experiment by Roll, Krolikov, and Dicke and by Bruginski and Papov\(^6\) compared the gravitational accelerations of a pair of test materials to the Sun, and hence would not have been sensitive to the intermediate-range force described by Eqs. (1) and (2). Motivated by our general analysis, we returned to the Eötvös experiment and asked whether there is evidence in their data of the presence of $\Delta V(r)$ in Eq. (1). Although the Eötvös experiment has been universally interpreted as having given null results, we find in fact that this is not the case. Furthermore, we will demonstrate explicitly that the published data of Eötvös, Pekár and
Eötvös Apparatus

Eötvös Results

The ““Generic” Fifth Force Theory

Many specific theories lead to new weak forces of intermediate range. These theories derive from 2 observations:

1. \[ m_{\text{hadron}} \sim 1 \text{ GeV} \quad \text{and} \quad m_{\text{Planck}} \sim 10^{19} \text{ GeV} \quad \Rightarrow \quad f = \frac{m_{\text{hadron}}}{m_{\text{Planck}}} \approx 10^{-19} \]

2a. \[ f \approx 10^{-19} \quad \text{and} \quad m_{\text{hadron}} \sim 1 \text{ GeV} \quad \Rightarrow \quad \mu = f \cdot m_{\text{hadron}} \approx 10^{-10} \text{ eV} \]
   \[ (\lambda = 1/\mu \approx 2 \text{ km}) \]

or

2b. \[ f \approx 10^{-19} \quad \text{and} \quad \langle \phi \rangle_{\text{GSW}} \approx 240 \text{ GeV} \quad \Rightarrow \quad \mu = f \langle \phi \rangle \approx 2.4 \times 10^{-8} \text{ eV} \]
   \[ (\lambda = 1/\mu \approx 8 \text{ m}) \]

These parameters \([f \sim 10^{-19}; \lambda \sim 10 \text{ m} - 10 \text{ km}]\) are typical of the values suggested by various theories.
Hence, new interactions like the fifth force may be natural consequences of many models.
Summary of Newtonian Gravity

\[ V(r) = -\frac{Gm_1 m_2}{r} \]

\[ \vec{F}(r) = -\frac{Gm_1 m_2}{r^2} \hat{r} = m_1 \vec{a}_1 \]

\[ \vec{a}_1 = -\frac{Gm_2}{r^2} \hat{r} \]

- a) independent of the nature of \( m_1 \) (Equivalence Principle)
- b) varies as \( 1/r^2 \)
Summary of Newtonian Gravity

• Newtonian Gravity

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a) independent of the nature of \( m_1 \)
   (Equivalence Principle)

b) varies as \( 1/r^2 \)

• Non-Newtonian Gravity

\[ V(r) = -\frac{G m_1 m_2}{r} \left\{ 1 + \alpha_{12} e^{-r/\lambda} \right\} \]

\[ F(r) = -\frac{G(r)m_1 m_2}{r^2} \hat{r} \]

doesn’t vary as \( 1/r^2 \) *

\[ G(r) = G[1 + \alpha_{12} e^{-r/\lambda} (1 + r / \lambda)] \]

not independent of 1 or 2 *

* Evidence for either of these would point to a new fundamental force in nature.
Non-Newtonian Gravity

\[ V(r) = -\frac{G m_1 m_2}{r} \left\{ 1 + \alpha_{12} e^{-r/\lambda} \right\} \]

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\[ G(r) = G[1 + \alpha_{12} e^{-r/\lambda} (1 + r/\lambda)] \]

* Evidence for either of these would point to a new fundamental force in nature.
Inverse-Square Law Tests: Spero 1980

FIG. 1. Schematic of the experimental apparatus.
Inverse-Square Law Tests:
Airy Method (Stacey 1984)
Inverse-Square Law: Solar System Tests

The presence of the non-Newtonian contribution leads to 2 measurable effects:

\[ V_5(r) = -\alpha \frac{G_\infty m_1 m_2 e^{-r/\lambda}}{r} \]

a) Planetary Precession:
\[ \delta \phi_a \equiv +\pi \alpha \left(\frac{a}{\lambda}\right)^2 e^{-a/\lambda} \text{ rad/rev} \equiv \pi \alpha x^2 e^{-x} \]
\[ a = \text{ mean value of semi - major axis} \]
\[ \delta \phi_a = cx^2 e^{-x} \text{ has a maximum at } x = 2 \]

b) Variation of \( \mu_{\text{sun}} = GM_{\text{sun}} \):
\[ V_5(r) \Rightarrow G(r) = G_\infty [1 + \alpha(1 + r/\lambda)e^{-r/\lambda}] \neq \text{ constant} \]
\[ \therefore 4 \pi^2 \frac{a_p^3}{T_p^2} = G(a) M_{\text{sun}} \neq \text{ constant} \]

Mikkelsen & Newman (1977); de Rujula (1986); Talmadge, Berthias, Hellings, & Standish (1988); Coy, Fischbach, Hellings, Standish & Talmadge (2003)
Limits on Extra Dimensions and New Forces: Long-Range Inverse-Square-Law Limits

Temperature of water is kept at $$(4.0 \pm 0.2) \, ^\circ C$$ (maximum water density)
Composition-Dependent Tests:
(Eöt-Wash, 1994)

## Summary of Non-Null Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>X ≡ Wrong</th>
<th>Disposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eötvös (1922)</td>
<td>?</td>
<td>???</td>
</tr>
<tr>
<td>Long (1976)</td>
<td>X</td>
<td>Tilt Problems</td>
</tr>
<tr>
<td>Stacey (1981)</td>
<td>X</td>
<td>Terrain Bias</td>
</tr>
<tr>
<td>Aronson (1982)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Thieberger (1987)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Hsui (1987)</td>
<td>X</td>
<td>Unknown Systematics</td>
</tr>
<tr>
<td>Boynton (1987)</td>
<td>X</td>
<td>Magnetic Contamination</td>
</tr>
<tr>
<td>Eckhardt (1988)</td>
<td>X</td>
<td>Terrain Bias</td>
</tr>
<tr>
<td>Ander (1989)</td>
<td>X</td>
<td>Gravitational Anomalies</td>
</tr>
</tbody>
</table>

## CONCLUSION

There is at present no credible evidence for any deviations from the predictions of Newtonian gravity on any length scale.
Limits on Extra Dimensions and New Forces: Long-Range Composition-Dependent Limits

Alternative Explanations for the Eötvös Results

Reference: Hall, et al., 1991
The Present
Gravity in $3 + n$ Non-Compact Dimensions

Potential Energy:

\[ V_{\text{Gravity}}(r) = -\frac{GM_1 M_2}{r^{1+n}} \]

Force:

\[ \vec{F}_{\text{Gravity}}(r) = -\vec{\nabla} V(r) \]

Observations $\Rightarrow n = 0$
Compact Spatial Dimensions

\[ r \gg R \rightarrow \text{Space appears 3-D} \]
\[ r < R \rightarrow \text{Extra dimensions appear} \]

**Experiment:**

- All matter sees extra dims \( \Rightarrow R < 10^{-15} \text{ m} \)
- Only gravity sees extra dims \( \Rightarrow R < 10^{-4} \text{ m} \)
Gravity with $n$ Compact Extra Dimensions

\[ V_{\text{Gravity}}(r) = \begin{cases} -\frac{G M_1 M_2}{r}(1 + \alpha e^{-r/\lambda}), & r >> R \\ -\frac{G' M_1 M_2}{r^{1+n}}, & r \leq R \end{cases} \]

Range of Yukawa: $\lambda ~ R$

Strength Constant $\alpha$:

- Models of extra dimensions: $\alpha ~ 1-10$
- New Force Models: $\alpha ~ ????
Numerical Estimates

- It is convenient to introduce an energy scale set by the usual Newtonian constant $G \equiv G_4$. This is the Planck mass $M_{Pl} \equiv M_4$

$$M_4 \equiv M_{Pl} = (\hbar c/G_4)^{1/2} = 2.18 \times 10^{-5} \text{ g} = 1.22 \times 10^{19} \text{ GeV/c}^2$$

- In natural units ($\hbar = c = 1$) $M^2_4 = 1/G_4$

- The analog of the Planck mass in higher dimensions is called $M_{4+n}$

- When expressed in terms of $M_4$ and $M_{4+n}$ the previous result $G_4 = G_5/4R$ generalizes to

$$M^2_4 \approx R^n(n)M^{n+2}_{4+n}$$

- This forms the basis for current experiments
How Big is $M_{4+n}$? How big is $n$?

1) The usual Planck mass $M_4$ and the associated length scale $\frac{\hbar}{M_4 c} \approx 10^{-33}$ cm are the scales at which gravitational interactions become comparable in strength to other interactions, and hence can be unified with these interactions.

2) It would be nice if this happened at a smaller energy scale $\Rightarrow$ bigger length scale. A natural choice is $\sim 1$ TeV $= 10^{12}$ eV where supersymmetry breaks down.

3) This can happen in some string theories with extra spatial dimensions if ordinary matter is confined to 3-dimensional walls ("branes"), and only gravity propagates in the extra dimensions.