EQUIVALENCE PRINCIPLE TESTS, EQUIVALENCE THEOREMS, AND NEW LONG-RANGE FORCES

P. FAYET

Laboratoire de Physique Théorique de l'Ecole Normale Supérieure
24 rue Lhomond, 75231 Paris CEDEX 05, France

ABSTRACT

We discuss the possible existence of new long-range forces mediated by spin-1 or spin-0 particles. By adding their effects to those of gravity, they could lead to apparent violations of the Equivalence Principle. While the vector part in the couplings of a new spin-1 U boson involves, in general, a combination of the B and L currents, there may also be, in addition, an axial part as well. If the new force has a finite range $\lambda$, its intensity is proportional to $1/(\lambda^2 F^2)$, $F$ being the extra $U(1)$ symmetry-breaking scale.

Quite surprisingly, particle physics experiments can provide constraints on such a new force, even if it is extremely weak, the corresponding gauge coupling being extremely small ($\ll 10^{-19}$!). An “equivalence theorem” shows that a very light spin-1 $U$ boson does not in general decouple even when its gauge coupling vanishes, but behaves as a quasimassless spin-0 particle, having pseudoscalar couplings proportional to $1/F$. Similarly, in supersymmetric theories, a very light spin-$3/2$ gravitino might be detectable as a quasi massless spin-$1/2$ goldstino, despite the extreme smallness of Newton’s gravitational constant $G_N$, provided the supersymmetry-breaking scale is not too large.

Searches for such $U$ bosons in $\psi$ and $\Upsilon$ decays restrict $F$ to be larger than the electroweak scale (the $U$ actually becoming, as an axion, quasi “invisible” in particle physics for sufficiently large $F$). This provides strong constraints on the corresponding new force and its associated EP violations. We also discuss briefly new spin-dependent forces.
TESTS DU PRINCIPE D’ÉQUIVALENCE,
THÉORÈMES D’ÉQUIVALENCE,
ET NOUVELLES FORCES À LONGUE PORTÉE

P. FAYET

Laboratoire de Physique Théorique de l’École Normale Supérieure
24 rue Lhomond, 75231 Paris CEDEX 05, France

RÉSUMÉ

Nous discutons de l’existence possible de nouvelles forces à longue portée induites par des particules de spin 1 ou 0. En se superposant à la gravitation, elles pourraient se manifester par des violations apparentes du Principe d’Équivalence. La partie vectorielle des couplages d’un nouveau boson $U$ de spin 1 fait intervenir, en général, une combinaison des courants baryonique et leptoniques; ces couplages peuvent inclure, tout aussi bien, une partie axiale. Si la nouvelle force est de portée finie $\lambda$, son intensité est proportionnelle à $1/(\lambda^2 F^2)$, $F$ étant l’échelle de brisure de la symétrie $U(1)$ supplémentaire.

De manière assez surprenante, la physique des particules peut apporter des informations sur une telle force, même si elle est extrêmement faible, la constante de jauge correspondante étant extrêmement petite ($\ll 10^{-19}$). Un “théorème d’équivalence” montre qu’un boson $U$ de spin 1 très léger ne se découpe pas lorsque sa constante de jauge s’annule, mais se comporte comme un boson de spin 0, muni de couplages pseudoscalaires proportionnels à $1/F$. De même, dans les théories supersymétriques, un gravitino de spin 3/2 très léger pourrait être détectable et apparaître comme un goldstino de spin 1/2, malgré l’extrême petite de la constante de Newton $G_N$, si l’échelle de brisure de la supersymétrie n’est pas trop grande.

Les recherches de tels bosons $U$ dans les désintégrations du $\psi$ ou du $\Upsilon$ indiquent que $F$ doit être un peu supérieur à l’échelle électrofaible (le $U$ devenant même, tel un axion, quasi “invisible” en physique des particules si $F$ est suffisamment grand). Ceci conduit à de fortes contraintes sur la nouvelle force correspondante, et les violations associées du Principe d’Équivalence. Nous discutons aussi brièvement de nouvelles forces dépendant du spin.

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2 UMR 8549, Unité Mixte du CNRS et de l’Ecole Normale Supérieure.
e-mail: fayet@physique.ens.fr
1 GENERAL OVERVIEW.

Why to test the Equivalence Principle? Could new long-range forces exist, in addition to gravitational and electromagnetic ones, and what could be their properties?

The Equivalence Principle is at the basis of the theory of General Relativity. Although we have no reason to believe that general relativity is incorrect, it is certainly not a satisfactory, complete theory. In particular there is a well-known clash between general relativity and quantum physics. More precisely, no consistent quantum theory of gravity exists, although one hopes to progress towards a solution within the framework of superstring and membrane theories. While the problem may be ignored temporarily for gravitational interactions of particles at physically accessible energies, it becomes crucial at very high energies of the order of the Planck energy, $\simeq 10^{19}$ GeV. This is the energy scale (corresponding in quantum physics to extremely small distances $\sim L_{\text{Planck}} \simeq 1.6 \times 10^{-33}$ cm) at which gravity is normally expected to become a strong interaction, so that quantum effects, still ill-defined, become essential. At such energies gravity has an effective intensity comparable to that of the three other interactions, strong, electromagnetic and weak. This is where a unification of all four interactions might conceivably occur.

Independently of gravity, the Standard Model of strong, electromagnetic and weak interactions is very successful in describing the physics of elementary particles and their fundamental interactions. But it also suffers from certain difficulties, and leaves a number of questions unanswered. To mention a few:

- it has about 20 arbitrary parameters, including the three gauge couplings of $SU(3) \times SU(2) \times U(1)$, two parameters $\mu^2$ and $\lambda$ ultimately fixing the $W$ and Higgs boson masses, and thirteen mass and mixing-angle parameters associated with the quark and lepton spectrum.

- it sheds no light on the origin of the various symmetries and of symmetry breaking, nor on the family problem (why three generations of quarks and leptons, ...).

- in the presence of very large mass scales it suffers from the problem of the stability of the mass hierarchy: how can the $W$ mass remain so small compared to the grand-unification or the Planck scales, in spite of radiative corrections which would tend to make it of the same order as $m_{\text{GUT}}$ or $m_{\text{Planck}}$?

- another problem concerns the vacuum energy, when coupled to gravity: unless it is zero or almost zero (i.e. really extremely small, when measured with the natural units of particle physics, even more in terms of Planck’s units), it tends to generate a much too large value of the cosmological constant $\Lambda$, exceeding by many orders of magnitude what is experimentally allowed ($|\Lambda| < 3 \times 10^{-56}$ cm$^{-2} \simeq 10^{-121} L_{\text{Planck}}^{-2}$).

- a delicate question concerns the symmetry or asymmetry between Matter and Antimatter. The $CP$ symmetry is almost a symmetry of all interactions, but it is violated by some weak interaction effects observed in kaon decays. Then it has no reason to be an exact symmetry of strong interactions, so that the neutron should
acquire an electric dipole moment. Since no such moment has been found the cor-
responding amount of CP-violation (measured by the dimensionless parameter $\theta_{\text{eff}}$)
should be smaller than $\approx 10^{-9}$, already a very small number. A possible mechanism
to understand this requires the existence of a new neutral, very light, spin-0 particle,
the axion (Wilczek, 1978; Weinberg, 1978).

Essentially all attempts to go beyond the Standard Model and try to bring a
solution to the above problems involve the introduction of new symmetries, new
particles, and therefore quite possibly new forces.

Such a situation already occurred thirty years ago, when the problems associ-
ated with the non-renormalisability of known (charged-current) weak interactions
led physicists to rely on the new gauge symmetry principle, and to postulate the
existence of a new particle, the neutral gauge boson $Z$, in addition to the (then
still hypothetical) charged ones, $W^+$ and $W^-$. This finally led to what is known
as the Standard Model. The $Z$ mass had to be of the same order as the $W$ mass,
$Z$-exchanges being responsible for a new class of weak-interaction effects (through
“neutral currents”) that were subsequently discovered in 1973, ten years before the
$W$’s and $Z$’s could be directly produced at CERN, in 1983. The corresponding new
force has a very small range of about $2 \times 10^{-16}$ cm, as for charged-current weak in-
teractions. It is now conceivable (and even likely) that the solution to the problems
associated with the quantization of gravity requires the existence of new particles
– in addition to the usual massless spin-2 graviton – and therefore of new forces,
possibly long-ranged, appearing as additions or modifications to the known force of
gravity.

Irrespective of gravitation, the grand-unification between electroweak and strong
interactions would involve very heavy spin-1 gauge bosons that could be responsi-
ble for proton decay. The supersymmetry between bosons and fermions requires
the existence of new superpartners for all particles (see e.g. Fayet, 2001). These
new particles – together with the two Higgs doublets required for the electroweak
breaking within supersymmetry – have a crucial effect on the evolution of the weak,
electromagnetic and strong gauge couplings, allowing them to converge, at a large
value of the grand-unification energy scale of the order of $10^{16}$ GeV. Supersymmetry
is also closely related with gravitation, since a locally supersymmetric theory must
be invariant under general coordinate transformations. And the lightest of the new
superpartners predicted by supersymmetric theories, which all have an odd $R$-parity
character (with $R$-parity equal to $(-1)^{2S} (-1)^{3B+L}$) turns out be to an almost ideal
candidate to constitute the non-baryonic Dark Matter that seems to be present in
the Universe.

More ambitious theories involve extended supersymmetry, new compact space
dimensions of various kinds, and extended objects like superstrings and membranes,
aiming at a completely unified description of all interactions, including gravity. They
involve many new particles, including in general new neutral spin-1 or spin-0 bosons
appearing as lower-spin partners or companions of the spin-2 graviton, etc.. The
exchanges of such new particles could lead to new forces adding their effects to those of gravity. They could manifest experimentally through (apparent) violations of the Equivalence Principle – according to which the gravitational and inertial masses may be identified – since what seems to be, experimentally, the force of gravity, might in fact be the superposition of gravity itself (acting proportionally to masses) with some other additional new force(s) having different properties.

In particular, spin-1 bosons hereafter called \( U \)-bosons could gauge extra \( U(1) \) symmetries (cf. Fayet, 1990), as will be discussed in more details below. \( U \)-exchanges would be responsible for a new force involving the vector part in the \( U \) current, and expected to act on ordinary matter in an additive way, proportionally to a linear combination of the numbers of protons and neutrons, \( Z \) and \( N \), as we shall see. If the \( U \) boson is massless or almost massless with an extra \( U(1) \) gauge coupling \( g^{\prime \prime} \) extremely small, the new force could lead to apparent violations of the Equivalence Principle, since the numbers of neutrons and protons in an object are not exactly proportional to its mass. Newton’s \( 1/r^2 \) law of gravitation could also appear to be violated, if the new force has a finite range.

The spin-0 dilaton (or “moduli”, etc.) fields originating from superstring scenarios may well (or even should) remain massless; they are then generally expected to lead to excessively large deviations from the Equivalence Principle. However these fields could have their vacuum expectation values attracted towards a point at which they would almost decouple from matter (Damour and Polyakov, 1994). Their residual interactions could then be detected through extremely small (apparent) violations of the Equivalence Principle, possibly at a level estimated to be of the order of \( 10^{-12} \) to \( 10^{-24} \).

The Equivalence Principle has already been tested to a very good level of precision, of about a few \( 10^{-12} \) at large distances (Roll et al., 1964; Adelberger et al., 1990; Su et al., 1994). Lunar laser ranging data also indicate that the acceleration rates of the (Fe/Ni-cored) Earth and the (silicate-dominated) Moon towards the Sun are practically equal, to a level of precision slightly better than \( 10^{-12} \) (cf. Williams et al., 1996; Müller et al., 1997; Müller and Nordtvedt, 1998). Strictly-speaking the interpretation of this result, however, also involves the consideration of gravitational-binding energies, in addition to the different compositions of the Earth and the Moon.

The sensitivity of Equivalence Principle tests could be further improved by monitoring the relative motion of two test masses of different compositions, circling around the Earth, in a drag-free satellite. The MICROSCOPE experiment (“MicroSatellite à Compensation de trainée pour l’Observation du Principe d’Equivalence”), whose construction has just been decided by CNES, aims at testing the validity of this principle at a level of precision of \( 10^{-15} \) (Touboul, 2001). The STEP experiment (“Satellite Test of the Equivalence Principle”) is a more ambitious project which aims at a level of sensitivity that could reach \( \sim 10^{-17} – 10^{-18} \) (Blaser, 1996; Vitale, 2001), a considerable improvement by five orders of magnitude or more compared to
the present situation.

The test masses, incidentally, cannot be taken spherical, but only cylindrical. A potential difficulty is the existence of residual interactions between the higher multipole moments of the test masses and the gravity gradients induced by disturbing masses within the satellite, which could lead to an unwanted signal simulating a “violation of the Equivalence Principle”. To minimize these effects one can use test masses approaching ideal forms of “aspherical gravitational monopoles”, which are homogeneous solid bodies for which all higher multipole moments vanish identically, despite the lack of spherical symmetry (Connes et al., 1997)!

Should deviations from the Equivalence Principle be observed, further informations relying on data from several differential accelerometers could allow one to distinguish between new spin-1 or spin-0 induced forces, adding their effects to those of gravity. In the first case the new force is generally expected to act on a linear combination of baryon and lepton numbers $B$ and $L$ (which coincides in practice with a combination of the numbers of protons and neutrons, $Z = L$ and $N = B - L$). For spin-0 exchanges the new force may be expected to act effectively on a linear combination of $B$ and $L$ with electromagnetic (and chromodynamics) energies. Should such a force be found, testing several pairs of bodies of different compositions could allow one to distinguish between the spin-1 and spin-0 cases.

In this paper we shall be concerned, mostly, with the properties of a new force due to the exchanges of spin-1 $U$ bosons. The couplings of such a new spin-1 $U$ boson associated with an extra $U(1)$ gauge invariance, that would both be very light and have a very small coupling constant $g''$, may be obtained using spontaneously broken gauge invariance, identifying both the vector part (in general a linear combination of the $B$ and $L$ currents with the electromagnetic current) and the axial part of the $U$ current, as we shall discuss in section 2. The resulting force acting on a body would add its effects to the force of gravity, but would depend on the composition of this body, not on its sole mass only. What can we know on the expected intensity of such a force? In general, unfortunately, not much! However, for a force of finite range $\lambda$ (even if it is very large), we shall see that its effective intensity $\tilde{\alpha}$ is related to the range $\lambda$ and to the symmetry-breaking scale $F$ of the extra $U(1)$ symmetry by $\tilde{\alpha} \sim 1/(\lambda^2 F^2)$ . But then, what can be the value of the symmetry-breaking scale $F$? Here particle physics comes back, through an “equivalence theorem”.

In a somewhat paradoxal way, the $U$ boson could be directly produced in particle physics experiments – even in the limit where its gauge coupling $g''$ gets extremely small, and even vanishes! This phenomenon, which sounds indeed, at first sight, rather surprizing, will be discussed in section 3 (together with the analogous phenomenon which occurs in supergravity theories, for the interactions of a light spin-3/2 gravitino). We shall see that such a massive but very light spin-1 $U$ boson behaves in fact very much as a quasi-massless pseudoscalar, having interactions proportional to $1/F^2$. This requires the symmetry-breaking scale $F$ to be large enough – the
$U$ boson even becoming, like an axion, quasi-”invisible” when the corresponding additional $U(1)$ symmetry is broken “at a high scale” – e.g. through a large singlet v.e.v.. In section 4 we shall see how particle decay experiments require, still in the above case of a $U$ boson having significant axial couplings, the extra $U(1)$ symmetry-breaking scale $F$ to be somewhat larger than the electroweak scale, and discuss the resulting implications for the possible violations of the Equivalence Principle, in this specific case. In section 5 we recall briefly that exchanges of new spin-1 or spin-0 bosons may also lead, in addition, to spin-dependent forces.

2 GENERAL FEATURES OF A NEW SPIN-1 INDUCED FORCE.

2.1 Possible extra $U(1)$ gauge symmetries.

For spin-1 particles we can rely on the general principle of gauge invariance to determine the possible couplings of a spin-1 $U$-boson, and the expected properties of the corresponding force, should it exist (Fayet, 1990). To do so we first identify the possible extra $U(1)$ symmetries of a Lagrangian density, which are potential candidates for being gauged. This turns out to depend crucially on the number of Higgs doublets responsible for the electroweak breaking. In the Standard Model there is no other $U(1)$ symmetry than those associated with the conservations of baryon and lepton numbers ($B$ and $L_i$), and with the weak hypercharge $Y$ generating the $U(1)$ subgroup of $SU(2) \times U(1)$. More generally, in any renormalizable theory with only one Higgs doublet, any $U(1)$ symmetry generator $F$ must act on quarks and leptons as a linear combination:

$$F = \alpha B + \beta_i L_i + \gamma Y. \quad (1)$$

Supersymmetric theories, however, require two Higgs doublets. This leaves room for an additional $U(1)$ invariance, since we may now perform independent phase rotations on these two doublets. With two Higgs doublets separately responsible for up-quark masses ($h_2$), and down-quark and charged-lepton masses ($h_1$), we now get:

$$F = \alpha B + \beta_i L_i + \gamma Y + \mu F_{ax}, \quad (2)$$

$F_{ax}$ being an extra $U(1)$ generator corresponding to a symmetry group $U(1)_A$ acting axially on quarks and leptons. This $U(1)_A$ itself or, more generally, an extra $U(1)$ generated by a linear combination as given in (2) was gauged, in the first supersymmetric models of 1976-1977, to trigger spontaneous supersymmetry breaking without having to resort to soft supersymmetry-breaking terms. Such models provided, very early, a natural framework for a possible new long-or-intermediate-range “fifth force”

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3 This, however, also raised the delicate question of anomaly cancellation, although anomalous $U(1)$’s might possibly be tolerated after all ...
(Fayet, 1980, 1981, 1986a, 1986b), which may now be considered, independently of supersymmetry (for which, in any case, other methods of supersymmetry breaking are now generally employed). Furthermore, in grand-unified theories with large gauge groups including $SU(5)$ or $O(10)$, quarks are related to leptons, so that $B$ and $L$ no longer appear separately, but only through their difference $B-L$. The general form of an extra $U(1)$ symmetry generator that could be gauged is then given by:

$$F = \eta \left( \frac{5}{2} (B-L) - Y \right) + \mu F_{ax} .$$

(3)

2.2 Expression of the new “charge” $Q_5$.

To know on which quantity the new force should really act (still within the framework of a renormalizable theory), we also have to take into account mixing effects between neutral gauge bosons. The resulting $U$ current involves a linear combination of the extra-$U(1)$ current identified previously, with the $Z$ weak neutral current $J_Z = J_3 - \sin^2 \theta J_{em}$. For simple Higgs systems the extra-$U(1)$ generator, and subsequently the $U$-current, does not depend on the quark generation considered. The new force should then act on quarks in a flavor-conserving and generation-independent way. There should be no couplings to strangeness, charm or beauty, nor on mass itself either (in which case no “deviation from the Equivalence Principle” would have to be expected). Couplings to a linear combination of $B$ and $L$ with the electrical charge $Q$, as well as couplings involving particle spins, are expected instead (Fayet 1986a, 1986b, 1990). They will originate from the vector and axial parts in the $U$ current, respectively.

The vector part in the $U$ current is found to be a linear combination of baryonic and leptonic currents with the electromagnetic current, associated with the (normally conserved) charge

$$Q_5 = xB + y_i L_i + zQ_{el} ,$$

(4)

which reduces to

$$Q_5 = x(B-L) + zQ_{el} ,$$

(5)

in the framework of grand-unification. Even if the new force acts in general on electrons as well as on protons and neutrons, the above formulas further simplify, for ordinary neutral matter, into

$$Q_5 = xB + yL = x(N+Z) + yZ ,$$

(6)

or, in grand-unification, to

$$Q_5 = x (B-L) = x N .$$

(7)

The action of such a spin-1-induced fifth force on neutral matter may then be written in an additive way, proportionally to a linear combination of the numbers of
protons (and electrons) and neutrons, $Z$ and $N$. This is of course not true for the gravitational force itself, and has no reason to be true in the case of a force induced by spin-0 exchanges. (As an illustration, this means, for example, that the $U$-induced force acting on a helium-4 atom should be twice the force acting on a deuterium atom — while the mass of this helium-4 atom differs from twice the mass of a deuterium atom.) In the framework of grand-unification, $B$ and $L$ only appear through their difference so that the new force is expected to act effectively on neutrons only. When the $U$ boson is massless or almost massless and the extra $U(1)$ gauge coupling is extremely small, one expects (very small) violations of the Equivalence Principle, since the numbers of neutrons and protons in an object are not exactly proportional to its mass.

Should such a force be discovered, its properties may be used to test its origin, and whether it is due to spin-1 or spin-0 particles, for example, since a spin-0 induced force has no reason to act additively, precisely on a linear combination of $B$ and $L$ (not to mention the very specific combination $B - L$ which could appear in grand-unified theories).

### 2.3 A relation between range and intensity?

The next things one would like to know are, of course, the possible range of the new force and its expected intensity, relatively to gravity.

The range could be infinite if the $U$ boson stays massless. This occurs for example if there is only a single Higgs doublet (and no other Higgses), so that the $SU(3) \times SU(2) \times U(1) \times$ extra-$U(1)$ gauge group gets broken down to $SU(3) \times U(1)_{\text{QED}} \times U(1)_{U\text{-boson}}$, the $U$ boson remaining exactly massless and coupled to a linear combination of the conserved $B$, $L$ and electromagnetic currents (Fayet, 1989). The intensity of the new force, determined by the value of the extra $U(1)$ gauge coupling constant $g''$, remains, at this stage, essentially arbitrary. It might be extremely small, especially if the extra $U(1)$ turns out to be linked in some way with gravitational interactions.

In general, however, both the range of the new force and its possible intensity appear as largely arbitrary. Still for any given symmetry breaking scale $F$ these two quantities turn out to be related as follows:

"the longer the range $\lambda$, the smaller the expected intensity".

The origin of this interesting relation is in fact not mysterious. The $U$ boson mass — when it does not vanish — determines the range of the corresponding force by the usual formula of quantum physics:

$$\lambda = \frac{\hbar}{m_U c} \approx 2 \text{ meters} \times \frac{10^{-7} \text{ eV}/c^2}{m_U}.$$  

(8)
Large masses \( \gtrsim 200 \text{ GeV} / c^2 \) – well within the domain of particle physics – would correspond to extremely short ranges \( \lambda \lesssim 10^{-16} \text{ cm} \), less than the range of weak interactions. On the other hand very small masses of \( 10^{-10} \text{ eV} / c^2 \) or less, for example, would lead to large macroscopic ranges of 2 kilometers or more. The new force would then superpose its effects to those of gravitation, leading to apparent violations of the Equivalence Principle; and also, depending on the range, to apparent deviations from Newton’s \( 1/r^2 \) law of gravitation.

Let us now turn to the intensity of the new force, considered relatively to gravity. It may be characterized, at distances smaller than the range \( \lambda \), by the dimensionless ratio

\[
\tilde{\alpha} \approx \frac{\left( \frac{g''}{4} \right)^2 / 4\pi}{G_{\text{Newton}} \, m^2_{\text{proton}}} \approx 10^{36} \, g''^2 ,
\]

(9)

\( g'' \) being the extra-\( U(1) \) gauge coupling constant, a priori unknown but which may be extremely small (especially, again, if the extra \( U(1) \) symmetry turns out to be linked in some way with gravity itself). The \( U \) mass is related to the extra-\( U(1) \) symmetry-breaking scale \( F \), determined by the appropriate Higgs v.e.v.’s, by a relation which may be written as

\[
m_U \approx g'' \frac{F}{2} .
\]

(10)

For a given scale \( F \), the relative intensity of the new force then behaves like

\[
\tilde{\alpha} \sim g''^2 \sim \frac{m_U^2}{F^2} \sim \frac{1}{\lambda^2 \, F^2} ,
\]

(11)

or, more precisely, with an uncertainty reflecting the effects of the model-dependent factors in the coefficients (Fayet, 1986a, 1986b):

\[
\tilde{\alpha} \approx \frac{1}{\lambda (\text{meter})^2} \left( \frac{250 \text{ GeV}}{F} \right)^2 .
\]

(12)

This relation looks very nice, but before we can really use it we must know or assume something about the symmetry-breaking scale \( F \). Before discussing this point in the next sections, let us assume for the moment, as an illustration, that the extra \( U(1) \) is broken at or around the electroweak scale \( (\approx 250 \text{ GeV}) \), a natural benchmark in particle physics. We would then get for small (or moderate) values of the range \( \lambda \), rather large (or not so small) values of \( \tilde{\alpha} \), e.g.

\[
\tilde{\alpha} \approx \begin{cases} 
10^7 - 10^9 & \text{if } \lambda \approx 10^{-1} \text{ mm} , \\
10^{-3} - 10^{-5} & \text{if } \lambda \approx 100 \text{ m} ,
\end{cases}
\]

(13)

values which are already forbidden by existing gravity experiments including those performed at short distances (Hoskins, 1985; Mitrofanov and Ponomareva, 1988;
Adelberger et al., 1990; Su et al., 1994; Lamoreaux, 1997; Long et al., 1999; Smith et al., 2000; Hoyle et al., 2001), which imply, for example, that $\tilde{\alpha}$ should be smaller than $10^{-1}$ for ranges $\lambda \gtrsim 1$ mm. This corresponds to the fact that in such cases the new extra $U(1)$ gauge coupling $g''$ is not so small compared to $10^{-19}$ or even significantly larger in the case of a small $\lambda$, so that the new force is not so small compared to gravity or may even dominate it at small distances.

On the other hand we would have

$$\tilde{\alpha} \approx \begin{cases} 10^{-5} - 10^{-7} & \text{if } \lambda \simeq 1 \text{ km} , \\ 10^{-11} - 10^{-13} & \text{if } \lambda \simeq 10^3 \text{ km} , \end{cases}$$

(14)

the latter case, which would lead to apparent violations of the Equivalence Principle at the level of $10^{-13}$ to $10^{-16}$, being within the reach of the future MICROSCOPE and STEP experiments – sensitive only to ranges $\lambda$ larger than a few hundreds of kilometers, given the elevation at which the satellite should orbitate. But, as we have already indicated, these estimates for $\tilde{\alpha}$ depend crucially on what the extra-$U(1)$ symmetry breaking scale $F$ is. Could there be some way to learn something about it?

No one would imagine, under normal circumstances, being able to search directly for ordinary massless gravitons in a particle physics experiment, due to the extremely small value of the Newton constant ($10^{-38}$, in units of GeV$^{-2}$), which determines the strength of the couplings of a single massless graviton to matter. Then how could we search directly, in particle decay experiments, for $U$-bosons with even smaller values of the corresponding coupling, $g''^2 \ll 10^{-38}$? Still this turns out to be possible! This rather astonishing result holds as soon as the $U$-current includes a (non-conserved, as the result of spontaneous symmetry breaking) axial part, as we shall see. The origin of this phenomenon involves an “equivalence theorem” between the interactions of spin-1 gauge particles and those of spin-0 particles, in the limit of very small gauge couplings. A similar “equivalence theorem” holds for the interactions of spin-3/2 and spin-1/2 particles, in the framework of supergravity/supersymmetric theories.

3 “EQUIVALENCE THEOREMS” FOR SPIN-1 AND SPIN-$^{3 \over 2}$ PARTICLES.

3.1 A very light spin-1 $U$ boson does not decouple for vanishing gauge coupling – but behaves like a spin-0 particle!

One might think that, in the limit of vanishing extra-$U(1)$ gauge coupling constant $g''$, the effects of the new gauge boson would be arbitrarily small, and may therefore be disregarded (as for graviton effects in particle physics). But in general this is
wrong, as soon as the $U$-current involves a (non-conserved) axial part – which is generally the case when a second Higgs doublet is present to break the electroweak symmetry, as in supersymmetric theories!

The amplitudes for emitting a very light ultrarelativistic $U$ boson are proportional to the new gauge coupling $g''$, and therefore seem to vanish with $g''$. This is, however, misleading, since the polarization vector for a longitudinal $U$ boson of four-momentum $k^\mu$, $\epsilon^\mu \simeq k^\mu/m_U$, becomes singular in this limit, since $m_U \approx g'' F/2$ also vanishes with $g''$. Altogether the amplitudes for emitting, or absorbing, a longitudinal $U$ boson, appear to be essentially proportional to $g''/m_U$. They have a finite limit, independent of $g''$, when this gauge coupling becomes very small and the mass of the $U$ boson gets also very small, so that this $U$ boson is ultrarelativistic (i.e. $k^\mu \gg m_U$). Such a $U$ boson then behaves very much like a spin-0 particle (Fayet 1980, 1981), somewhat reminiscent of an axion.

This “equivalence theorem” expresses that in the high-energy or low-mass limit ($E \gg m_U$), the third (longitudinal) degree of freedom of a massive $U$-boson continues to behave like the massless Goldstone boson which was “eaten away”. For very small $g''$ the spin-1 $U$-boson simply behaves as this massless spin-0 Goldstone boson. This applies as well to virtual exchanges. The exchanges of the $U$ boson do not disappear in this limit, owing to the non-conserved axial part in the $U$ current (in general present when there is more than one Higgs doublet). They become equivalent to the exchanges of a massless (pseudoscalar, $CP$-odd) spin-0 particle $a$, having effective axionlike couplings to leptons and quarks

$$2^{1/4} \frac{G_F}{F} \text{m}_{l,q} \begin{cases} x (\text{i.e. } 1/\tan\beta) \text{ for } u, c, t \text{ quarks} \\ 1/x (\text{i.e. } \tan\beta) \text{ for } \begin{cases} d, s, b \text{ quarks} \\ e, \mu, \tau \text{ leptons} \end{cases} \end{cases} \times \left( \frac{r \approx 250 \text{ GeV}}{F} \right) \gamma_5 \ , \quad (15)$$

$x$ denoting the ratio of the two Higgs doublet vacuum expectation values. Using notations which are standard in supersymmetry\textsuperscript{4}, where the first Higgs doublet is responsible for down-quark and charged-lepton masses, and the second one for up-quark masses, one has $1/x = v_2/v_1 = \tan\beta$. More precisely, these effective pseudoscalar couplings to quarks and leptons read

$$2^{1/4} \frac{G_F}{F} \text{m}_{l,q} \begin{cases} x (\text{i.e. } 1/\tan\beta) \text{ for } u, c, t \text{ quarks} \\ 1/x (\text{i.e. } \tan\beta) \text{ for } \begin{cases} d, s, b \text{ quarks} \\ e, \mu, \tau \text{ leptons} \end{cases} \end{cases} \times \left( \frac{r \approx 250 \text{ GeV}}{F} \right) \ ,$$

as for a standard axion

as for an “invisible” axion, if $r \ll 1$

\textsuperscript{4}The pseudoscalar $a$, here eaten away to become the third (longitudinal) degree of freedom for the massive $U$ boson, is of course by construction reminiscent of the well-known pseudoscalar $A$ of supersymmetric extensions of the standard model, which becomes the Goldstone boson of the $U(1)_A$ invariance when this one is taken as a symmetry of the Lagrangian density.
From there one can get, from particle physics, constraints on such a new spin-1 gauge boson, as we shall discuss in section 4. They will require the extra $U(1)$ symmetry-breaking scale $F$ to be larger than the electroweak scale. Note that the transverse polarization states of the $U$-boson still continue to behave as usual, and would be responsible, for small but non-vanishing $g^\prime$, for a very weak long-ranged “EP-violating” force, of intensity proportional to $g^\prime 2$, to which we shall return in section 4.

3.2 Increasing the symmetry-breaking scale $F$ (“invisible $U$-boson” and “invisible axion” mechanisms).

If the extra $U(1)$ gauge symmetry is broken at the electroweak scale ($F \approx 250$ GeV) by the two Higgs doublets $h_1$ and $h_2$ only, the spin-1 $U$-boson acquires, from its non-vanishing axial couplings, exactly the same effective pseudoscalar couplings (16) as a “standard” spin-0 axion (i.e., $r \equiv 1$). Just as the latter, it then turns out to be excluded by the results of $\psi$ and $\Upsilon$ decay experiments, i.e. searches for the decays $\psi \rightarrow \gamma + \text{“nothing”}$, $\Upsilon \rightarrow \gamma + \text{“nothing”}$, in which “nothing” stands for a quasimassless neutral spin-1 particle (the $U$-boson), or a spin-0 particle (such as the axion), remaining undetected in the experiments. Exit such a $U$ boson, and therefore the corresponding new force that could be due to $U$-boson exchanges?

Not necessarily! As we observed in 1980, to save the possibility of such a light $U$ boson (or just as well, to save the idea of the axion), one can introduce an extra Higgs singlet acquiring a large v.e.v. $\gg 250$ GeV, which would make the $U$ boson significantly heavier (although still remaining light!) without modifying the values of its (vector and axial) couplings to ordinary quarks and leptons. Its effective interactions with quarks and leptons, fixed by the ratio of the axial couplings – proportional to $g^\prime$ – to the mass $m_U$ (i.e. finally to the parameter $1/F$) may then become arbitrarily small, as one sees easily from the expression (16) of the resulting effective pseudoscalar couplings to quarks and leptons. The mechanism, which involves for the effective interaction of the $U$ boson, or of its equivalent pseudoscalar $a$, the suppression factor $r \approx 250$ GeV/$F \ll 1$, allows for making the $U$ boson effects in particle physics practically “invisible”, provided the extra $U(1)$ is broken “at a large scale” $F$ significantly higher than the electroweak scale.

Incidentally since a spin-1 $U$-boson, when very light, is produced and interacts very much as a spin-0 pseudoscalar axionlike particle (excepted that it does not decay into two photons), the mechanism we explained also provided us, at the same time, with a way to make the interactions of the axion almost “invisible”, at least in particle physics (Fayet 1980, 1981). This can be realized by breaking the corresponding global $U(1)_A$ symmetry, then considered as a Peccei-Quinn symmetry, at a very large scale, through a very large singlet vacuum expectation value, the resulting axion being mostly an electroweak singlet. We thus obtained simultaneously both the “invisible
3.3 The gravitino/goldstino “equivalence theorem” in supersymmetric theories.

The same phenomenon, in the case of local supersymmetry, called supergravity, expresses that a very light spin-$\frac{3}{2}$ gravitino (the superpartner of the spin-2 graviton, and also the gauge particle of the local supersymmetry), having interactions fixed by the gravitational “gauge” coupling constant $\kappa = \sqrt{8\pi G_N} \approx 4.1 \times 10^{-19}$ (GeV)$^{-1}$, would behave very much like a massless spin-$\frac{1}{2}$ goldstino, according to the “equivalence theorem” of supersymmetry (Fayet, 1977, 1979). Just as the mass of the $U$-boson is given in terms of the extra $U(1)$ gauge coupling $g''$ and symmetry breaking scale $F$ by the formula $m_U \approx \frac{g''}{2} F$, the mass of the spin-$\frac{3}{2}$ gravitino is fixed by its (known) gravitational “gauge” coupling constant $\kappa$ and the (unknown) supersymmetry-breaking scale parameter $d$, as follows:

$$m_{3/2} = \frac{\kappa d}{\sqrt{6}} \approx 1.68 \left( \frac{\sqrt{d}}{100 \text{ GeV}} \right)^2 10^{-6} \text{ eV}/c^2 . \quad (17)$$

The interactions of a light gravitino are in fact determined by the ratio $\kappa/m_{3/2}$, or $G_N/m_{3/2}^2$. As a result a sufficiently light gravitino might be detectable in particle physics experiments, despite the extremely small value of the Newton constant $G_N \approx 10^{-38}$ (GeV)$^{-2}$, provided the supersymmetry-breaking scale $\sqrt{d}$ is not too large. The gravitino would then be the lightest supersymmetric particle, with all other $R$-odd superpartners expected to ultimately produce a gravitino among their decay products, if $R$-parity is conserved. (In particular the lightest neutralino could decay into photon + gravitino, so that the pair-production of “supersymmetric particles” could lead to final states including two photons with missing energy carried away by unobserved gravitinos.)

For a sufficiently light gravitino one can also search for the direct production of a single gravitino associated with an unstable photino $\tilde{\gamma}$ (or more generally a neutralino), decaying into gravitino + $\gamma$, in $e^+e^-$ annihilations. Or for the radiative pair-production of two gravitinos in $e^+e^-$ or $p\bar{p}$ annihilations at high

\footnote{An equivalent notation makes use of a parameter $\sqrt{F} = \sqrt{d}/2^{1/4}$, defined so that $F^2 = d^2/2$. Furthermore, the supersymmetry-breaking scale ( $\sqrt{d}$ or $\sqrt{F}$) associated with a (stable or quasistable) light gravitino should in principle be smaller than a few $10^6$ GeV’s, for its mass to be sufficiently small ($m_{3/2} \lesssim 1 \text{ keV}/c^2$), so that relic gravitinos do not contribute too much to the energy density of the Universe. (Unless, of course, gravitinos turn out to be adequately diluted as the result of some appropriate inflation mechanisms.)}
energies (Fayet, 1982, 1986c; Brignole et al., 1998a, 1998b), e.g.
\[ e^+e^- \quad \text{(or \ } p\bar{p} \text{)} \rightarrow \gamma \quad \text{(or \ jet)} \quad + \quad 2 \ \text{unobserved \ gravitinos,} \quad (18) \]
which have cross-sections
\[ \sigma \propto \frac{G_N^2}{m_{3/2}^4} \alpha\text{ (or } \alpha_s\text{) } s^3 \propto \frac{\alpha\text{ (or } \alpha_s\text{) } s^3}{d^4}. \quad (19) \]
Although the existence of so light gravitinos may appear as relatively unlikely, such experiments are sensitive to gravitinos of mass \( m_{3/2} \lesssim 10^{-5} \text{ eV}/c^2 \), corresponding to supersymmetry-breaking scales smaller than a few hundreds of GeV’s.

4 IMPLICATIONS OF PARTICLE PHYSICS EXPERIMENTS ON NEW LONG-RANGE FORCES.

Without necessarily having to consider very large values of \( F \), we can use formula (16) (obtained with two Higgs doublets and an axial part in the \( U \)-current) to write the branching ratios for the radiative production of \( U \) bosons in quarkonium decays, proportionally to \( r^2 \) (or \( 1/F^2 \)):
\[
\begin{align*}
B ( \psi \rightarrow \gamma + U ) & \simeq 5 \times 10^{-5} \quad r^2 \frac{x^2}{C_\psi} \quad (20) \\
B ( \Upsilon \rightarrow \gamma + U ) & \simeq 2 \times 10^{-4} \quad (r^2/x^2) \quad C_\Upsilon
\end{align*}
\]
\( (C_\psi \text{ and } C_\Upsilon, \text{ expected to be larger than } 1/2, \text{ take into account QCD radiative and relativistic corrections). The } U \text{ boson, quasi-stable or decaying into } \nu\bar{\nu}, \text{ would remain undetected (as for an axion decaying into two photons outside the detector). From the experimental limits (Edwards et al., 1982; Crystal Ball coll., 1990; CLEO coll., 1995):} \]
\[
\begin{align*}
B ( \psi \rightarrow \gamma + \text{“nothing”} ) & < 1.4 \times 10^{-5} , \\
B ( \Upsilon \rightarrow \gamma + \text{“nothing”} ) & < 1.5 \times 10^{-5} , \quad (21)
\end{align*}
\]
we deduce \( r \lesssim 1/2 \), i.e. that the extra-\( U(1) \) symmetry should be broken at a scale \( F \) at least of the order of twice the electroweak scale (Fayet, 1980, 1981, 1986a, 1986b). (Scales larger than \( \sim 10^7 - 10^{10} \text{ GeV might be preferred, however, for astrophysical reasons.})

This result, obtained for a \( U \) with non-vanishing axial couplings, can be translated (assuming vector and axial parts in the \( U \) current to be of similar magnitudes) into an approximate upper bound on the relative strength of the new force, as a function of its range \( \lambda \):
\[
\tilde{\alpha} \approx \frac{\left( \frac{q^2}{4} \right)^2}{4\pi G_{\text{Newton}} m_{\text{proton}}^2} \approx \frac{1}{\lambda (\text{meter})^2} \left( \frac{250 \text{ GeV}}{F} \right)^2 \lesssim \frac{1}{\lambda (\text{meter})^2}. \quad (22)
\]
These particular constraints allow for a new force that, if it had a short range, could be very large compared to the gravitational force (e.g. up to $\tilde{\alpha} \approx 10^6$ for a range $\lambda \simeq 1$ millimeter, for example), but such large values are already forbidden by short-range gravity experiments (Hoyle et al., 2001). If, on the other hand, the range $\lambda$ turns out to be large, the constraints (22) become quite significant, and may be used to restrict or even practically exclude, in many cases, the existence of the new force of the special type considered here, whose relative intensity is then experimentally constrained to be rather small. As an illustrative example with $\lambda = 10^3$ km, we would get $\tilde{\alpha} \lesssim 10^{-11} - 10^{-13}$, corresponding to expected violations of the Equivalence Principle

$$\lesssim 10^{-13} - 10^{-16},$$

with an upper bound still within the sensitivity of the MICROSCOPE and STEP experiments. For significantly larger $\lambda$'s, however, the violations are likely to remain undetectable, in the present case of a spin-1 $U$-boson with non-vanishing axial couplings.

5 NEW FORCES ACTING ON PARTICLE SPINS.

5.1 Spin-spin interactions.

In addition to the previous effects, the exchanges of a new spin-1 $U$ boson could also lead to a new, possibly long-ranged, spin-spin interaction between two quarks and/or leptons (Fayet, 1986b). It is, at distances $\rho$ small compared with the range $\lambda = h/m_U c$:

$$\frac{G_F}{8 \pi \sqrt{2}} \frac{3 \bar{\sigma}_1 \cdot \hat{\rho} \bar{\sigma}_2 \cdot \hat{\rho} - \bar{\sigma}_1 \cdot \bar{\sigma}_2}{\rho^3} (x \text{ or } 1/x) (x \text{ or } 1/x) r^2 \quad (24)$$

($\hat{\rho} = \hat{\rho}/\rho$ denoting the unit vector defined by the two particles), with the constraint $r \lesssim 1/2$ deduced from $\psi$ and $\Upsilon$ decay experiments. The spin-spin potential (24), proportional to $1/F^2$, preserves all $P$, $C$ and $T$ symmetries and is the same as for the exchange of a quasimassless axionlike pseudoscalar (Moody and Wilczek, 1984), in agreement with the general equivalence theorem discussed in section 3.

This can be understood from the expression of the spin-1 $U$ boson propagator,

$$\left( g^{\nu 2} \right) \frac{g^{\mu \nu} + q^\mu q^\nu}{q^2 + m_U^2} = \left( g^{\nu 2} \right) \frac{q^\mu q^\nu}{m_U^2} + \frac{q^\mu q^\nu}{q^2 + m_U^2} + \ldots \quad (25)$$

For small $m_U$ (or large energies $E \gg m_U$) the dominant contribution arises from the $\frac{q^\mu q^\nu}{m_U^2}$ term, contracted with (non-conserved) axial contributions to the $U$ current. Moreover $g^{\nu 2}/m_U^2 \approx 1/F^2 \approx G_F r^2$, while $\frac{1}{q^2 + m_U^2}$ leads to a Yukawa potential at distance $\rho$ proportional to $\frac{\alpha_4}{\rho}$; $q^\mu$ and $q^\nu$ (corresponding to derivative operators
in position space) are contracted with axial current contributions proportional to \( \bar{q} \gamma^\mu \gamma_5 q \) and \( \bar{l} \gamma^\mu \gamma_5 l \) which, in the non-relativistic limit, involve the spin \( \vec{\sigma} \) of the quarks or leptons between which \( U \) bosons are exchanged.

Both in the spin-1 \( U \)-boson and in the spin-0 axion cases, the spin-spin potential is proportional to \( 1/F^2 \). In the axion case however, there is a specific relationship between the range \( \lambda \) and the symmetry breaking scale \( F \), which may be written as:

\[
\lambda_{\text{axion}} = \frac{\hbar}{m_a c} \approx 2 \text{ mm} \quad \frac{F}{10^{11} \text{ GeV}} \lesssim \text{ cm} .
\] (26)

From astrophysics constraints one usually expects \( F \) to be in the \( \approx 10^7 \) (or \( 10^{10} \)) GeV up to \( \approx 10^{12} \) GeV range, so that an axion-induced force should in principle be short-ranged (\( \lesssim \text{ cm} \)). (For larger values of \( F \) and \( \lambda \) the axion-induced force, proportional to \( 1/F^2 \), would be negligible anyway.) In the spin-1 \( U \)-boson case, on the other hand, the relation between \( \lambda \) and \( F \) involves the extra-\( U(1) \) gauge coupling \( g^* \) (with \( \lambda_U = \hbar/m_U c \approx 1/g^* F \)), so that the \( U \)-boson spin-spin force may be short-ranged or long-ranged as well.

### 5.2 A \( CP \)-violating “mass-spin” coupling?

If \( CP \)-violation effects are introduced, exchanges of a spin-1 \( U \)-boson may also lead to a very small \( CP \)-violating interaction, resulting in a monopole-dipole force which may be tested in a mass-spin coupling experiment. Again this spin-1-induced force (Fayet, 1996) is similar to the one obtained for a quasi-massless spin-0 axion (or axionlike particle) (Moody and Wilczek, 1984).

Indeed in the presence of \( CP \)-violation effects, we may get – again from the \( q^\mu q^\nu \) term in the spin-1 propagator – additional contributions originating from the product of a \( \vec{\sigma}. \vec{q} \) term for one fermion, times a scalar density for the other. They can mimic an effective interaction resulting from the exchanges of a spin-0 particle having the usual pseudoscalar couplings (16), now supplemented with very small effective (\( P \) and \( CP \)-violating) scalar couplings with quarks. We may use an angle “\( \theta \)” to parametrize these \( CP \)-violation effects, and write the effective \( CP \)-violating quark scalar couplings as proportional to \( G_F^{1/2} r m \theta \). This leads to an interaction between the spin and the gradient of the Yukawa potential \( e^{-\frac{\rho}{\rho}} \). The resulting \( CP \)-violating interaction, at distance \( \rho \), is proportional to

\[
G_F r^2 m \theta \quad \vec{\sigma}_1. \hat{\rho} \quad \left( \frac{1}{\lambda \rho} + \frac{1}{\rho^2} \right) \quad e^{-\frac{\rho}{\rho}} \approx \frac{\theta}{F^2} ... ,
\] (27)

in which \( r \) (\( \approx 250 \text{ GeV}/F \)) is smaller than unity, and \( \theta \), presumably \( \lesssim 10^{-9} \), measures the magnitude of \( CP \)-violating effects. It can be rewritten in terms of effective pseudoscalar and scalar couplings – both proportional to \( 1/F \) – as

\[
\frac{g_p^{(1)}}{8 \pi m_1} \quad \frac{g_s^{(2)}}{8 \pi m_1} \quad \vec{\sigma}_1. \hat{\rho} \quad \left( \frac{1}{\lambda \rho} + \frac{1}{\rho^2} \right) \quad e^{-\frac{\rho}{\rho}} \approx \frac{\theta}{F^2} ... .
\] (28)
Could such an interaction (which violates the $P$, $CP$ and $T$ symmetries) be detected in an appropriate experiment searching for a coupling between bulk matter and polarized spins (“mass-spin coupling experiment”)? This depends on the range $\lambda$ of the interaction and of its effective intensity, proportional to $\frac{g}{F^2}$ both in the spin-1 and spin-0 cases. Again for a spin-0 axion the range $\lambda$ is proportional to $F$ and expected to be rather short ($\lesssim \text{cm}$, for $F \lesssim 10^{12}$ GeV). Even in the most favorable case for which $\lambda \sim \text{mm}$, the new axion force seems generally too weak to be detectable.

In contrast the mass of a spin-1 $U$ boson, governed by $g^* F$, may be very small (and therefore the range $\lambda$ rather large, $\gtrsim \text{cm}$) as the result of a very small value of $g^*$, even with a symmetry-breaking scale $F$ not much larger than the electroweak scale. This could make the new “mass-spin” coupling both long-ranged and relatively “intense” (since it is proportional to $1/F^2$). The $CP$-violating spin-dependent potential, still proportional to $\theta/F^2$ (i.e. in this case $\approx g^*^2 \theta \lambda^2$) may then be significantly larger than for an axion, and could, optimistically, be experimentally accessible, in favorable situations.

6 CONCLUSIONS.

As we just saw the exchanges of a new spin-1 $U$ boson, or of a spin-0 particle such as the axion, could lead to new forces acting on particle spins, so that one can search for a ($P$ and $CP$-conserving) spin-spin interaction, and a ($P$ and $CP$-violating) “mass-spin coupling” interaction.

Returning to possible “violations of the Equivalence Principle”, we emphasize that the contraints discussed section 4, which are rather drastic in the case of a long-range force, concern the case of a spin-1 $U$ boson having non-vanishing axial couplings, on which we have been concentrating here. In this case the corresponding expected EP violations, proportional to $1/\lambda^2 F^2$, are generally too small to be experimentally accessible to satellite tests of the Equivalence Principle, excepted maybe for ranges of about a few hundreds to a few thousands kilometers. For a $U$-boson coupled to a purely vectorial current, on the other hand – or in the case of a new force due to spin-0 exchanges – no such constraints are obtained. Then the strength of the new force and its range (finite or infinite) remain unrelated parameters.

Very precise tests of the Equivalence Principle could then be sensitive to new forces, and could in principle allow us to distinguish between the two possibilities of spin-0 or spin-1 induced forces. For a spin-1 $U$ boson with non-vanishing axial couplings the intensity of the new force is in general constrained to be extremely weak if it is long-ranged, otherwise it remains essentially a free parameter. Testing, to a very high degree of precision, the Equivalence Principle in Space would bring new constraints on Fundamental Physics, and might conceivably lead to the spectacular discovery of a new long-ranged interaction, should a deviation from this Principle be found.
REFERENCES

Adelberger, E.G., et al., *Phys. Rev.* D **42**, 3267, 1990.
Blaser, J.-P., et al., STEP, Report on the Phase A Study, ESA report SCI (96) 5, 1996.
Brignole, A., et al., *Nucl. Phys.* B **516**, 13, 1998a [erratum B **555**, 653, 1999].
Brignole, A., et al., *Nucl. Phys.* B **526**, 136, 1998b [erratum B **582**, 759, 2000].
CLEO Coll., *Phys. Rev.* D **51**, 2053, 1995.
Connes, A., T. Damour, and P. Fayet, *Nucl. Phys.* B **490**, 391, 1997.
Crystal Ball Coll., *Phys. Lett.* B **251**, 204, 1990.
Damour, T., and A.M. Polyakov, *Nucl. Phys.* B **423**, 532, 1994.
Dine, M., W. Fischler, and M. Srednicki, *Phys. Lett.* B **104**, 199, 1981.
Edwards, C., et al., *Phys. Rev. Lett.* **48**, 903, 1982.
Fayet, P., *Phys. Lett.* B **70**, 461, 1977.
Fayet, P., *Phys. Lett.* B **86**, 272, 1979.
Fayet, P., *Phys. Lett.* B **95**, 285, 1980.
Fayet, P., *Nucl. Phys.* B **187**, 184, 1981.
Fayet, P., *Phys. Lett.* B **117**, 460, 1982.
Fayet, P., *Phys. Lett.* B **171**, 261, 1986a; B **172**, 363, 1986b; B **175**, 471, 1986c.
Fayet, P., *Phys. Lett.* B **227**, 127, 1989.
Fayet, P., *Nucl. Phys.* B **347**, 743, 1990.
Fayet, P., *Class. Quant. Grav.* **13**, A19, 1996.
Fayet, P., hep-ph/0107228, Int. Symp. “30 years of supersymmetry”, Nucl. Phys. Proc. Suppl. 101, 81, 2001.
Hoyle, C.D., et al., *Phys. Rev. Lett.* **86**, 1418, 2001.
Hoskins, J.K., et al., *Phys. Rev.* D **32**, 3084, 1985
Lamoreaux, S.K., *Phys. Rev. Lett.* **78**, 5, 1997.
Long, J.C., H.W. Chan, and J.C. Price, *Nucl. Phys.* **539**, 23, 1999.
Mitrofanov, V.P., and O.I. Ponomareva, Zh. Eksp. Teor. Fiz. **94**, 16, 1988 [Sov. Phys. JETP **67**, 1963, 1988].
Moody, J.E., and F. Wilczek, *Phys. Rev.* D **30**, 130, 1984.
Müller, J., et al., Proc. 8th Marcel Grossmann Meeting, Jerusalem, 1151, 1997.
Müller, J., and K. Nordtvedt, *Phys. Rev.* D **58**, 062001, 1998.
Roll, P.G., R. Krotkoov, and R.H. Dicke, *Ann. Phys.* **26**, 442, 1964.
Smith, G.L., et al., *Phys. Rev.* D **61**, 022001, 2000.
Su, Y., et al., *Phys. Rev.* D **50**, 3614, 1994.
Touboul, P., MICROSCOPE, in *Advances in Space Research*, 2001, to appear.
Vitale, S., The STEP Project, in *Advances in Space Research*, 2001, to appear.
Weinberg, S., *Phys. Rev. Lett.* **40**, 223, 1978.
Wilczek, F., *Phys. Rev. Lett.* **40**, 279, 1978.
Williams, J.G., X.X. Newhall, and J.O. Dickey, *Phys. Rev.* D **53**, 6730, 1996.
Zhitnisky, A.P., *Yad. Fiz.* **31**, 497, 1980 [Sov. J. Nucl. Phys. **31**, 260, 1980].