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The existence of a light or massive scalar field with a coupling to matter weaker than gravitational strength is a possible source of violation of the weak equivalence principle. We use the first results on the Eötvös parameter by the MICROSCOPE experiment to set new constraints on such scalar fields. For a massive scalar field of mass smaller than 10^{-12} eV (i.e. range larger than a few 10^5 m) we improve existing constraints by one order of magnitude to $|\alpha| < 10^{-11}$ if the scalar field couples to the baryon number and to $|\alpha| < 10^{-12}$ if the scalar field couples to the difference between the baryon and the lepton numbers. We also consider a model describing the coupling of a generic dilaton to the standard matter fields with five parameters, for a light field: we find that for masses smaller than 10^{-12}eV, the constraints on the dilaton coupling parameters are improved by one order of magnitude compared to previous equivalence principle tests.

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Scalar-tensor theories are a wide class of gravity theories that contain general relativity [1]. In the Newtonian limit, they imply the existence of a fifth force, that can be well-described by a Yukawa deviation to Newtonian gravity. Its range depends mostly on the mass of the scalar field and can vary from sub-millimetric to cosmological scales [2, 3]. It has so far been constrained on all scales from a few microns to the largest scales of the Universe (see e.g. Refs.[1, 4, 5]).

This new force may or may not be composition-dependent, depending on whether or not its coupling to matter is universal or not. A non-universal coupling implies both a violation of the weak equivalence principle (WEP) and a variation of the fundamental constants. The former effect has already been exploited by the Eöt-Wash group to bring the current best constraints on Yukawa-type interactions and on light dilaton interactions [6–8], while the latter allows one to set constraints on cosmological to local scales [9–11].

The MICROSCOPE satellite aims to constrain the WEP in space [12, 13] by measuring the Eötvös parameter, defined as the difference of acceleration between two bodies i and j in the same gravity field, $\eta = (\Delta a/a)_{ij} = 2|\vec{a}_i - \vec{a}_j|/|\vec{a}_i + \vec{a}_j|$. First results [14] give

$$\eta = (-1 \pm 27) \times 10^{-15} \tag{1}$$

at a 2-σ confidence level. MICROSCOPE tests the WEP by finely monitoring the difference of acceleration of freely-falling test masses of different composition (Platinum and Titanium) as they orbit the Earth, measured along the principal axis of the (cylindrical) test masses. The measurement equation is given e.g. in [14] as $a_{\rm Pt} - a_{\rm Ti} = g_x\eta + f(\vec{p}, n)$, where g_x is the projection of the Earth gravity field onto the axis of the test and $f(\vec{p}, n)$ is a function of the instrumental and environmental parameters and measurement noise.

The constraint (1) was obtained after analyzing only two measurement sessions; therefore, the error bars should be considered as the largest that can be expected from the whole MICROSCOPE mission. The statistical error is expected to decrease with increasing data and with the refinement of the data analysis by the end of the mission in 2018. In the meantime, this new constraint of the WEP can already be used to set new bounds on fifth force characteristics. This letter focuses on the implications of the first results of MICROSCOPE for an interaction between matter and a light dilaton.

Scalar fifth force. The existence of a light scalar field ϕ modifies the Newtonian interaction between two bodies i and j of masses m_i and m_j by a Yukawa coupling [15]

$$V_{ij}(r) = -\frac{Gm_i m_j}{r}\left(1 + \alpha_{ij}\mathrm{e}^{-r/\lambda}\right). \tag{2}$$

The scalar coupling to matter α_{ij} can be decomposed as the product $\alpha_i\alpha_j$ of the scalar couplings to matter measured by the dimensionless factors

$$\alpha_i \equiv \frac{\partial \ln m_i/M_P}{\partial\phi/M_P} \tag{3}$$

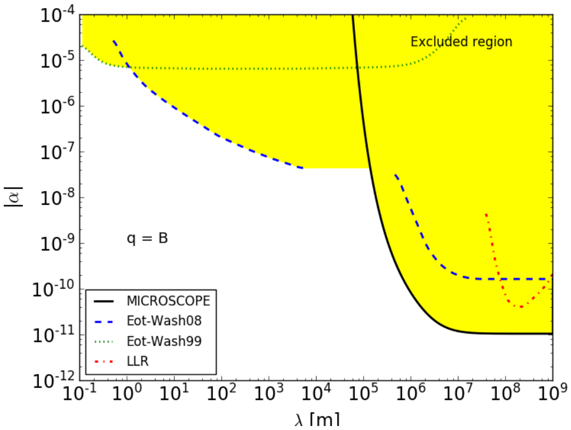

FIG. 1. Constraints on the Yukawa potential parameters (α, λ) with $q = B$. The excluded region is shown in yellow and compared to earlier constraints from Ref. [16] (dotted), Ref. [6] (dashed) and Refs. [17, 18] (dot-dashed). MICROSCOPE (solid line) improves on the Eöt-Wash contraints by one order of magnitude for $\lambda >$ a few 10^5 m.

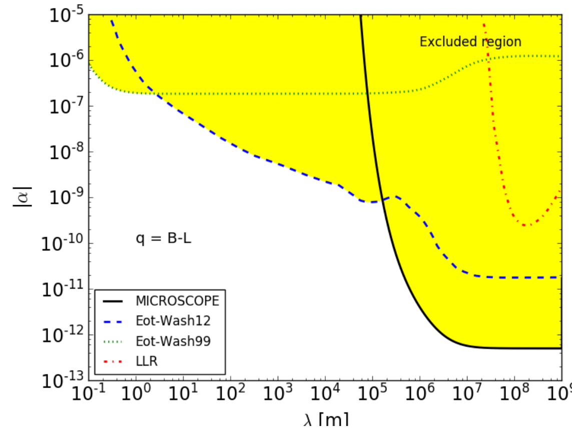

FIG. 2. Same as Fig. 1, but with $q = B - L$, compared to the earlier constraints from Ref. [16] (dotted), Ref. [7] (dashed) and Refs. [17, 18] (dot-dashed).

with $M_P^{-1} = \sqrt{4\pi G}$ the Planck mass. The range λ of the Yukawa interaction is related to the mass of the field by $\lambda = \hbar/m_\phi c$. The amplitude of the WEP violation is related to the presence of a scalar field that does not couple universally to all forms of energy, contrary to general relativity. The magnitude of the scalar force varies from element to element and is characterized by $\alpha_i(\phi)$ which requires to determine $m_i(\phi)$ and thus to specify the couplings of the scalar field to the standard model fields. Any dynamics or gradient of this scalar fields thus induce a spatial dependence of the fundamental constants [9, 10]. For two test masses in the external field of a body E, the Eötvös parameter reduces to

$$\eta = \frac{(\alpha_i - \alpha_j)\alpha_E}{1 + \frac{1}{2}(\alpha_i + \alpha_j)\alpha_E} \simeq (\alpha_i - \alpha_j)\alpha_E. \qquad (4)$$

In order to set constraints, we need to specify the couplings of the field to matter as well as its masses.

Baryonic/Leptonic charges. The simplest analysis consists in assuming that the composition-dependent coupling α_{ij} depends on a scalar dimensionless "Yukawa charge" q, characteristic of each material as [6, 7]

$$\alpha_{ij} = \alpha \left(\frac{q}{\mu}\right)_i \left(\frac{q}{\mu}\right)_j, \qquad (5)$$

where α is a universal dimensionless coupling constant which quantifies the strength of the interaction with respect to gravity and μ is the atomic mass in atomic units (e.g. $\mu = 12$ for carbon-12, or $\mu = 47.948$ for titanium). Different definitions of the charge q are possible depending on the detailed microscopic coupling of the scalar field to the standard model fields. At the atomic levels, taking into account the electromagnetic and nuclear binding energies, the charge are usually reduced to the materials's baryon and/or lepton numbers (B and L) (see e.g. Refs. [19, 20]). Hence, for a macroscopic body, we must considered its isotopic composition. Hereafter, we shall set constraints on such interactions with either $q = B$ or $q = B - L$.

Following Ref. [14] and their approximations, it follows that for MICROSCOPE, the Eötvös parameter due to a Yukawa potential is

$$\eta = \alpha \left[\left(\frac{q}{\mu}\right)_{\rm Pt} - \left(\frac{q}{\mu}\right)_{\rm Ti}\right]\left(\frac{q}{\mu}\right)_E \left(1 + \frac{r}{\lambda}\right) e^{-\frac{r}{\lambda}} \qquad (6)$$

where $r = R_E + h$ is the mean distance from the satellite to the center of the Earth, with $h \approx 710$ km its mean altitude [21] and R_E is the Earth mean radius. The Earth charge takes into account the Earth differentiation between core and mantle

$$\left(\frac{q}{\mu}\right)_E = \left(\frac{q}{\mu}\right)_{\rm core} \Phi\left(\frac{R_c}{\lambda}\right) + \left(\frac{q}{\mu}\right)_{\rm mantle}\left[\Phi\left(\frac{R_E}{\lambda}\right) - \Phi\left(\frac{R_c}{\lambda}\right)\right], \qquad (7)$$

where R_c is the Earth core radius. The function $\Phi(x) \equiv 3(x\cosh x - \sinh x)/x^3$ [4] takes into account the fact that all Earth elements do not contribute similarly to the Yukawa interaction at the satellite's altitude [22] ($\Phi = 1$ for the test masses since their sizes are much smaller than the ranges λ that can be probed in orbit). We assume that the core of the Earth is composed of iron and that the mantle is composed of silica (SiO_2) [23]. The baryonic and lepton charges for the MICROSCOPE experiment are summarized in Table I.

At the 2-σ level, MICROSCOPE's constraints on the Eötvös parameter are given by Eq. (1), and can readily be transformed into constraints on Yukawa's $(\alpha,\ \lambda)$.

TABLE I. Baryonic, leptonic and dilaton charges for MICROSCOPE's test masses.

Material	B/μ	$(B-L)/\mu$	$Q'_{\tilde m}$	Q'_e
Pt/Rh	1.00026	0.59668	0.0859	0.0038
Ti/Al/V	1.00105	0.54044	0.0826	0.0019

Figs 1 and 2 depict the corresponding exclusion regions respectively for $q = B$ and $q = B - L$. In both analyses, we compare our new constraint to the bounds from Eöt-Wash's torsion pendulum experiments [6, 7, 16] and the constraints from the Lunar-Laser Ranging experiment [17, 18]. This shows that MICROSCOPE's first results allow us to gain one order of magnitude compared to previous analyses for $\lambda >$ a few 10^5m. As MICROSCOPE orbits Earth at about 7000 km from its center, one would naively expect that it can only probe interactions with $\lambda >$ a few 10^6m; smaller ranges could not be probed as they imply too much of a damping at MICROSCOPE's altitude. However, would a fifth force with $\lambda \approx$ a few 10^5m be strong enough to affect MICROSCOPE, the contribution from the nearest point to the Earth (as seen from MICROSCOPE) would be higher than that of the farthest point of the Earth, implying an asymmetric behavior that can be probed by MICROSCOPE (as captured by the function $\Phi(x)$ above). Hence, MICROSCOPE is sensitive to scalar interactions with ranges as low as a few hundreds of kilometers.

Dilaton models. We now consider the characteristics of a generic dilaton with couplings described in Refs [23–25]. The mass of an atom (atomic number Z and mass number A) can be decomposed as $m(A,Z) = Zm_\mathrm{p} + (A-Z)m_\mathrm{n} + Zm_\mathrm{e} + E_1 + E_3$ where $m_{\mathrm{n,p}}$ is the mass of the neutron or proton and E_1 and E_3 are the electromagnetic and strong interaction binding energies. Following Ref. [23], we consider that the coupling coefficients of the dilaton to the electromagnetic and gluonic fields are d_e and d_g while d_{m_e}, d_{m_u} and d_{m_d} are its coupling to the electron, u and d quarks mass terms. The latter two can be replaced by the couplings $d_{\delta m}$ and $d_{\tilde m}$ to the symmetric and antisymmetric linear combination of u and d. Assuming a linear coupling, one deduces that the variation of the fine structure constants and masses of the quarks are given by $\Delta\alpha_{\mathrm{EM}}/\alpha_{\mathrm{EM}} = d_e\phi/M_p$ and $\Delta m_{u,d}/m_{u,d} = d_{u,d}\phi/M_p$.

First, we consider a massless dilaton ($m_\phi = 0$), whose range λ_ϕ is infinite, as was done by the Eöt-Wash group [7]. The dilaton coupling to matter, and hence the fifth force, is parametrized by the 5 numbers (d_g, d_e, $d_{\tilde m}$, $d_{\delta m}$, d_{m_e}) so that the coupling to matter (3) takes the form

$$\alpha_i \approx d_g^* + \left[(d_{\tilde m} - d_g)\, Q'_{\tilde m} + d_e Q'_e\right]_i , \quad (8)$$

where $d_g^* = d_g + 0.093(d_{\tilde m} - d_g) + 0.00027 d_e$. The dilaton

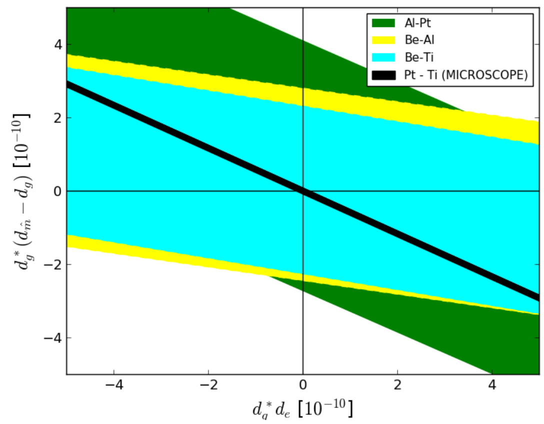

FIG. 3. Constraints on the couplings of a massless dilaton ($D_{\tilde m}, D_e$). The region allowed by the MICROSCOPE measurement (black band) is compared to earlier constraints by torsion pendulum experiments from Ref. [26] (green) and Ref. [7] (yellow, cyan). The difference of slopes arises from the difference of material used in these 3 experiments. MICROSCOPE allows us to shrink the allowed region by one order of magnitude.

charges depend on the chemical composition of the test masses and on the local value of the dilaton. Following Ref. [23], they are well-approximated by

$$Q'_{\tilde m} = 0.093 - \frac{0.036}{A^{1/3}} - 1.4 \times 10^{-4}\frac{Z(Z-1)}{A^{4/3}} \quad (9)$$

and

$$Q'_e = -1.4 \times 10^{-4} + 7.7 \times 10^{-4}\frac{Z(Z-1)}{A^{4/3}}. \quad (10)$$

In the limit where λ is much larger than any other spatial scales, the Eötvös parameter reduces to Eq. (4) so that

$$\eta \; = \; D_{\tilde m}\left([Q'_{\tilde m}]_{\mathrm{Pt}} - [Q'_{\tilde m}]_{\mathrm{Ti}}\right) + D_e\left([Q'_e]_{\mathrm{Pt}} - [Q'_e]_{\mathrm{Ti}}\right), \quad (11)$$

where the coefficients $D_{\tilde m} = d_g^*(d_{\tilde m} - d_g)$ and $D_e = d_g^* d_e$ are to be estimated. The values for $Q'_{\tilde m}$ and Q'_e in the MICROSCOPE case are given in Table I.

Fig. 3 summarizes our new constraints and compare them to the earlier ones from the Eöt-Wash [7] and the Moscow groups [26]. The different slopes of the allowed regions are due to the different pairs of materials used by each experiment.

Massive dilaton. The mass of the dilaton modifies the range of its interaction so that Eq. (11) is modified as

$$\eta \;\; = \;\; \eta_{\mathrm{massless}} \times \Phi\left(\frac{R_E}{\lambda_\phi}\right)\left(1 + \frac{r}{\lambda_\phi}\right)\mathrm{e}^{-r/\lambda_\phi}. \quad (12)$$

From Figs. 1 and 2, we expect that MICROSCOPE shall mainly be sensitive to masses in the range 10^{-14} –

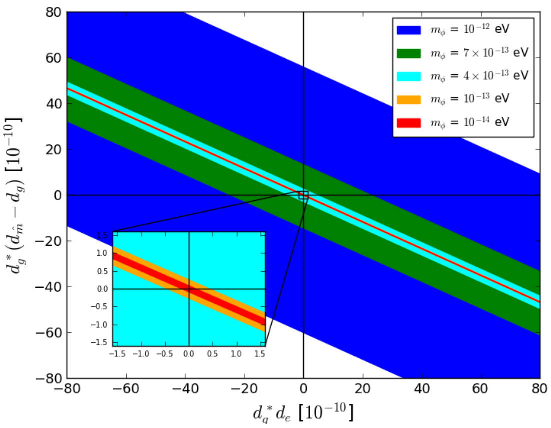

FIG. 4. Constraints on the couplings of a massive dilaton for various values of its mass. Each color shows the allowed $(D_{\tilde{m}}, D_e)$ for a given mass of the scalar field. The inset is a zoom on smaller $(D_{\tilde{m}}, D_e)$. Constraints saturate for light fields $m_\phi < 10^{-14}$ eV. MICROSCOPE is not sensitive to masses larger than a few 10^{-12} eV.

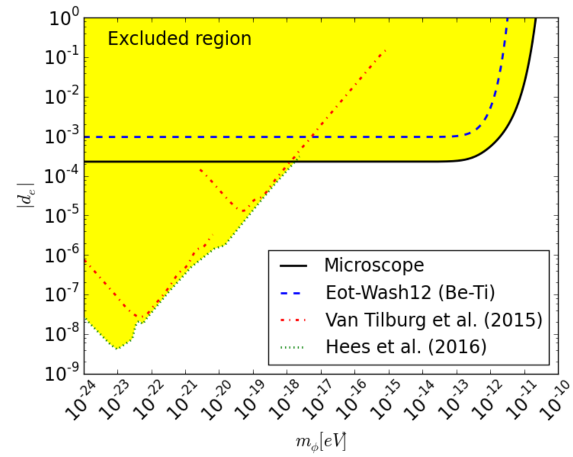

FIG. 5. Constraints on d_e, for a dilaton coupled only to the electromagnetic sector, compared with constraints from atomic spectroscopy (dot-dashed [28]) and Eöt-Wash WEP test (dashed [6]).

10^{-12} eV. Lower masses will result in constraints similar to those for a massless dilaton (see Fig. 3) while larger masses cannot be constrained, as they correspond to ranges that MICROSCOPE cannot probe. This is indeed what we conclude from our analysis summarized in Fig. 4. Constraints in the $(D_{\tilde{m}}, D_e)$ plane are rather loose for high-enough masses, $m_\phi > 10^{-12}$eV, and converge to those of a long-range dilaton for $m_\phi < 10^{-14}$eV.

Finally, we assume that the dilaton field couples only to the electromagnetic field, i.e. the only non-vanishing coupling is d_e. The coupling to proton and neutron is then induced from their binding energy [27]. Van Tilburg et al [28] measured the fine structure constant oscillations in a spectroscopic analysis of two isotopes of dysprosium to set constraints on such a dilaton. The MICROSCOPE constraints are obtained by considering the $D_{\tilde{m}} = 0$-subspace of the parameter space $(D_{\tilde{m}}, D_e, m_\phi)$ of Fig. 4, and recognizing that $D_e = d_g^* d_e = 0.00027 d_e^2$. Fig. 5 shows our constraints, compared with those from the Eöt-Wash test of the WEP and with atomic spectroscopy [28, 29]. MICROSCOPE allows us to exclude a new region above $|d_e| = 10^{-4}$, for a field of mass $10^{-18} < m_\phi/\text{eV} < 10^{-11}$. Atomic spectroscopy stays more competitive for lighter fields.

Conclusion. This letter gave the first constraints on a composition-dependent scalar fifth force from MICROSCOPE's first measurement of the WEP [14]. We first considered the case of a massive scalar field coupled to either B or $B - L$ to conclude that MICROSCOPE is particularly competitive for a Yukawa potential of range larger than 10^5m (corresponding to a field of mass smaller than 10^{-12}eV). In that case, we improved existing constraints on the strength of the field by one order of magnitude. Below that range, torsion pendulum experiments remain unbeaten. Then, we considered a model describing the coupling of a generic dilaton to the standard matter field with 5 parameters, both for a massless and massive field. For $m_\phi < 10^{-14}$ eV, our constraints are similar to those for a massless field and better by one order of magnitude than the previously published ones.

From a theoretical perspective, a scalar long-range interaction is severely constrained by its effects on planetary motion. Since general relativity passes all tests on Solar-System scales many mechanisms have been designed to hide this scalar field in dense regions (e.g. chameleons [30, 31], symmetron [32], K-mouflage [33, 34] or Vainshtein [35]). The generic dilaton model considered in this letter can incorporate the behavior of many theories, such as string theory. The local prediction of the violation of the WEP can be compared to the variation of the fundamental constants on local and astrophysical scales. Better constraints can be obtained from modeling the profile (and time variation) of the scalar field along MICROSCOPE's orbit, as well as its propagation inside the satellite up to the test masses; this is non-trivial, requires some care, and will be done in a further work. Constraints on the violation of the WEP will also have strong consequences for bigravity models [36].

From an experimental perspective, these new constraints were obtained from only two MICROSCOPE's measurement sessions of the Eötvös parameter [14]. As the mission is scheduled to continue until 2018, new data are currently coming in, thereby offering the possibility of decreasing the statistical errors. We are also refining our data analysis procedures to optimize the measurement of the WEP. We therefore expect to improve on MICROSCOPE's constraint on the

Eötvös parameter by the end of the mission. Would MICROSCOPE reach its objective, we could improve the constraints reported in that letter by another order of magnitude. But this forecast is valid only for $\lambda > \text{a few}\,10^5$ m ($m_\phi < 10^{-12}$ eV). Probing lower-range (more massive) scalar fields can be done only using small scale experiments. Torsion pendulum and atomic interferometry experiments represent our best hopes to look for such extra-fields. New, improved torsion pendulum will then be required to probe laboratory and smaller scale gravity, either through the measurement of the WEP or of the gravitational inverse square law. A torsion pendulum experiment in space seems the way forward to beat the current on-ground limits [37].

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