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MICROSCOPE Mission: First Constraints on the Violation of the Weak Equivalence Principle by a Light Scalar Dilaton

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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 submillimetric 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. A nonuniversal coupling implies both a violation of the weak equivalence principle (WEP) and a variation of the fundamental constants [6,7]. 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 [8–10], while the latter allows one to set constraints on cosmological to local scales [11].

The *MICROSCOPE* satellite aims to constrain the WEP in space [12,13] by measuring the Eötvös parameter, defined as the normalized 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 2σ 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 Earth, measured along the principal axis of the (cylindrical) test masses. The measurement equation is given, e.g., in Ref. [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 one measurement session; 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 [4,15,16]:

$$V_{ij}(r) = -\frac{Gm_im_j}{r}(1 + \alpha_{ij}e^{-r/\lambda}). \tag{2}$$

The scalar coupling to matter α_{ij} can be decomposed as the product $\alpha_i\alpha_j$ of the scalar couplings to matter for each test body measured by the dimensionless factors (e.g., [23])

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

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 the determination of $m_i(\phi)$ and thus the specification of the couplings of the scalar field to the standard model fields. Any dynamics or gradient of this scalar field thus induces a spatial dependence of the fundamental constants [6,7]. For two test masses in the external field of a body E, the Eötvös parameter reduces to

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

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

Baryonic and 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 [8,9]

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

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 is usually reduced to the material's baryon and/or lepton numbers (B and L) (see, e.g., Refs. [24,25]). Hence, for a macroscopic body, we must consider 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 is straightforward to show [using Eqs. (2) and (4)] that, for *MICROSCOPE*, the Eötvös parameter due to a Yukawa potential is

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

where r is the mean distance from the satellite to the center of Earth [26]. The Earth charge takes into account the Earth differentiation between the core and mantle:

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	1.000 26	0.596 68	0.0859	0.0038
Ti/Al/V	1.001 05	0.540 44	0.0826	0.0019

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

where R_E is the Earth mean radius and R_c 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 [27] ($\Phi = 1$ 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 Earth is composed of iron and that the mantle is composed of silica (SiO_2) [28]. The baryonic and lepton charges for the *MICROSCOPE* experiment are summarized in Table I.

At the 2σ level, *MICROSCOPE*'s constraints on the Eötvös parameter are given by Eq. (1) and can readily be transformed into constraints on Yukawa parameters (α, λ). Figures 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 [8,9,29] and the constraints from the lunar-laser ranging (LLR) experiment [30,31]. Note that, while we plot only the latest, most competitive constraints, several other experimental constraints are available (e.g., [4,32–40]). Moreover, the LLR constraint could

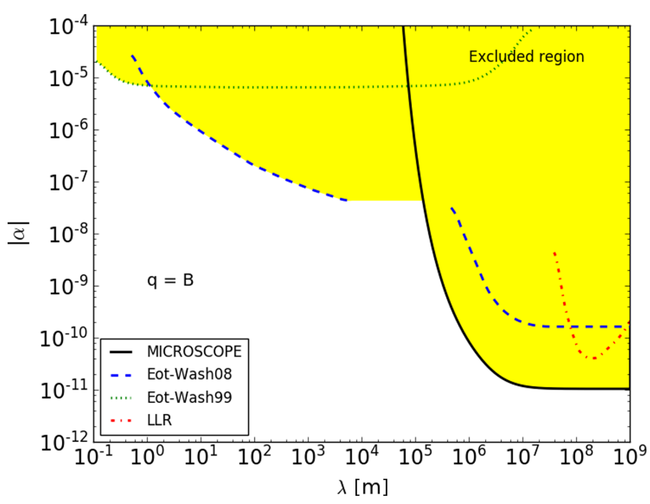

FIG. 1. Constraints on the Yukawa potential parameters (α, λ) with $q = B$. The excluded region is shown in yellow and compared to earlier constraints from Refs. [29] (dotted line), [8] (dashed line), and [30,31] (dot-dashed line). *MICROSCOPE* (solid line) improves on the Eöt-Wash constraints by one order of magnitude for $\lambda >$ a few10^5 m.

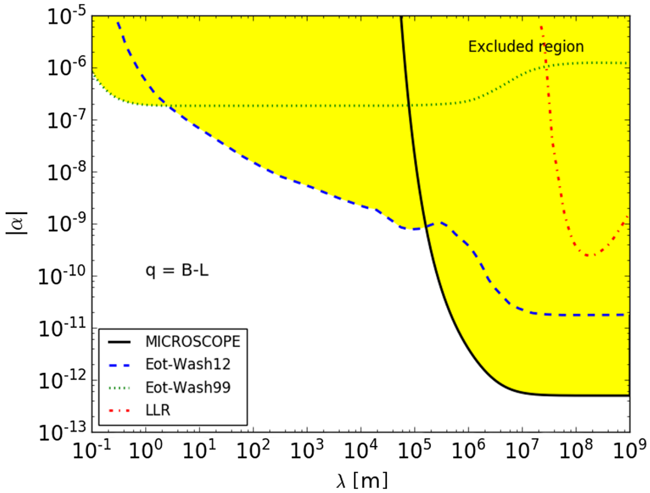

FIG. 2. The same as Fig. 1, but with $q = B - L$, compared to the earlier constraints from Refs. [29] (dotted line), [9] (dashed line), and [30,31] (dot-dashed line).

be slightly strengthened in the near future [41]. This shows that *MICROSCOPE*'s first results allow us to gain one order of magnitude compared to previous analyses for $\lambda >$ a few10^5 m. As *MICROSCOPE* orbits Earth at about 7000 km from its center, one would naively expect that it can probe only interactions with $\lambda >$ a few10^6 m; smaller ranges could not be probed, as they imply too much of a damping at *MICROSCOPE*'s altitude. However, if a fifth force with $\lambda \approx$ a few10^5 m were strong enough to affect *MICROSCOPE*, the contribution from the nearest point of Earth (as seen from *MICROSCOPE*) would be higher than that of the farthest point of 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. [17,18,28]. The mass of an atom (atomic number Z and mass number A) can be decomposed as $m(A,Z) = Zm_p + (A-Z)m_n + Zm_e + E_1 + E_3$, where $m_{n,p}$ is the mass of the neutron or proton and E_1 and E_3 are the electromagnetic and strong interaction binding energies. Following Ref. [28], 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 and u and d quark mass terms, respectively. 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 $\Delta\alpha_{\rm EM}/\alpha_{\rm EM} = d_e\phi/M_p$ 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 [9]. The dilaton coupling to matter, and hence the fifth force, is parametrized by the five numbers (d_g, d_e, $d_{\tilde{m}}$, $d_{\delta m}$, and d_{m_e}) so that the coupling to matter (3) takes the form

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

where $d_g^* = d_g + 0.093(d_{\tilde{m}} - d_g) + 0.00027 d_e$. The dilaton charges depend on the chemical composition of the test masses and on the local value of the dilaton. Following Ref. [28], they are well approximated by

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

and

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

In the limit where λ is much larger than any other spatial scales, the Eötvös parameter reduces to Eq. (4) so that (at first order in dilaton charges Q'_j—given that $|Q'_j| \ll 1$) [28]

$$\eta_{\rm massless} = D_{\tilde{m}}([Q'_{\tilde{m}}]_{\rm Pt} - [Q'_{\tilde{m}}]_{\rm Ti}) + D_e([Q'_e]_{\rm Pt} - [Q'_e]_{\rm Ti}), \tag{11}$$

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.

Figure 3 summarizes our new constraints and compare them to the earlier ones from the Eöt-Wash [9] and the Moscow groups [42]. The different slopes of the allowed

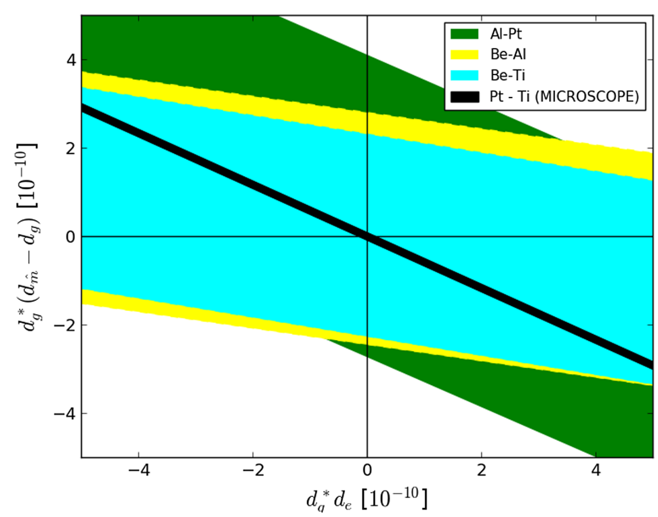

FIG. 3. Constraints on the couplings of a massless dilaton ($D_{\tilde{m}}$, D_e). The region allowed by the *MICROSCOPE* measurement (black band) is compared to earlier constraints by torsion pendulum experiments from Refs. [42] (green) and [9] (yellow and cyan). The difference of slopes arises from the difference of material used in these three experiments. *MICROSCOPE* allows us to shrink the allowed region by one order of magnitude.

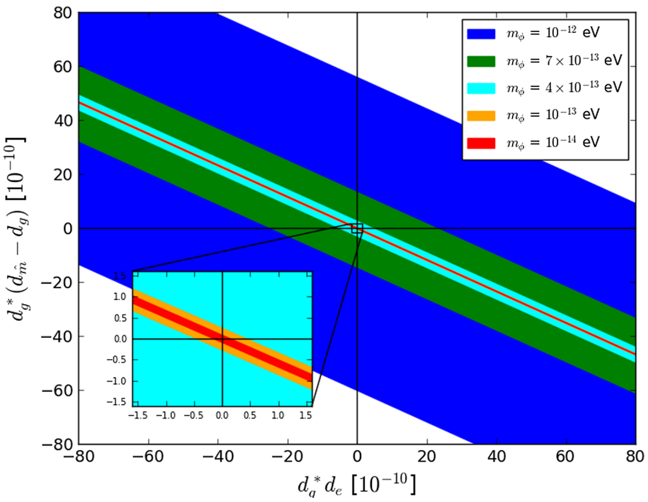

FIG. 4. Constraints on the couplings of a massive dilaton for various values of its mass. Each color shows the allowed ($D_{\tilde{m}}$, D_e) for a given mass of the scalar field. The inset is an enlargement of smaller ($D_{\tilde{m}}$, D_e). Constraints saturate for light fields $m_\phi < 10^{-14}$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

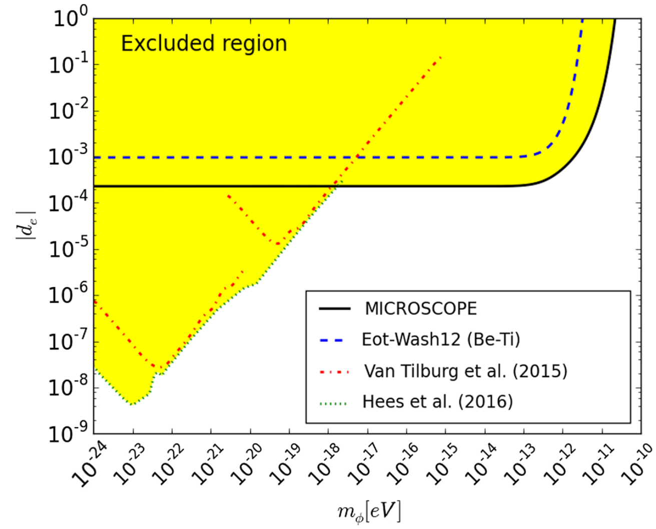

FIG. 5. Constraints on d_e, for a dilaton coupled only to the electromagnetic sector, compared with constraints from atomic spectroscopy (dot-dashed line [44,45]) and the Eöt-Wash WEP test (dashed line [8]).

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

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

Note that this equation is simpler than Eq. (7), because Eq. (11) does not depend on the Earth dilaton charge, and it is therefore independent of the exact Earth model used.

From Figs. 1 and 2, we expect that *MICROSCOPE* shall mainly be sensitive to masses in the range 10^{-14}–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 nonvanishing coupling is d_e. The coupling to proton and neutron is then induced from their binding energy [43]. Several groups set constraints on such a dilaton from the fine structure constant oscillations in atomic frequency comparisons [44–46]. These results are based on the time evolution of the scalar field that oscillates within its self-potential. It has been argued that these oscillations may lead to oscillations of the Newtonian potentials if the scalar field behaves like cold dark matter [19] (thereby affecting *MICROSCOPE* in an unexpected way) or even break the Yukawa approximation [20]. Here, we do not tie our scalar field to describe dark matter, and we restrict our analysis to linear couplings, thence avoiding those possible pitfalls [47]. The *MICROSCOPE* constraints are obtained by considering the $D_{\tilde{m}} = 0$ subspace of the parameter space ($D_{\tilde{m}}$, D_e, m_ϕ) of Fig. 4 and recognizing that $D_e = d_g^* d_e = 0.00027 d_e^2$. Figure 5 shows our constraints, compared with those from the Eöt-Wash test of the WEP and with atomic spectroscopy [44,45]. *MICROSCOPE* allows us to exclude a new region above $|d_e| = 10^{-4}$, for a field of mass $10^{-18} < m_\phi/\mathrm{eV} < 10^{-11}$. 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 a range larger than 10^5 m (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 five parameters, for both massless and massive fields. 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 [48,49], symmetron [50], K-mouflage [51,52], or Vainshtein [53]). The generic dilaton model considered in this Letter corresponds to another type of screening (the least coupling principle [17]) and can incorporate the behavior of many theories, such as the 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 (e.g., [54–57]). 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 nontrivial, 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 [58].

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: 10 times as many data will be available than were used in Ref. [14]; furthermore, although we expect the data to become systematic dominated, the control on systematics will be improved compared to Ref. [14], since calibration sessions have been performed, whose results will be used in the next data analysis. Therefore, we could improve the constraints reported in that Letter by up to another order of magnitude (unless a WEP violation becomes apparent). 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 [59].

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