A cosmic scalar field evolving very slowly in time can account for the observed dark energy of the Universe. Unlike a cosmological constant, an evolving scalar field also has local spatial gradients due to gravity. If the scalar field has a minimal derivative coupling to electromagnetism, it will cause modifications of Maxwell’s equations. In particular, in the presence of a scalar field gradient generated by Earth’s gravity, regions with a magnetic field appear to be electrically charged and regions with a static electric field appear to contain electric currents. We propose experiments to detect such effects with sensitivity exceeding current limits on scalar field interactions from measurements of cosmological birefringence. The scalar field with derivative couplings to fermions or photons is also observable in precision spin precession experiments.

Many different astrophysical observations point to the existence of dark energy constituting the majority of the energy density of the Universe [1]. The origin of this energy is presently unknown, but the two leading theoretical possibilities are a cosmological constant or a very slowly evolving dynamical field [2]. These two possibilities can be distinguished by astrophysical measurements of the equation of state \( w = p/\rho - 1 \). Present measurements are consistent with \( w = -1 \), as expected for a cosmological constant, but also allow \( w + 1 \approx 0.1 \) [3], as can be obtained in dynamical scalar field models. Can these two possibilities be distinguished by local measurements, without relying on astrophysical observations of the dynamical history of the Universe?

Even though scalar field models are Lorentz covariant, the existence of a cosmic scalar \( \phi \) introduces a special frame in which \( \phi \) is homogeneous. Therefore, any interaction of ordinary matter with the scalar field can lead to an apparent violation of local Lorentz invariance [4, 5]. If the scalar field is slowly evolving in time, it defines a preferred cosmic rest frame. Our motion relative to that frame with velocity \( v \approx 10^{-3}c \) will lead to small violations of rotational invariance. However the expected energy shift due to such an effect is on the order \( \hbar H_0 \approx 10^{-45} \) GeV, too small to hope to detect in the laboratory.

However, a scalar field is also affected by gravity [6] and will develop a local gradient due to Earth’s gravity with a much larger characteristic energy scale of \( \hbar g/c \approx 10^{-31} \) GeV. Such a gradient in the local value of the scalar field is potentially observable if the field has any interactions with ordinary matter. In this Letter we explore possible experimental signatures of such a gravity-induced local scalar field gradient.

The scalar field equation of motion in the vicinity of a local gravitational potential, \( U \) can be obtained as follows. On length and time scales that are short compared to the cosmological expansion, we use a weak field metric:

\[
d s^2 = -(1 + 2U/c^2)c^2dt^2 + (1 - 2U/c^2)dx^2. \tag{1}
\]

We consider a static perturbation \( \delta \phi \) to the homogeneous solution \( \phi_0 \) in the cosmological background: \( \phi = \phi_0 + \delta \phi(r) \). Working to linear order, and temporarily setting \( h = c = 1 \), the scalar field equation of motion \( \Box \phi = V' \) can be expanded as \( \partial_\mu (\sqrt{-g} g^{\mu \nu} \partial_\nu (\phi_0 + \delta \phi)) / \sqrt{-g} = V'(\phi_0 + \delta \phi) \) whereupon the background and perturbation equations are

\[
\Box_0 \phi_0 = V'_0, \\
\Box_0 \delta \phi - 2U \Box_0 \phi_0 = V''_0 \delta \phi, \tag{2}
\]

where the subscript 0 means that it is evaluated in the unperturbed spacetime. Using the background solution to simplify the equation for \( \delta \phi \), for the case of spherical symmetry we obtain

\[
\frac{d^2}{dr^2}\delta \phi + \frac{d}{r}\delta \phi = V'_0 \delta \phi + 2UV_0'. \tag{3}
\]

Using Earth’s gravitational potential \( U = -GM_E/r \), the inhomogeneous solution is \( \delta \phi = -2(V'_0/V_0)U/c^2 \). Since the gradient in the gravitational potential gives the local acceleration, \( g = -\nabla U \), we may write the gradient in the scalar field as

\[
\nabla \delta \phi = 2\frac{V'_0}{V_0}g/c^2. \tag{4}
\]

One of the theoretical challenges to the idea that dark energy is due to a cosmic scalar field is to explain why the field remains so dark. That is, why doesn’t the cosmic scalar mediate a long-range force between Standard Model particles? One possibility is a global shift symmetry \( \phi \to \phi + \text{constant} \), as occurs in pseudo Nambu-Goldstone boson models of dark energy [10], which keeps the cosmic scalar dark [11]. The global symmetry allows...
only derivative couplings of the scalar field with ordinary matter. For example, consider the interaction with electromagnetism

\[ \mathcal{L} = \frac{1}{2M} \nabla_\mu \phi A_\nu \tilde{F}^{\mu \nu} = -\frac{\phi}{4M} F_{\mu \nu} \tilde{F}^{\mu \nu}. \] (5)

In the above, the middle and right terms differ by a total derivative. We define \( \tilde{F}_{\mu \nu} \equiv \frac{1}{2} \epsilon_{\mu \nu \rho \sigma} F^{\rho \sigma} \), and \( M \) is a mass. This coupling introduces a modification of Maxwell’s equations, expressed in SI units where \( \phi \) units of energy, given by

\[ \nabla \cdot E - \rho/\epsilon_0 = -\frac{1}{Mc} \nabla \phi \cdot B, \] (6)

\[ \nabla \times B - \mu_0 \epsilon_0 \frac{\partial E}{\partial t} - \mu_0 J = \frac{1}{Mc^3} \left( \dot{\phi} B + \nabla \phi \times E \right), \] (7)

whereas the homogeneous equations are unchanged [12].

The quintessence field equation is likewise modified,

\[ \Box \phi - V'(\phi) = \frac{1}{4M} F_{\mu \nu} \tilde{F}^{\mu \nu}, \] (8)

(again setting \( h = c = 1 \)) where \( V(\phi) \) denotes the scalar field potential. For the pseudo Nambu-Goldstone boson dark energy model, the field self-interacts through a potential

\[ V(\phi) = \mu^4 (1 + \cos(\phi/f)). \] (9)

In the vicinity of the Earth we can now rewrite Maxwell’s equations as

\[ \nabla \cdot E - \rho/\epsilon_0 = -\frac{\epsilon_\gamma}{c} g \cdot B, \] (10)

\[ \nabla \times B - \mu_0 \epsilon_0 \frac{\partial E}{\partial t} - \mu_0 J = \frac{\epsilon_\gamma}{c^3} g \times E, \] (11)

where we introduced a dimensionless parameter

\[ \epsilon_\gamma \equiv \frac{2V_0'}{V_0'' M c^2} \] (12)

and ignored the \( \dot{\phi} \)-term.

The spatial gradient of the cosmic scalar then introduces novel effects. Specifically, sources of a magnetic field give rise to an anomalous electric field, while sources of an electric field will give rise to an anomalous magnetic field.

There is not a unique prediction for \( |\epsilon_\gamma| \). It could be of order unity, or tiny with no lower bound. The pseudo-scalar coupling [5] causes a parity-violating rotation of the polarization of light traveling over cosmological distances in a phenomenon referred to as cosmic birefringence [11]. The cosmic microwave background Stokes vector rotates [13] by an angle

\[ \alpha = \frac{\Delta \phi}{2Mc^2}, \] (13)

where \( \Delta \phi \) is the change in the cosmic scalar between recombination and the present day. Current bounds, based on the statistical properties of the polarization pattern detected in the cosmic microwave background, give \(-1.41^\circ < \alpha < 0.91^\circ \) (95\% C.L.), based on a combined analysis [13] of the WMAP [15], BICEP [16] [17], and QUaD [18 19] experiments. (Also see Refs. [20 21] for the analysis of particular scalar field models.) The first CMB constraints on a direction-dependent polarization rotation through cosmological birefringence has recently been obtained [22], at a similar amplitude. For a particular model of quintessence, we can use these observations to place a lower bound on the mass scale \( M \).

Typical parameters for the pseudo Nambu-Goldstone boson model potential [9] that satisfy current observational constraints on dark energy have values \( \mu \simeq 0.002 \) eV/c² and \( f \sim M_p \). The initial value of the field is not predicted, however, so that in turn the present-day value of \( \phi_0 \) is undetermined. Moreover, the field evolution may have been damped by Hubble friction until quite recently, with a present-day equation of state close to \(-1 \). This means that \( V_0'' \) or \( \Delta \phi \) may be small, in which case \( |\epsilon_\gamma| \) might conceivably be quite large. Two families of quintessence models for which the maximum value of \( |\epsilon_\gamma| \) ranges over three orders of magnitude are shown in Fig. 1 Models with even larger maxima can be constructed. For the two models indicated by the square and circle, the maximum value \( |\epsilon_\gamma| \) is 5. For the model indicated by the square in the figure, \( \mu = 0.002 \) eV/c², \( f = 0.64 M_p \) with an initial value \( \phi_i = 0.38 M_p \). We assume that the field is frozen by the Hubble friction, and only begins to slowly roll at late times. From the time of last scattering to the present, \( \Delta \phi = 0.0062 M_p \), with a current value \( \phi_0 = 0.39 M_p \) and \( w = -0.9985 \). For the model indicated by the circle, \( \mu = 0.0024 \) eV/c², \( f = 0.39 M_p \) and \( \phi_i = 0.63 M_p \). From the time of last
scattering to the present, $\Delta \phi = 0.037 \, M_p$, with a current value $\phi_0 = 0.67 \, M_p$ and $w = -0.946$. Both models, as well as the entire families illustrated, are consistent with current cosmological data. Whereas the model with $w = -0.946$ (circle) may be distinguished from a cosmological constant by future astrophysical observations, it seems unlikely that improvements in observations will permit the model with $w = -0.9985$ (square) to be distinguished. (See Ref. [23] for recent forecasts.)

We first consider the experimental consequences of Eq. (10). A region of magnetic field will appear electrically charged, with the sign of the charge depending on whether the magnetic field is directed up or down relative to Earth’s gravity. For a magnetic field $B = 1$ T and $\epsilon_5 = 5$, the effective charge density is $\rho = 1.4 \times 10^{-18} \, \text{C/m}^3 = 9e \, \text{m}^{-3}$ and can be detected using fairly conventional techniques. For example, consider an apparatus shown in Fig. 2. The magnetic field is created by a permanent Halbach magnet that is rotated around a horizontal axis to modulate the sign of the effective electric charge inside the cylinder. The charge is detected by measuring the voltage across a cylindrical capacitor inserted into the Halbach magnet. The expected unloaded voltage amplitude can be expressed as

$$V = (0.4 \, \text{nV}) \left( \frac{B}{1 \, \text{T}} \right) \left( \frac{D}{20 \, \text{cm}} \right)^2 \left( \frac{\epsilon_5}{5} \right).$$

For optimum detection efficiency the input capacitance of the amplifier should be equal to the capacitance inside the Halbach magnet, which is about 10 pF for a 30 cm long capacitor. A low-noise JFET transistor with an input capacitance $C_{in} = 2.3$ pF operating at room temperature has a noise level of $\delta V = 4 \, \text{nV/Hz}^{1/2}$ at 10 Hz [24]. One can use four such transistors in parallel to match the impedance of the source and reduce noise. With such an amplifier the signal due to a scalar field with $\epsilon_5 = 5$ can be observed at the 4$\sigma$ level after 1 hour of integration.

There is considerable room for improvement using more advanced techniques. Using a superconducting magnet both the magnetic field and the diameter of the detection region can be increased. The sensitivity could also be potentially improved using single electron transistors (SET), which can reach an energy resolution on the order of $\hbar$ [25], a large improvement over the JFET energy resolution of $C_{in}\delta V^2/2 = 1.8 \times 10^{-29} \, \text{J}$. However, SETs suffer from $1/f$ noise, so the best energy resolution demonstrated so far at 10 Hz is $8 \times 10^{-32} \, \text{J}$ [26]. In addition, SETs usually have very small input capacitance, so they would need to be fabricated either with a larger input gate [27] or with many of them connected in parallel [28].

Systematic errors in such an experiment would be primarily due to the Faraday effect. Even if the capacitor is fabricated to be very axially symmetric and is rotated together with the magnet, it will inevitably undergo deformations due to gravity, which will lead to a Faraday induction signal. However, Faraday signals can be distinguished because they are proportional to the rotational velocity $\omega$ and reverse sign with the direction of rotation.

We can also consider an experimental approach to detection of the signal through Eq. (11) as shown in Fig. 3. The central grounded cylindrical container is surrounded by electrodes with alternating high voltage $V$, creating a radial electric field $E$. This field in the presence of the scalar field gradient generates a circular pattern of effective current density similar to a solenoid. The effective current generates an approximately uniform magnetic field inside the central cylinder, which can be sensed by a magnetometer. Several regions with alternating field polarity allow one to cancel common magnetic field noise by using a magnetic gradiometer. The magnetic field in an ideal geometry is given by

$$B = (1.8 \times 10^{-19} \, \text{T}) \left( \frac{V}{100 \, \text{kV}} \right) \left( \frac{\sigma_5}{5} \right).$$

Currently the most sensitive magnetometers using optically-pumped alkali-metal atoms have a sensitivity of about $\delta B = 10^{-16} \, \text{T/Hz}^{1/2}$ for a 1 cm$^3$ measurement volume [29]. In a long term measurement such a magnetometer has achieved a sensitivity of $5 \times 10^{-19} \, \text{T}$ [30]. The
sensitivity of atomic magnetometers improves as \(\sqrt{V}\), so with 100 cm\(^3\) active volume one can achieve a sensitivity \(\delta B = 10^{-17} \text{T}/\text{Hz}^{1/2}\), which would allow detection of the scalar field signal at the 1σ level after 1 hour of integration. SQUID magnetometers with a large pick-up coil can also potentially achieve similar levels of sensitivity [31].

The experiment can be run similar to an electric dipole moment (EDM) measurement, in which the electric field polarity is periodically reversed to modulate the magnetic field. In fact, the recent search for \(^{199}\text{Hg}\) EDM [32] has some sensitivity to \(\epsilon\), coming from \(^{199}\text{Hg}\) magnetometer cells maintained at a high potential with no internal electric fields. While the experiment was not optimized to look for this effect, analysis of existing data could reach a sensitivity on the order of \(\epsilon_{\gamma} \sim 3 \times 10^4\). A dedicated search can reach a much higher sensitivity since the electric field does not need to be applied inside the magnetometer cells. Systematic effects in such a measurement would be similar to an EDM search, primarily due to magnetic fields generated by charging and leakage currents.

One can consider other ways of detecting such pseudoscalar interactions. The interaction [6] leads to an apparent violation of the equivalence principle [33], but only for spin-polarized bodies since it is proportional to a pseudoscalar \(E \cdot B\). For example, an electric field around a nucleus with charge \(Ze\) would generate a magnetic field at the origin given by

\[
B = \frac{Ze \epsilon_{\gamma}}{6 \pi c^4 \varepsilon_0} \frac{g}{R},
\]

where \(R\) is an integration cut-off which we take to be roughly equal to the nuclear charge radius [6]. This magnetic field interacts with the nuclear magnetic moment, causing an effective spin-gravity \(S \cdot g\) frequency shift. Two experiments [34] have constrained such interaction for \(^{199}\text{Hg}\) atoms at a level of \(\Delta \nu < 1 \mu\text{Hz}\), which can be used to place a limit \(\epsilon_{\gamma} \lesssim 3 \times 10^4\). One can also obtain interesting limits for electrons from a spin pendulum experiment [34], which also has \(\mu\text{Hz}\) sensitivity.

Astrophysical sources of gravitational potential can also generate an observable signal. The polarization of light escaping from a gravitational potential which changes by \(\Delta U\) will be rotated by an angle

\[
\alpha = \frac{\Delta U}{2c^2} \epsilon_{\gamma}.
\]

For example, for Crab nebulae the polarization of gamma rays is measured to be parallel to the rotation axis of the pulsar within 11° [37]. There is considerable uncertainty in the location where the gamma rays are generated [38], but assuming a distance near the light-cylinder radius \(R_L \sim 10^{6}\text{m}\) in the potential of a neutron star with \(M = 1.5M_\odot\), one can place a limit \(\epsilon_{\gamma} \lesssim 200\).

In addition to the pseudoscalar derivative coupling to electromagnetism, we can also consider derivative coupling to fermions, similar to the interaction discussed, for example, in [6].

\[
\mathcal{L} = \frac{1}{2M_f} \partial_{\mu} \phi \bar{\gamma}_{\mu} \gamma_5 \psi.
\] (18)

It will lead in the non-relativistic limit to a spin coupling with the gradient of the scalar field \(H = \hbar \sigma \cdot \nabla \phi/(2M_f c)\). Using the gravitationally induced spin gradient from Eq. [4], we obtain a frequency shift between spin-up and spin-down states equal to

\[
\Delta \nu = \frac{g}{2\pi c} \epsilon_f = (10\mu\text{Hz}) \epsilon_f,
\] (19)

where we defined \(\epsilon_f \equiv 2V_0'/\left(V_0'' M_f c^2\right)\). This frequency shift is similar to the result obtained in [6] but without requiring an additional scalar coupling of the quintessence field to matter, since the scalar gradient is already generated by ordinary gravity. Atomic physics experiments can easily reach this frequency resolution [30] but so far the most sensitive measurements [34] have \(\mu\text{Hz}\) sensitivity, constraining \(\epsilon_f < 100\). New experiments are being developed to realize higher sensitivity [39].

In conclusion, we have considered local experimental signatures of a cosmic scalar field. We point out that Earth’s gravity generates a gradient of the scalar field. Even a minimal derivative coupling of the scalar field to photons or fermions results in experimentally observable effects. We propose experiments searching for electromagnetic and spectroscopic signatures of scalar field interactions. Unlike astrophysical observations, such experiments could detect the presence of quintessence even if its equation of state is virtually indistinguishable from a cosmological constant.

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