Search for Chameleon Scalar Fields with the Axion Dark Matter Experiment

G. Rybka, M. Hotz, and L. J Rosenberg
University of Washington, Seattle, Washington 98195, USA

S. J. Asztalos,* G. Carosi, C. Hagmann, D. Kinion, and K. van Bibber†
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

J. Hoskins, C. Martin, P. Sikivie, and D. B. Tanner
University of Florida, Gainesville, Florida 32611, USA

R. Bradley
National Radio Astronomy Observatory, Charlottesville, Virginia 22903, USA

J. Clarke
University of California and Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
(Received 26 April 2010; revised manuscript received 28 June 2010; published 26 July 2010)

Scalar fields with a "chameleon" property, in which the effective particle mass is a function of its local environment, are common to many theories beyond the standard model and could be responsible for dark energy. If these fields couple weakly to the photon, they could be detectable through the afterglow effect of photon-chameleon-photon transitions. The ADMX experiment was used in the first chameleon search with a microwave cavity to set a new limit on scalar chameleon-photon coupling β_γ excluding values between 2×10^9 and 5×10^{14} for effective chameleon masses between 1.9510 and 1.9525 μeV.

DOI: 10.1103/PhysRevLett.105.051801 PACS numbers: 14.80.Va, 07.57.Kp, 14.70.Bh, 95.36.+x

Astrophysical observations from a variety of sources all suggest that the expansion of the universe is accelerating [1]. The negative pressure required for this phenomenon, under the name dark energy, can be interpreted as a nonzero cosmological constant, but could also be the signature of a light scalar field slowly rolling down a shallow potential [2,3]. Light scalar fields are ubiquitous in physics theories beyond the standard model, but have been severely constrained by short-range gravity experiments [4].

It has been suggested, however, that scalar fields with nonlinear self-interactions can have a "chameleon" property [5] which causes the effective mass of perturbations to the field to be dependent on the local energy density. This effect can shield all but a thin shell of test masses from the new force carried by a scalar field, significantly relaxing bounds on couplings from gravity experiments while still offering a viable low mass dark energy candidate on cosmological scales [6–8]. A possible effective potential for such a field is [7]

$$V_{\rm eff}(\phi, \vec{x}) = \Lambda^4 \exp\left(\frac{\Lambda^n}{\phi^n}\right) + e^{\beta\phi/M_{\rm pl}}\rho_m(\vec{x}) + e^{\beta_\gamma\phi/M_{\rm pl}}\rho_\gamma(\vec{x}). \quad (1)$$

Here ϕ is the chameleon field, β and β_γ are unitless couplings to matter and photons, $M_{\rm pl}$ is the reduced Planck mass (2.4×10^{18} GeV), ρ_m and ρ_γ are the matter and electromagnetic energy densities, and Λ and n are model parameters, with $\Lambda \simeq 3 \times 10^{-12}$ GeV for dark energy. The field ϕ minimizes the potential at each location with some value $\phi_0(\vec{x})$, and the mass of excitations of the field is then

$$m_\phi^2(\vec{x}) \simeq \frac{\partial^2}{\partial\phi^2} V(\phi_0(\vec{x}), \vec{x}). \quad (2)$$

The experimentally accessible parameters are the coupling strengths β, β_γ and the effective mass of the chameleon m_ϕ inside the experiment.

Scalar chameleons may have a different coupling strength to the electromagnetic field than to matter [9]. If the electromagnetic coupling is dominant, electromagnetic experiments searching for dark energy may be more fruitful than gravitational ones. For example, laser experiments utilize the unique nature of chameleons to look for the "afterglow" of photon-chameleon-photon transitions [10,11]. In general, these experiments involve shining a laser through a closed, empty container subjected to a large magnetic field. In the magnetic field, some photons from the laser mix into chameleons. For models in which the chameleon mass inside the walls of the container is much greater than that in vacuum, the chameleons are trapped because their effective mass in the walls is greater than their total energy. If the mixing time between chameleons and photons is longer than the time the photons spend in the container, photons may be detected for a time after the laser is turned off while the trapped chameleons mix back into photons, which subsequently escape the container.

Current limits from such experiments exclude chameleon-photon couplings of $5 \times 10^{11} < \beta_\gamma < 6.2 \times 10^{12}$ for effective chameleon masses less than 1 meV [12]. The vacuum chameleon masses covered by this type of experiment are model dependent, since the presence of residual gas and the nearby container walls change the effective chameleon mass inside the container.

An alternative technique is to trap chameleons inside a microwave cavity. Microwave cavities operate at lower energies than lasers, but have the advantage that the resonant nature of the cavity enhances the conversion probability between photons and chameleons. As a result, microwave cavity experiments can potentially be more sensitive to β_γ. We use the Axion Dark Matter Experiment (ADMX) to demonstrate this potential improvement for the first time.

ADMX is a cavity search for dark matter axions [13]. These axions are a consequence of the Peccei-Quinn solution to the strong CP problem [14–16]. A full description of ADMX can be found in Ref. [17], and recent results from this axion search in Ref. [18]. In brief, ADMX consists of a 220 l cylindrical copper-plated microwave cavity situated inside a 7 T magnet. The cavity is held under vacuum and maintained at a temperature of 2 K produced by pumping on liquid helium. Two copper rods are used to tune the resonant frequencies of the cavity. When the TM_{010} resonant frequency of the cavity is tuned to correspond to the axion mass, the resonant mode will be excited by photons produced by the Primakoff conversion of dark matter axions. The excitation of the resonant mode will be detected by an antenna probe inside the cavity and amplified by a microwave receiver.

As with axions, chameleons can mix with photons in the microwave cavity. Unlike axions, the chameleon mechanism may trap the chameleon scalars inside the cavity along with the photons [19]. In this case the cavity will contain both electromagnetic resonances and chameleonic resonances, and the two will mix. Consequently, the same technology ADMX uses to search for axion to photon conversion can be used to search for chameleon afterglow.

For the purposes of this analysis, it is assumed that the effective chameleon mass in the walls of the microwave cavity is much larger than the effective mass inside the cavity, yielding Dirichlet boundary conditions on the wave function. Model dependent effects can modify this assumption, shrinking the effective cavity radius for chameleons, and changing their effective mass. For a detailed analysis of chameleon behavior in cavities, see Ref. [20].

Chameleon and photon mode mixing is maximized when the modes have the same frequency. In ADMX, this mixing should be most easily achieved between the TE_{011} electromagnetic cavity mode, which can be tuned between 850 and 950 MHz with the current cavity geometry, and the lowest chameleon mode, which has a frequency that is the quadrature sum of the effective chameleon mass (m_ϕ) and wave number (k_ϕ).

The position of the tuning rods inside the cavity can be moved to change the TE_{011} mode frequency and the lowest chameleon mode wave number by different amounts, and thus can be used to probe different chameleon masses.

The procedure used to search for chameleons in ADMX was as follows (Fig. 1): (1) The TE_{011} electromagnetic mode was excited by driving the antenna with an external power source with a frequency swept over 20 kHz, roughly the width of the cavity resonance, for 10 minutes. During this time period, if a chameleon mode were to overlap with the TE_{011} mode, some energy would be transferred to the chameleon mode. (2) The external source was switched off. During the time required to switch on first-stage amplifier (100 ms), the conventional electromagnetic modes decayed. (3) With the first-stage amplifier on, the power spectrum within 20 kHz of the TE_{011} cavity resonance was recorded for 10 minutes. If a chameleon mode had been excited in the previous step, its decay could be visible as an electromagnetic mode excitation. (4) The tuning rods in the cavity were moved to change the frequency of the TE_{011} mode, making it sensitive to a slightly different range of effective chameleon masses.

Following the prescription used in Refs. [13,21], if $\beta_\gamma/M_{\mathrm{pl}}$ is sufficiently small, and the rate of chameleon loss to the cavity walls is negligible, the rate of mixing between the lowest chameleon mode mixing with the TE_{011} mode would be

$$\Gamma = \frac{\beta_\gamma^2 f^2 B^2 Q k_{\mathrm{tr}}^2}{M_{\mathrm{pl}}^2 \omega^3}, \tag{3}$$

where β_γ and M_{pl} are as defined above, f is a form factor (the overlap between the chameleon mode and the TE_{011} mode, calculated to be 0.43 in the case of ADMX), B is the magnetic field strength, Q is the cavity quality (around 10 000 for ADMX at this mode), $\frac{\omega}{2\pi}$ is the driving frequency (around 900 MHz), and k_{tr} is the wave number of the

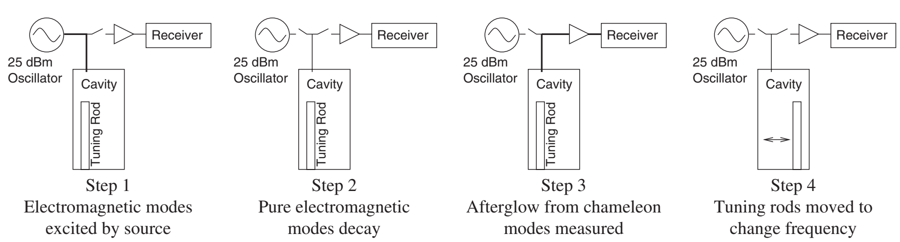

FIG. 1. Chameleon search procedure.

chameleon mode transverse to the applied magnetic field (set by the cavity height). The power detected in the cavity electromagnetic modes from chameleon decay would be

$$P_{\rm out} = P_{\rm in}\frac{\pi\Gamma}{2b}(1 - e^{-\Gamma/2t_0})^2 e^{-\Gamma t}, \qquad (4)$$

where $P_{\rm in}$ is the excitation power, b is the bandwidth over which the driving frequency is swept (20 kHz in this experiment), t_0 is the duration for which the cavity has been excited, and t is the time elapsed since the cavity excitation has ceased. This is valid only when the sweep bandwidth is much larger than the chameleon resonance width, and the chameleon mode decay rate is smaller than the electromagnetic mode decay rate.

The power excess would appear in the power spectrum as a peak at frequency $\omega = \sqrt{k_\phi^2 + m_\phi^2}$ with a width Γ. The power observed decreases exponentially with observation time as the chameleon mode decays with rate Γ. The expected excess power in the ADMX experiment immediately after turning on the first-stage amplifier as a function of coupling strength is shown in Fig. 2, and a simulated signal superimposed on real data is shown in Fig. 3. The signal-to-noise ratio of a chameleon signal, which determines its detectability, is given by the signal power Eq. (4) divided by the system noise temperature of the experiment. The physical temperature of the ADMX cavity was 2 K at the time of data taking, and the SQUID (Superconducting Quantum Interference Device) amplifier [22] had a noise temperature of 1 K, yielding a 3 K system noise temperature, which dominated the uncertainty in the power measurement [23].

The above discussion assumes that decay into photons is the dominant energy loss mechanism for excited chameleon modes. Short-range gravity experiments have limited the effective force between chameleons and matter to be weaker than the gravitational force, making energy loss to the walls negligible [24]. Therefore, the vast majority of chameleons must eventually decay into photons. As the wavelength of the chameleon mode is similar to that of the electromagnetic mode, both of which are much larger than the scale of any penetrations into the cavity, the bulk of the photons from chameleon decay are produced inside the cavity where they can be detected. For this experiment, this translates to an assumption that the chameleon power loss through means other than mixing with photons leads to an unloaded Q of greater than 10^{12}, not far from that achievable in superconducting microwave cavities [25].

There are two ways for a chameleon signal to be missed. First, if the coupling is too weak, too little power is transferred from the electromagnetic mode to the chameleon mode and back to be detected. Second, if the coupling is too strong, the chameleon mode can completely decay away in the time between the turn-off of the excitation and turn-on of the amplifier, and be indistinguishable from the decay of the electromagnetic mode.

The procedure outlined here was followed with the ADMX experiment using a 25 dBm oscillator as the excitation source with a total integration time of 3.6×10^4 seconds. The attenuation from the source to the cavity antenna was measured to be 28 dB, making the excitation power about 0.5 mW. Given that no statistically significant power excess was observed, chameleon-photon couplings of $2 \times 10^9 < \beta_\gamma < 5 \times 10^{14}$ could be excluded at 90% confidence over a mass range spanning 1.9510 μeV to 1.9525 μeV, as shown in Fig. 4. As a reminder, the mass listed in the figure is the effective mass in the cavity, where the magnetic field was 7.1 T and the pressure was 10^{-6} torr. The exact relation between this effective mass and true chameleon vacuum mass depends on one's choice of model.

Compared to previous limits, the limit set by ADMX improves the lower bounds on chameleon-photon coupling by several orders of magnitude, but is valid only for a narrow range of effective masses. The range of masses

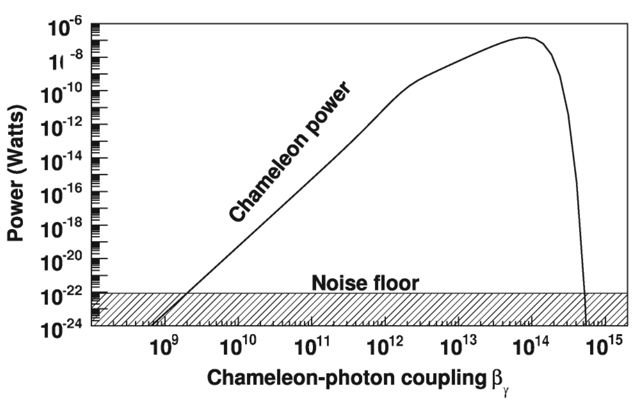

FIG. 2. Predicted excess power in the ADMX experiment from Primakoff conversion of chameleons immediately after turn-on of the first-stage amplifier as a function of chameleon-photon coupling strength β_γ. Smaller β_γ power is limited by coupling strength, larger β_γ power is limited by decay time. Noise floor corresponds to 3 K system temperature.

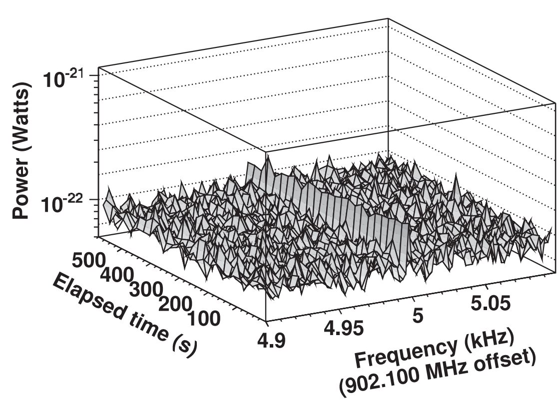

FIG. 3. A simulated chameleon signal corresponding to $\beta_\gamma = 2 \times 10^9$ with an effective mass of 1.952 μeV superimposed on real data. The data is shown as a series of sequential power spectra; for this case the chameleon decay time is long compared to the integration time.

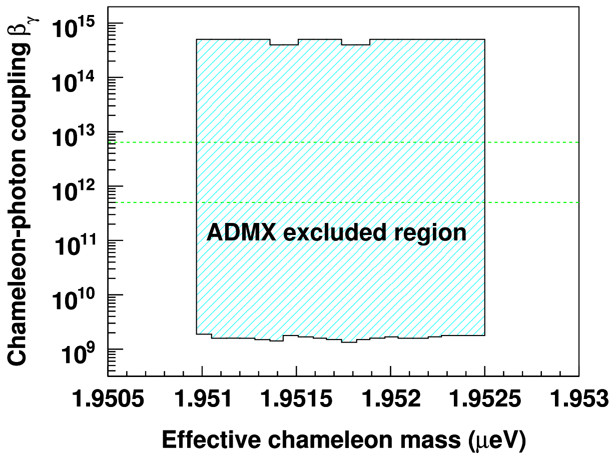

FIG. 4 (color online). Shaded region: 90% confidence limit excluded parameters for scalar chameleons from ADMX search. Dashed lines: upper and lower exclusion bounds from Ref. [12].

explored was limited by the time spent running; with a longer time, more chameleon masses could be explored at a rate of 10^{-3} μeV per day at the same sensitivity.

In summary, we used ADMX to demonstrate the viability of microwave cavity searches for chameleon scalars. Couplings of $2 \times 10^9 < \beta_\gamma < 5 \times 10^{14}$ were excluded for chameleons with an effective mass in the cavity between 1.9510 and 1.9525 μeV for models which allow the chameleons to be trapped in the cavity. This technique is sensitive only to a narrow range of masses at each tuning setting, so it is most useful if a precise theoretical prediction can be made, or to confirm potential positive signals seen in other chameleon searches, such as those performed with lasers or short-range gravity experiments.

ADMX will be upgraded soon from a system noise temperature of 3 K to an improved noise temperature of 200 mK by cooling the cavity to 100 mK, reducing the black body noise, and by lowering the temperature of the SQUID amplifier to 200 mK [26]. With a modest increase in excitation power, this would lead to an improvement on the lower bound of chameleon-photon coupling by an order of magnitude. Much stronger couplings could be probed by a faster radio frequency switching technique or lower magnetic field. Even smaller chameleon-photon couplings can be probed by exciting the cavity for a longer time, but this impacts the speed over which masses can be scanned by a factor of 100 for every factor of 10 improvement in chameleon-photon coupling sensitivity. An accurate prediction of chameleon mass is still necessary to complete a search in a timely manner.

The ADMX collaboration gratefully acknowledges support by the U.S. Department of Energy, Office of High Energy Physics under Contracts No. DE-FG02-96ER40956 (University of Washington), No. DE-AC52-07NA27344 (Lawrence Livermore National Laboratory), and No. DE-FG02-97ER41029 (University of Florida). Additional support was provided by Lawrence Livermore National Laboratory under the LDRD program. Development of the SQUID amplifier (J. C.) was supported by the Director, Office of Science, Office of Basic Energy Sciences, Materials Sciences and Engineering Division, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

*Present address: XIA LLC, 31057 Genstar Road, Hayward CA, 94544., USA.
†Present address: Naval Postgraduate School, Monterey, CA, 93943, USA.

[1] J. A. Frieman, M. S. Turner, and D. Huterer, Annu. Rev. Astron. Astrophys. **46**, 385 (2008).
[2] B. Ratra and P. J. E. Peebles, Phys. Rev. D **37**, 3406 (1988).
[3] R. R. Caldwell, R. Dave, and P. J. Steinhardt, Phys. Rev. Lett. **80**, 1582 (1998).
[4] E. Adelberger, B. Heckel, and A. Nelson, Annu. Rev. Nucl. Part. Sci. **53**, 77 (2003).
[5] J. Khoury and A. Weltman, Phys. Rev. Lett. **93**, 171104 (2004).
[6] S. S. Gubser and J. Khoury, Phys. Rev. D **70**, 104001 (2004).
[7] P. Brax, C. van de Bruck, A.-C. Davis, J. Khoury, and A. Weltman, Phys. Rev. D **70**, 123518 (2004).
[8] J. Khoury and A. Weltman, Phys. Rev. D **69**, 044026 (2004).
[9] P. Brax, C. van de Bruck, and A.-C. Davis, Phys. Rev. Lett. **99**, 121103 (2007).
[10] M. Ahlers, A. Lindner, A. Ringwald, L. Schrempp, and C. Weniger, Phys. Rev. D **77**, 015018 (2008).
[11] H. Gies, D. F. Mota, and D. J. Shaw, Phys. Rev. D **77**, 025016 (2008).
[12] A. S. Chou *et al.*, Phys. Rev. Lett. **102**, 030402 (2009).
[13] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983).
[14] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977).
[15] S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978).
[16] F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).
[17] H. Peng *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **444**, 569 (2000).
[18] S. J. Asztalos *et al.*, Phys. Rev. Lett. **104**, 041301 (2010).
[19] J. Jaeckel, E. Massó, J. Redondo, A. Ringwald, and F. Takahashi, Phys. Rev. D **75**, 013004 (2007).
[20] P. Brax, C. van de Bruck, A.-C. Davis, D. F. Mota, and D. Shaw, Phys. Rev. D **76**, 085010 (2007).
[21] P. Sikivie, Phys. Rev. D **32**, 2988 (1985).
[22] M. Mück, M.-O. André, J. Clarke, J. Gail, and C. Heiden, Appl. Phys. Lett. **72**, 2885 (1998).
[23] S. J. Asztalos *et al.*, Phys. Rev. D **69**, 011101 (2004).
[24] E. G. Adelberger *et al.*, Phys. Rev. Lett. **98**, 131104 (2007).
[25] M. A. Allen, Z. D. Farkas, H. A. Hogg, E. W. Hoyt, and P. B. Wilson, IEEE Trans. Nucl. Sci. **18**, 168 (1971).
[26] M. Mück, J. B. Kycia, and J. Clarke, Appl. Phys. Lett. **78**, 967 (2001).