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Abstract. The physical origin of the dark energy, which is postulated to cause the accelerated expansion rate of the universe, is one of the major open questions of cosmology. A large subset of theories postulate the existence of a scalar field with a nonlinear coupling to matter chosen so that the effective range and/or strength of the field is greatly suppressed unless the source is placed in vacuum. We describe a measurement using neutron interferometry which can place a stringent upper bound on chameleon fields proposed as a solution to the problem of the origin of dark energy of the universe in the regime with a strongly-nolinear coupling term. In combination with other experiments searching for exotic short-range forces and laser-based measurements, slow neutron experiments are capable of eliminating this and many similar types of scalar-field-based dark energy models by laboratory experiments.

1. Introduction

The observation of an accelerated expansion of the universe was recently recognized with the Nobel Prize in physics [1, 2]. This discovery was a major surprise to physicists and astronomers but has now been confirmed beyond a reasonable doubt [3, 4, 5, 6]. In combination with other cosmological observations it implies that a component of the universe called dark energy constitutes about 70% of the mass-energy of the universe. It is known that a contribution to the vacuum energy density (similar to the cosmological constant that is one of the few allowed terms in classical general relativity) acts like a negative pressure in Einstein's equations and therefore can cause the expansion to accelerate, and the zero-point fluctuations of the quantum fields of the Standard Model provide a natural source for this vacuum energy density. Unfortunately this contribution of the quantum fluctuations of the known Standard Model fields exceeds the observed dark energy density by $50 - 100$ orders of magnitude, thereby constituting the largest finite discrepancy between theory and experiment in the history of physics.

There is no consensus on the nature and physical origin of the dark energy. The number and variety of new theoretical ideas is almost uncountable. At the moment most of the non-theoretical research in this area consists of astronomical observations to more precisely characterize the effects of dark energy on the universe expansion rate and other cosmological

and astronomical observables. However an interesting coherent set of theoretical ideas on the origin of dark energy has been proposed which are in principle subject to experimental tests in laboratory measurements. One subset of theories to explain the dark energy postulates the existence of a nonlinear scalar field coupled to matter which propagates over long ranges in vacuum but is highly suppressed in the presence of matter, extending only to distance scales on the order of 100 microns, which is the distance scale associated with the dark energy density.

The first example of this set of ideas [7, 8, 9, 10], known now as the "chameleon mechanism", exploits the $\lambda\phi^4$ term in the usual $L = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{m^2}{2}\phi^2 + \lambda\phi^4$ relativistic Lagrangian of a scalar field (such a term must appear in the presence of radiative corrections in quantum field theory even if the original Lagrangian does not include it). The interesting observation made in this model was that, for a broad range of parameters λ, the effective distance that the scalar field propagates is a strong function of the local mass density, and that one can naturally arrange for this distance to be on the order of cosmological scales in the vacuum of outer space relevant for the accelerated expansion observations yet at the same time contract to a very small distance scale in high-density regions (even the mass density of gas at atmospheric pressure is more than sufficient for this suppression). The latter feature allows this chameleon mechanism to escape many precision gravity measurements which have been conducted mainly for other purposes, and therefore this idea along with a range of similar ideas has yet to be ruled out by experiment. The details of these and other similar ideas are under active investigation and have been the subject of a number of recent papers [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21] and reviews [22, 23, 24].

2. A Search using Neutron Interferometry

The neutron possesses certain advantages as a system with which to probe for the possible existence of chameleon and related scalar fields in the strongly-coupled chameleon regime. Unlike almost all other experimental probes, the neutron does not possess enough local mass density to suppress the chameleon field but at the same time it can easily penetrate matter densities (typical gas pressures of a few mbar suffice) for which the chameleon field is greatly suppressed. As the chameleon fields must couple directly to mass to be relevant for the observed universe expansion acceleration, other possible probes such as photons possess a more model-dependent coupling to the scalar fields. The chameleon couples to the trace of the energy momentum tensor of matter. In a photon field at the level of the geometrical optics approximation, $T_{\mu\nu} = Ak_\mu k_\nu$ where k_μ is the momentum and A the amplitude, so as long as $k^2 = 0$ as it is for null vectors (photons), we have $T = 0$ and therefore no chameleon effect on photons. This is true in general as long as one does not break conformal invariance and introduce an explicit coupling to F^2 in the Lagrangian, and even in this case the chameleon becomes sensitive to $F^2 = E^2 - B^2$ which is zero for a laser field [25]. So in first approximation chameleons do not see the photon density.

The fact that neutron experiments are a sensitive method to probe chameleon fields was pointed out [27] in the context of measurements of the quantum states of bouncing ultracold neutrons. Recently these measurements have been improved and have set a new experimental limit on chameleon fields [28]. Neutron interferometry measurements can also set interesting limits on chameleon models of dark energy in the "strongly-coupled" limit of the theory. The methodology of the experiments would be very similar to those performed [29] to precisely measure neutron coherent scattering lengths. These measurements are conducted using a gas cell with two chambers, one of which was evacuated and one which contained the gas to be measured. The chameleon field basically fills the volume of the empty cell but in the cell full of gas it would have only extended a distance of order 100 microns outside of the cell walls. Therefore the difference of the phase shifts from these two cells can be analyzed to produce an upper bound on the chameleon field. A calculation [30] showing the limits accessible in neutron interferometry experiments has already appeared.

When combined with other constraints [26] shown in Figure 2 from searches for deviations
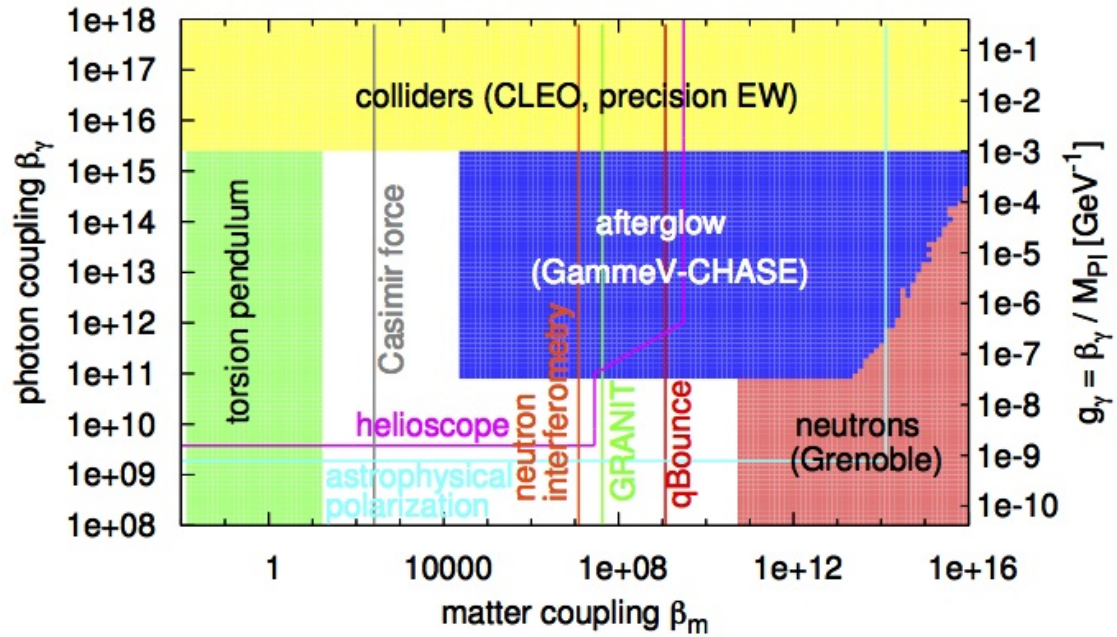
Figure 1. Constraints on the chameleon-matter coupling constant β_m and the chameleon-photon coupling β_γ for a nonlinear effective potential for the chameleon field of the form $V(\phi) = M_\Lambda^4(1 + M_\Lambda/\phi)$ Existing constraints are shown as shaded regions, and forecasts are shown as solid lines. From [26]. The recent results of the qBounce collaboration from [28] now extend slightly beyond the projection shown.

from the gravitational $1/r$ law at short distances at the 100 micron scale (these experiments are sensitive to chameleon fields as they are conducted in high vacuum) and from dedicated experiments involving photons which can couple to the chameleon field indirectly through quantum loop effects, one can foresee the very interesting possibility of experimentally confirming or refuting this model for dark energy. Even if this search finds no evidence for such an interaction it would represent the first nontrivial laboratory test of a plausible explanation for the accelerated expansion of the universe and therefore represent a result of fundamental significance for cosmology. We anticipate that this work might also be used to constrain other dark energy theories based on nonlinear scalar fields. Chameleons are only one example of a larger subclass of scalar field theories which all must possess similar properties to both explain the dark energy and still evade laboratory constraints. With the discovery by the LHC of the first (apparently) fundamental scalar field (the Standard Model Higgs boson) and the continued success of the scalar field mechanism as the explanation for cosmic inflation, past theoretical prejudice against fundamental scalar fields is evaporating with time and perhaps dark energy also really makes use of such a field in nature.

We are preparing a dedicated experiment at the NIST Neutron Interferometer and Optics Facility to search for chameleon fields using an optimized gas cell, a ^{4}He-H2 gas mixture tuned to possess nearly zero strong-interaction-induced phase shift, and a measurement sequence optimized to increase sensitivity to the chameleon field by exploiting its nonlinear contribution to the neutron phase shift as a function of gas pressure. The phase shift expected in the interferometer as a function of gas pressure can be modeled by the equation $\chi = \chi_0 + \chi_{gas} + \chi_{cham}$ where χ_0 is the difference of the phase shifts from the aluminum in the cell walls in the two
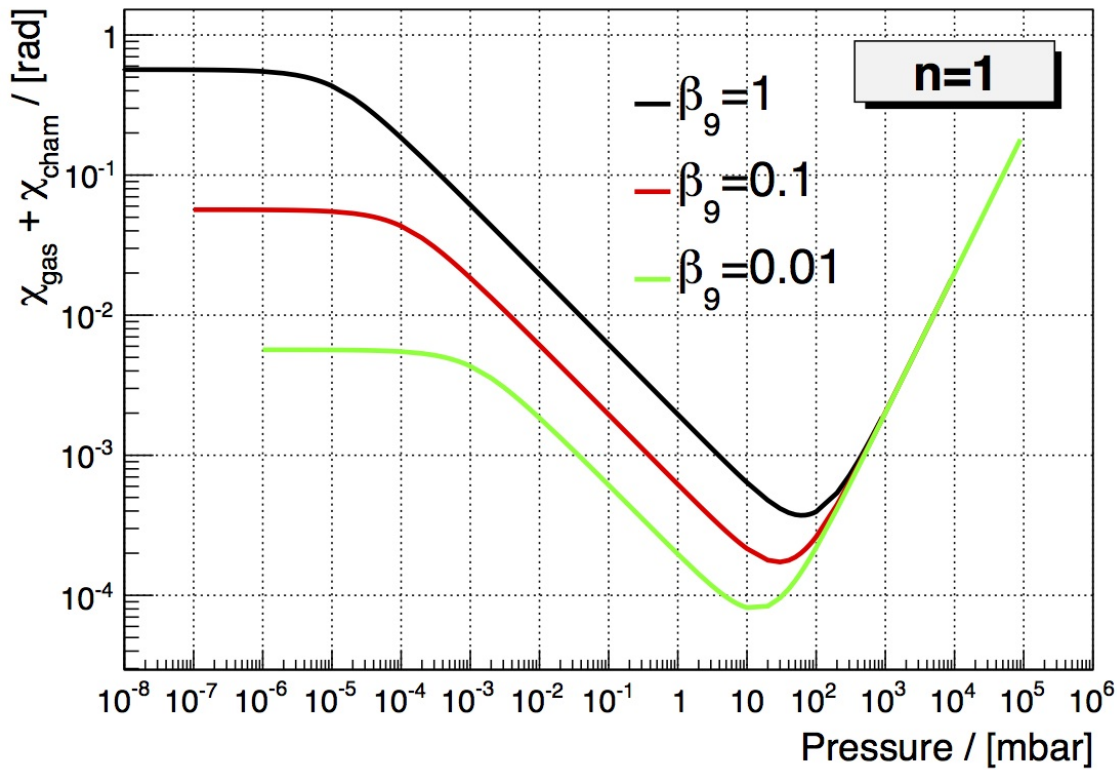
Figure 2. Calculation of the sum of the chameleon and gas mixture phase shifts for the conditions described in the text as a function of the gas pressure. The linear term at high pressure comes from the phase shift due to the neutron optical potential of the gas. The yellow line for β_m of 1×10^7 sets the sensitivity goal for the experiment.

subbeams, $\chi_{gas} = \phi_g P$ is the phase shift from the gas mixture which is linear with pressure, and $\chi_{cham} = \chi_0 f(P)$ is the chameleon phase shift which is a nontrivial function $f(P)$ of pressure which goes to zero at high pressure and approaches unity for pressures around 10^{-4} millibar. Therefore the main idea of the experiment is to conduct a series of measurements of χ as a function of gas pressure and fit to the calculated form of the chameleon field P dependence.

Here we construct a simple model for the experiment to estimate the sensitivity we can achieve. The phase shift from the aluminum cell wall is $\chi_0 = -\lambda N b (D_{II} - D_I)$ where $\lambda = 0.235$ nm is the neutron wavelength, b is the neutron coherent scattering length of aluminum, N is the aluminum density, and D_{II} and D_I are the cell wall thicknesses on the two sides of the interferometer. The world average value for hydrogen is $b_{coh,H2} = -3.741 \pm 0.001$ fm and for ^{4}He is $b_{coh,4He} = +3.26 \pm 0.03$ fm. Assuming we can achieve a gas cell length along the neutron beam of 3 cm with 0.5 cm thick walls which are equal in thickness to the same accuracy achieved in the cell used in the Schoen et al measurement, the phase shift expected from the cell material is about $\chi_0 = 1$ rad and the effect of the gas pressure on the phase shift from the walls of the chamber is negligible. We also expect that we can tune the coherent scattering length of the gas mixture to be zero to an accuracy of 0.006 fm. In this case we expect the cell phase shift from the gas from one chamber of the interferometer with the other side empty to be approximately $\chi_{gas} = 0.002P$ rad with P expressed in units of bar. The neutron phase shift χ_{cham} due to the scalar chameleon field is

$$\chi_{cham} = \int dx \frac{\beta}{M_{PL}} \frac{m^2 \phi(x)}{k} \qquad (1)$$

where β is the chameleon coupling, M_{PL} is the Planck mass, m is the mass of the neutron, $\phi(x)$ is the chameleon field, and k is the neutron wave vector. The goal of the experiment is to place a limit on β. Recall that the chameleon is a scalar field that is the solution to a nontrivial density-dependent equation of motion engineered to allow the range of the field to constitute the dark energy at the low matter densities relevant for the observations of cosmic acceleration but to "disappear" at normal matter densities beyond the 100 micron dark energy scale. Figure 3 shows the expected total phase shift as a function of gas pressure evaluated for the proposed conditions of the experiment with $\lambda = 0.235$ nm, $L = 3$ cm, $\chi_0 = 1$ rad, and $\chi_{gas} = 0.002P$ rad using our numerical solution of the chameleon equations of motion, which reduce in this case to a nonlinear 1D differential equation. Our calculation is in agreement with that shown by Brax.

A second step that can be taken to further improve the sensitivity of the measurement while still using the existing NIST monolithic interferometer setup would be to exploit the previously-demonstrated possibility of neutron Fabry-Perot cavities and implement one in an arm of the interferometer. An extended series of measurements at the ISIS pulsed neutron facility improved the efficiency of neutron Fabry-Perot cavities made from carefully aligned and separated perfect silicon crystals to the point where neutrons were observed to bounce 2500 times back and forth in the resonator structure [31, 32, 33, 34, 35, 36]. Other experimental measurements of perfect crystal reflectivity with thermal neutrons have observed phenomena which are interpreted as implying that the neutrons made more than $20,000$ reflections [37]. Since the chameleon field extends along the entire length of the interferometer arm when the system is in vacuum, the total neutron phase shift from a chameleon field would add coherently as the neutron is reflected back and forth inside the resonator. If one constructs a resonator which operates in both parallel neutron paths of a skew-symmetric interferometer configuration and is able to establish a vacuum in one path and a gas cell in the other path one can increase the sensitivity of the phase shift measurement by an amount as large as the total number of neutron passages through the resonator. However there are major challenges in efficiently implementing this idea on a neutron interferometer. In addition to the obvious issues involved in the stable alignment of separated perfect crystal elements and in loading and unloading the neutrons into the resonator structure, one must also maximize the fraction of neutron phase space accepted by the combination of the neutron interferometer perfect crystal and that accepted in the Bragg geometry of the resonator structure to avoid crippling losses in intensity.

One can imagine yet another step which would further increase the sensitivity of a neutron interferometer-based chameleon search: increase the neutron path length in the interferometer by constructing a separated crystal neutron interferometer. Although such a separated crystal interferometer has not to our knowledge been operated anywhere, it is widely believed by practitioners in the field that it is now technically possible to construct such a device and control it with sufficient precision to maintain a high interferometer contrast [38]. Simulations of the required crystal positioning and operational stability with respect to the Bragg axis show that milliarcsecond precision and mK temperature stability is required for high contrast [39], much more stringent than that needed for a split X-ray interferometer [40, 41]. The milliarcsecond angular stability requirement has already been demonstrated experimentally in the course of measurements conducted at NIST in an attempt to measure the neutron -electron scattering length using neutron interferometry [42]. The crystal positioning can be controlled in principle by registering the appearance of Moire patterns in a position sensitive neutron detector [43]. Were this possible, one could overcome the existing size limitation of monolithic perfect crystal interferometers and achieve a qualitative increase in the neutron path length in the interferometer arms. Development of either effective neutron Fabry-Perot cavities for neutron interferometry

or separated perfect crystal interferometers would also be very exciting for many other neutron interferometry studies such as research on decoherence-free subspaces [44]

3. Conclusion

We propose a search for chameleon dark energy fields using the neutron interferometer at NIST. We can perform a sensitive search in the regime of strongly nonlinear coupling and improve the existing upper bound on the coupling parameter β. Further neutron interferometer and gravitational resonance spectroscopy measurements have the capability to either discover chameleons or provide the first laboratory experiment refutation of a plausible dark energy theory. Further improvements in the sensitivity of a neutron interferometer measurement could come in the future in principle from the use of neutron Fabry-Perot cavities [31, 36] or through the implementation of a separated crystal interferometer [38, 42, 43].

4. Acknowledgements

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