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# Neutron interferometry constrains dark energy chameleon fields

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ABSTRACT

We present phase shift measurements for neutron matter waves in vacuum and in low pressure Helium using a method originally developed for neutron scattering length measurements in neutron interferometry. We search for phase shifts associated with a coupling to scalar fields. We set stringent limits for a scalar chameleon field, a prominent quintessence dark energy candidate. We find that the coupling constant $\beta$ is less than $1.9 \times 10^7$ for $n = 1$ at 95% confidence level, where $n$ is an input parameter of the self-interaction of the chameleon field $\varphi$ inversely proportional to $\varphi^n$.



## 1. Introduction

The accelerating expansion of the universe suggests that most of the energy in the universe is 'dark energy'. The nature and origin of this energy remain unknown. Candidates for dark energy are either Einstein's cosmological constant or dynamical dark energy, i.e. the so-called quintessence canonical scalar field $\varphi$, responsible for the late–time acceleration of the universe expansion. Chameleon fields are a prime example of dynamical dark energy. Their effective mass depends on the energy density of matter in which it is immersed [1]. As a result, in a sufficiently dense environment the chameleon field is very massive and, correspondingly, substantially Yukawa-suppressed, i.e. very short-ranged. In turn, it is essentially massless on cosmological scales [2,3]. Because of its sensitivity on the environment, such a mass-changing scalar field has been called *chameleon*. Moreover, the chameleon field always couples to matter and generates a fifth force with an effective range inversely proportional to its effective mass.

All models of dark energy involve a light scalar field [1,2] whose effects on solar system tests of gravity needs to be shielded. Three main screening mechanisms [3] have been unraveled so far. The K-mouflage and Vainshtein screenings are very powerful inside a large domain surrounding the earth, rendering their test in laboratory experiments extremely arduous. On the other hand, the chameleon mechanism is at work in the presence of dense objects and can be tested in near-vacuum experiments [4]. This is the case for the Eotwash [5] and Casimir experiments [6], where the boundary plates are screened. Another way of testing the chameleon mechanism involves small and unscreened objects, like neutrons under certain conditions [7].

Concerning chameleon models, a chameleon–photon coupling $g_{\rm eff} = \beta_\gamma / M_{\rm Pl}$ has been proposed, and the detailed analysis of the chameleon–photon interaction and a comparison with the cosmological data has been carried out in [8–12]. A search for photon–chameleon–photon transition has been performed by the experiment CHASE (the GammeV CHameleon Afterglow SEarch) [13] and by the Axion Dark Matter eXperiment (ADMX) [14]. A search for chameleon particles created via photon–chameleon oscillations within a magnetic field is described in [15].

Searches with neutrons directly test the chameleon–matter interaction $\beta$ and do not rely on the existence of a chameleon–photon interaction. The coupling $\beta$ is restricted from below, e.g. $\beta$ must be larger than 50 at $n = 1$ [16], and experiments with neutrons have the potential ultimately to find a chameleon field or exclude it in the whole parameter space.

As it has been pointed out by Pokotilovski [17], the use of a neutron Lloyd's interferometer for measurements of the phase-shift of the wave function of cold neutrons should allow to determine the chameleon–matter coupling constant. The *q*Bounce Collaboration has searched for the chameleon field using gravity resonance spectroscopy and ultra-cold neutrons [18–21]. In a recent

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experiment [22], the upper limit for $\beta$ has been determined as $\beta < 5.8 \times 10^8$ which is five orders of magnitude below the previous limit determined by atomic spectra [16].

Here we present a new search for chameleon fields by means of neutron interferometry as proposed in [7]. The self-interaction of the chameleon field $\varphi$ and its interaction to an environment with mass density $\rho$ are described by the effective potential [23,24]

$$\mathcal{V}_{\mathrm{eff}}(\varphi) = \frac{\Lambda^{n+4}}{\varphi^n} + \frac{\beta \rho \hbar^3 c^3 \varphi}{M_{\mathrm{Pl}}}, \quad (1)$$

where $\beta$ is the coupling constant, $n$ is an input parameter (the so-called Ratra–Peebles index) and $\Lambda \approx 2.4 \times 10^{-12}$ GeV defines an energy scale [7]. $M_{\mathrm{Pl}} = \sqrt{\hbar c/(8\pi G)} = 4.341 \times 10^{-9}$ kg denotes the reduced Planck mass. The chameleon field $\varphi$ creates a potential for neutrons given by $V = \beta \varphi m / M_{\mathrm{Pl}}$ where $m$ denotes the neutron mass. When passing this potential, neutrons accumulate the phase

$$\zeta = -\frac{m}{k\hbar^2} \int V(x)\, dx = -\frac{m}{k\hbar^2} \int \beta \frac{m}{M_{\mathrm{Pl}}} \varphi(x)\, dx, \quad (2)$$

where $k$ denotes the neutron wave vector modulus $k = 2\pi/\lambda$.

For strong coupling ($\beta \gg 1$) the chameleon field is suppressed at the presence of matter, even at low mass densities like air at ambient pressure. Only in vacuum the chameleon field can persist. By placing a vacuum cell into one arm of the neutron interferometer and allowing ambient air in the other arm we can directly probe the chameleon field. The setup resembles a standard setup for measuring neutron scattering lengths [25], but instead of measuring the phase shift of sample material we measure the phase shift of vacuum.

The chameleon field vanishes at the walls of the vacuum chamber but increases bubble-like towards the middle of the chamber, cf. Fig. 1 (c). The lower the remaining gas pressure is, i.e. the better the vacuum, the more the field increases. Thus we have two options of performing a relative phase measurement which is necessary to cancel the unknown intrinsic interferometer phase and the air phase shift. In the pressure mode we vary the pressure in the vacuum cell by letting in different amounts of Helium. In the profile mode we keep the pressure constant but move the chamber transversally to the beam in order to record a profile of the chameleon bubble. Neither method detects any chameleon-like signature, giving rise to new constraints of the chameleon theory.

## 2. Setup

The experiment is carried out at the neutron interferometry setup S18 at the Institut Laue-Langevin (ILL) in Grenoble. A perfect crystal silicon interferometer is used, Fig. 1 (a), at 45° Bragg angle and 2.72 Å mean wave length $\lambda$ with 0.043 Å wavelength distribution width (FWHM). The two beam paths within the interferometer are separated by 50 mm over a length of 160 mm. Neutron detectors with an efficiency above 99% measure the intensities of the two exit beams labeled O and H respectively. A vacuum chamber with inner dimensions 40 × 40 × 94 mm is inserted in the left or right beam path. The other beam path always contains one of the two air chambers which sit alongside the vacuum chamber. The whole chamber box can be moved sidewards for swapping the vacuum cell between the left and the right beam path and to probe different beam trajectories within the vacuum cell. The air chambers ensure that both beam paths contain the same amount of wall material (aluminium). In addition, the extension of the vacuum cell by air chambers minimizes possible disturbances of the thermal environment of the crystal when the chamber box is moved. We label different chamber positions by the letters ‘a’ to ‘n’ as indicated in the figure.

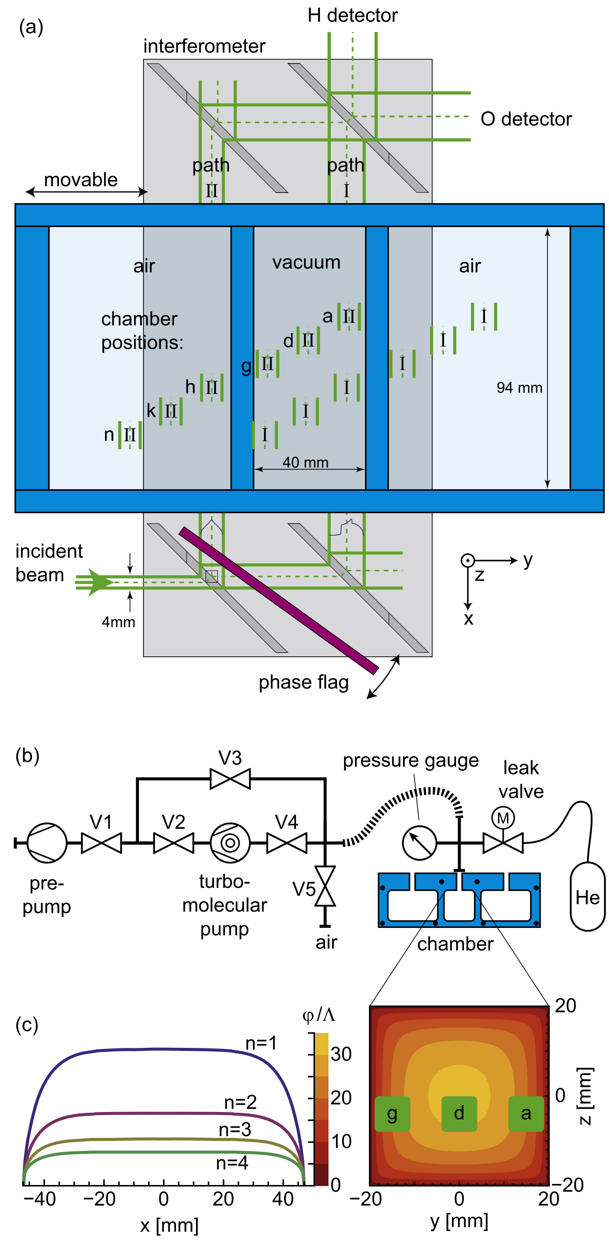


**Fig. 1.** (a) Top view of the interferometry setup shown in chamber position ‘h’. The chamber box (blue) can be moved transversally allowing the beams to pass at different positions, labeled by ‘a’ to ‘n’. (b) Scheme of the vacuum handling and axial view of the vacuum chamber. (c) Longitudinal and transverse bubble shape of the chameleon field in the vacuum cell. The beam positions ‘a’, ‘d’ and ‘g’ are indicated by green rectangles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The air chambers are connected to ambient air by a hole in the top of the chambers. The vacuum chamber is connected to a vacuum control system consisting of pressure gauge, motorized leak valve and pumps, as indicated in Fig. 1 (b). The pumps (pre-pump and turbomolecular pump) are running continuously while a controlled amount of Helium is let in through the leak valve in order to tune the pressure. The pressure gauge is corrected for the use with Helium.

## 3. Data acquisition and evaluation

Phases in neutron interferometry are measured by rotating an auxiliary phase flag and recording the intensity oscillations be-