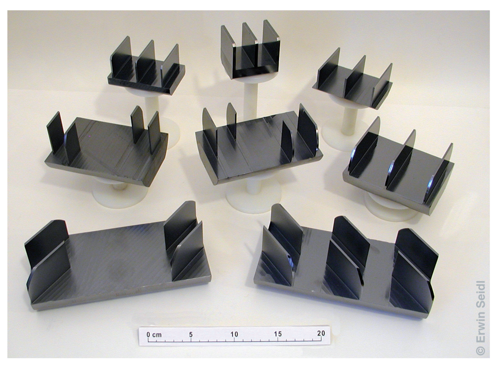

Neutron Interferometry constrains Dark Energy Chameleon Fields

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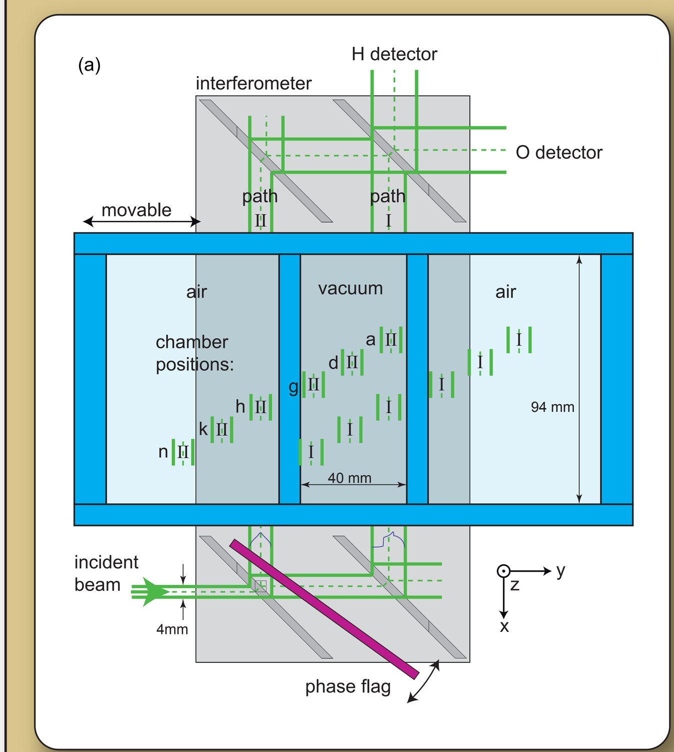
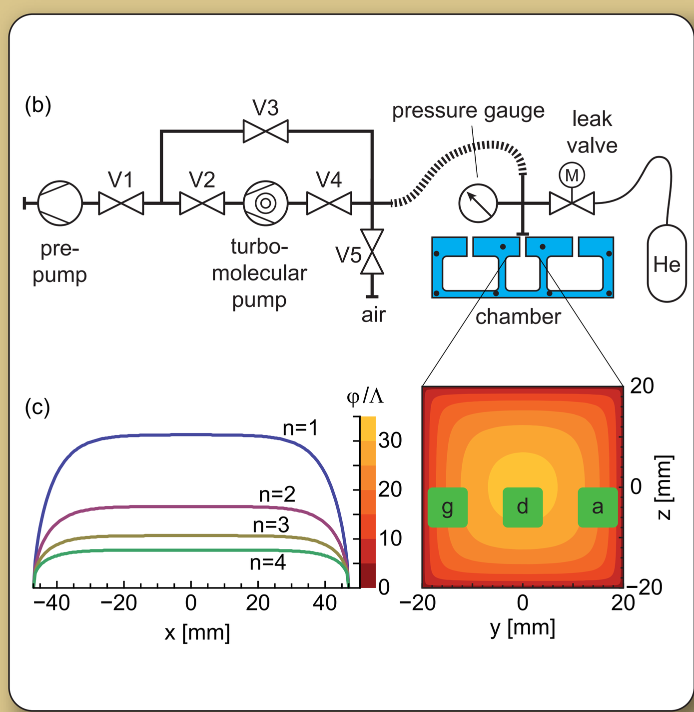
The accelerating expansion of the universe suggests that most of the energy in the universe is 'dark energy'. Its nature and origin remain unknown. Candidates are either Einstein's cosmological constant or dynamical dark energy, i.e. the so-called quintessence canonical scalar field. Chameleon fields are a prime example of dynamical dark energy. Here, 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 and set stringent limits for scalar chameleon fields.

Experimental Concept



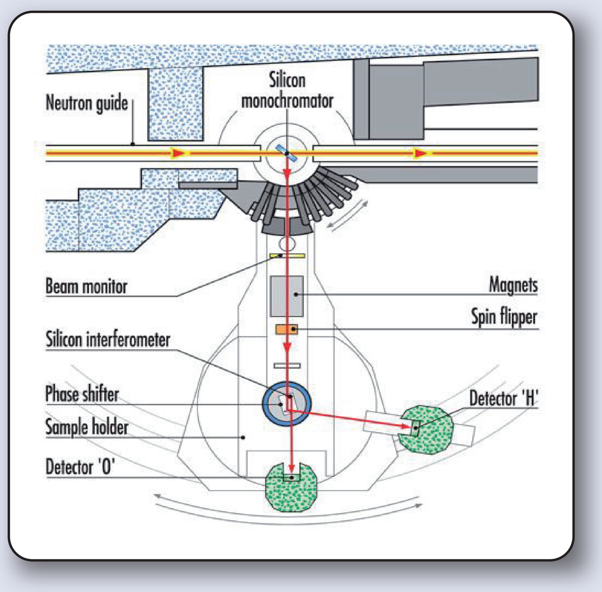
At the neutron interferometry setup S18 at the Institut Laue-Langevin (ILL) in Grenoble, monochromated thermal neutrons with a wavelength of 2.72Å and a FWHM of 0.043Å enter a perfect crystal silicon interferometer operated at a Bragg angle of 45°.
The two beam paths within the interferometer are separated 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 made of Aluminium 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 system can be moved sidewards to swap the vacuum cell between the two beams or to probe different beam trajectories. The design ensures that both beam paths contain the same amount of wall material.



The search for hypothetical chameleon fields translates in a search for a vacuum-dependant additional phaseshift following two methods:
(A) "Pressure Mode":
The phaseshift is determined wrt. to the pressure inside the vacuum chamber.
(B) "Profile Mode":
For a constant (low) pressure, the phaseshift is measured wrt. the distance between the beam and the vacuum chamber walls.

Neutron Interferometry at S18

The instrument S18 is situated at the Institut Laue-Langevin in Grenoble/France, and operated by the Atominstitut TU Wien, Vienna/Austria. It is dedicated to neutron interferometry using perfect crystal thermal neutron interferometers. The instrument can also be configured Bonse Hart camera to perform Ultra Small Angle Neutron Scattering (USANS) experiments.



The research focusses on measurements of basic quantum physics laws, on neutron-nuclei scattering lengths, experiments regarding Quantum contextuality, Decoherence, dephasing and depolarisation, and experiments with non-classical neutron states.

Chameleon Dark Energy

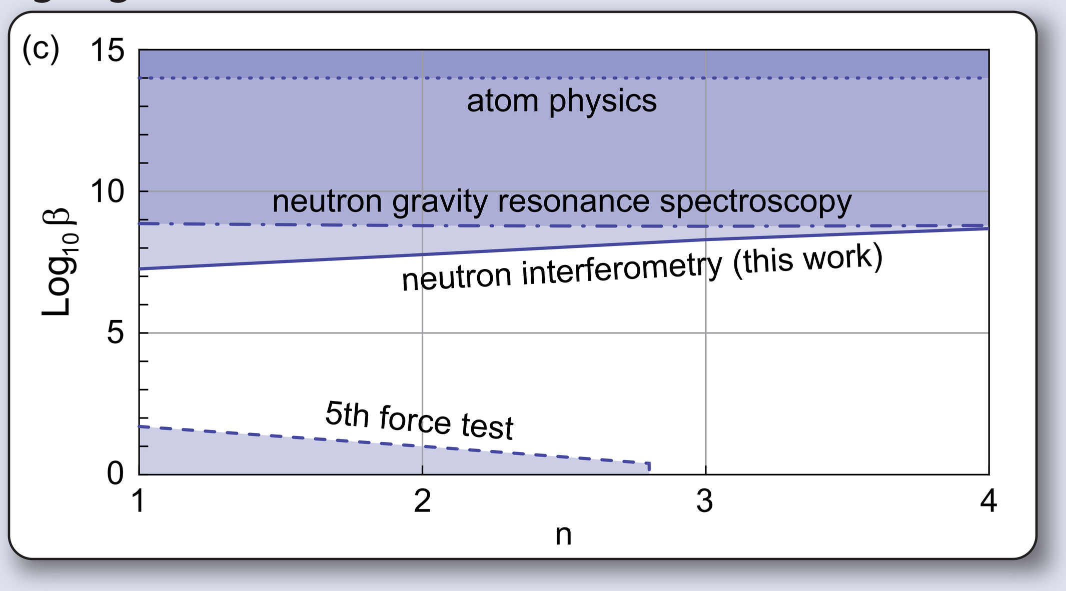
Chameleon fields are a prominent realization of dynamical dark energy. Their effective mass depends on the surrounding energy density of matter.
As a result, in a dense environment the chameleon field is very massive and, correspondingly, Yukawa- suppressed, i.e. very short-ranged. In turn, it is essentially massless on cosmological scales.
The chameleon field couples to matter and generates a fifth force with an effective range inversely proportional to its effective mass.
The equation of the chameleon field in our neutron interferometer reads:

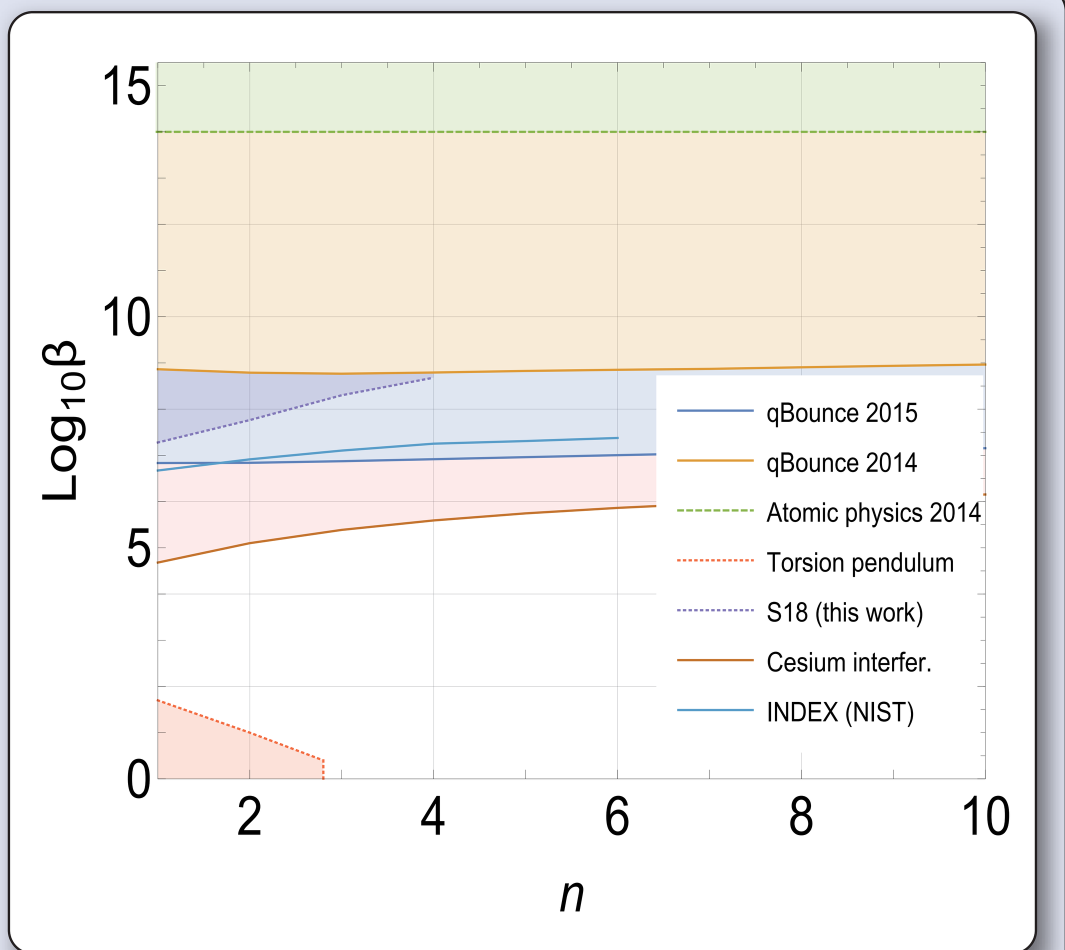
$$(\hbar c)^2 \, \Delta\varphi = -\frac{n\Lambda^{n+4}}{\varphi^{n+1}} + \frac{\beta\rho(\hbar c)^3}{M_{Pl}} \quad \text{and } \varphi = 0 \text{ at the boundary of the cell}$$

It is solved numerically in full 3D for our vacuum chamber geometry.

New Limits on Chameleon Fields

The search for hypothetical chameleon fields is a hot topic in the fundamental physics community. The plot below shows the new exclusion plot at the time of publication of this work, the plot on the right highlights the current state of the art.

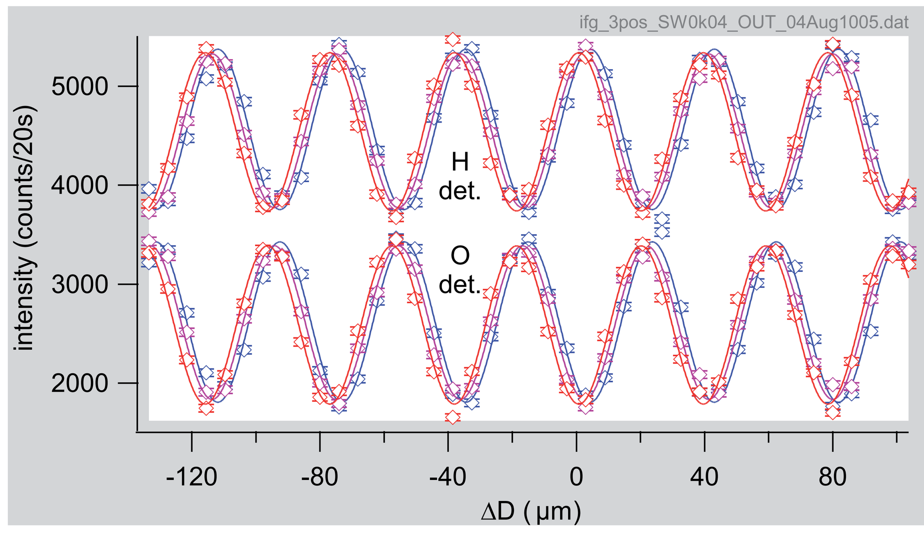




Data Aquisition and Analysis

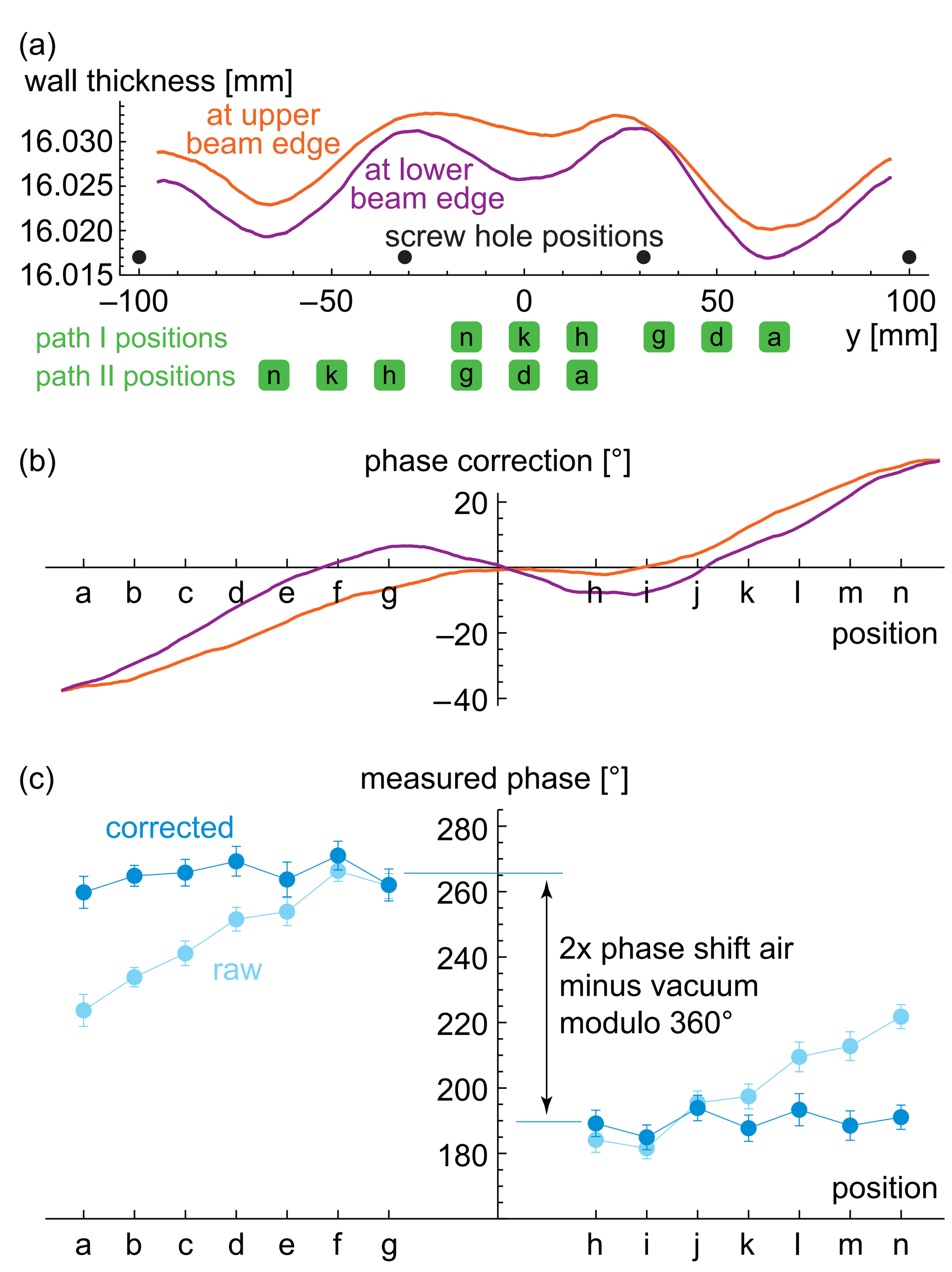
In summer 2013, two dedicated beam times were used to search for hypothetical chameleon dark energy fields. The published results are presented here.
In 2015 and 2016, further measurements were carried out. The data evaluation process is still on-going.

Typical Interferograms (raw data)



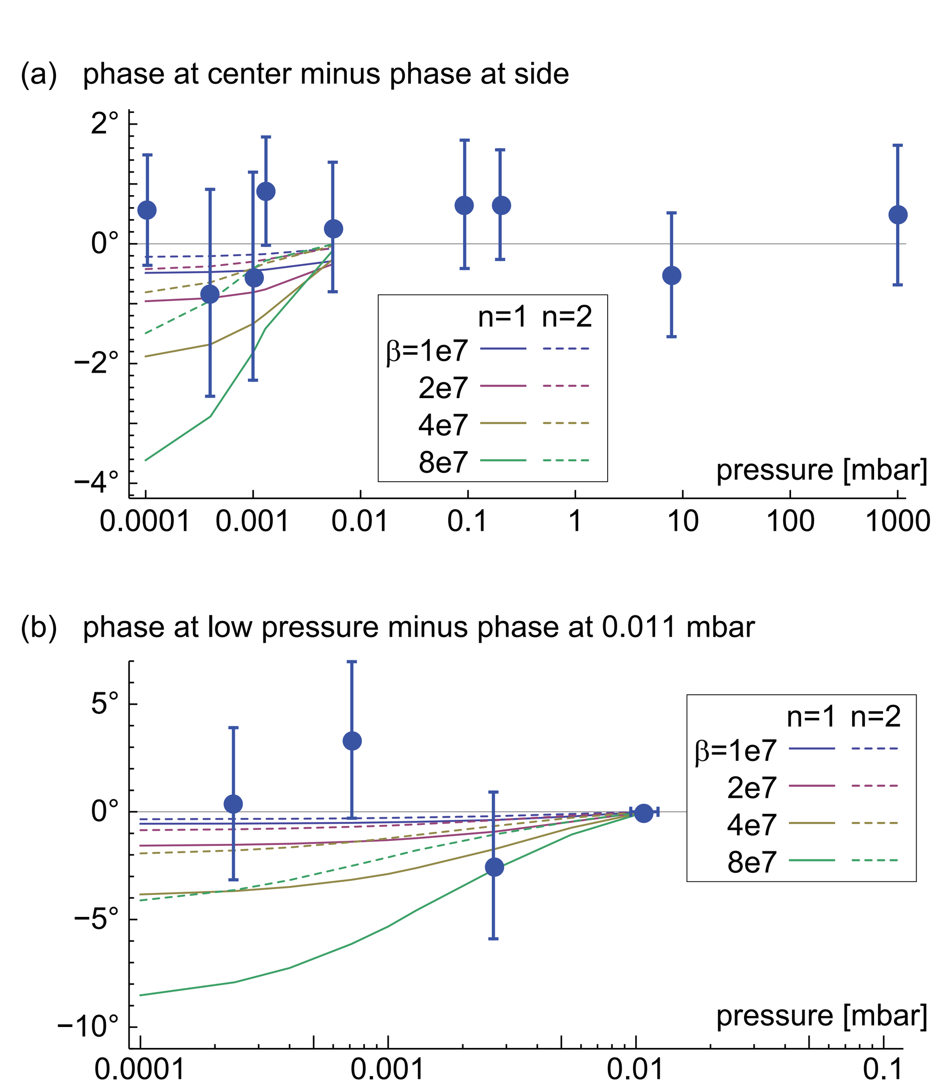
Recorded intensity oscillations between O- and H-detector as a function of the optical path length difference.
The different curves represent different positions of the vacuum chamber.

Correction for non-flat vacuum chamber walls



The profile of the entrance- and exit-walls of the vacuum chamber were measured mechanically (see Fig.(a)).
The thickness variations are due to the hole-drilling process while producing the vacuum chamber. Here, the surfaces were milled before drilling some holes, which lead to mechanical stress and thickness variations in the micron regime in the aluminium.
These variations explain the behaviour of the phase wrt. beam position (see fig. c, raw).

Results: Phase vs. Cell Pressure



All meassurements wer carried out in profile mode and in pressure mode for differet pressure values in the vacuum chamber ranging from 1000mbar down to 0.0001mbar.
The extracted phases show no pressure-dependance.
The colored lines show the behaviour of the phase in case that chameleon dark energy would exist at this level.

For inquiring minds...

... this work:
H. Lemmel et al., Phys. Lett. B743, 310-314 (2015).
... How neutron interferometry constrains chameleons:
Ph. Brax, Phys. Rev. D 88, 083004 (2013).
... Neutron Interferometry @NIST searches for Chameleons:
K. Li et al., Phys. Rev. D 93, 062001 (2016).
... The invention of chameleons...
J. Khoury, A. Weltman, Phys. Rev. D 69, 044026 (2004).

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