Searching for Dark Matter with a Cryogenic Silicon Fabry-Pérot Cavity

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We are developing an experiment of detection of dark matter at FEMTO-ST. This experiment is based on the interaction of ultra-light dark scalar fields with the spacer of a cryogenic silicon Fabry-Pérot cavity and a fibered interferometer. The detection is made via the oscillation of the frequency of an ultra-stable laser locked on the optical cavity.

Keywords—dark matter; optical cavity; ultra-light scalar fields; ultra-stable laser; silicon cryogenic cavity

I. Introduction

With the emergence of the problem of rotation curves in galaxies [1], it was proposed that a new kind of matter populates the Universe. This specific matter, reaching up to five times the density of the ordinary matter, is added to explicate the motion of stars in the galaxies, and of galaxies in galaxy clusters [2]. Among all the scenarios, the study of dark matter has focused on the direct detection of massive constituents between 10 and 1000 GeV.c^{-2}, the WIMPs (weakly interacting massive particle), without success [3]. Another possible candidate, the ultra-light dark matter, is now the subject of increased research, particularly since the discovery of the Higgs boson has shown the possibility of the existence of scalar fields.

Here, we present an experiment of detection of ultra-light dark matter under development, with a silicon cryogenic cavity at FEMTO-ST.

II. Methods

The proposed experiment aims to detect the presence of dark matter scalar fields via their interaction with several fundamentals constants. In the ultralight dark matter model, an oscillating scalar field of mass m_φ is linearly coupled to the Lagrangian of the Standard Model, with m_φ<<1 eV.c^{-2} [4]. An oscillation of the scalar field will produce a variation of the values of some fundamental constants, and in particular the fine structure constant α and the electron mass m_e.

As the Bohr radius depends on α and m_e, the length of objects varies when the Bohr radius oscillates. However, it is not possible to detect these variations by measuring it with a material etalon, such as a rule, since its length would oscillate also. The light speed is nevertheless not affected by scalar fields, so an ultra-stable Fabry-Pérot cavity, made of two mirrors sticked on a rigid spacer, constitutes the ideal tool for this detection. As a laser will be frequency locked on the ultra-stable cavity, the change in frequency of the laser becomes proportional to the change in length of the cavity δl(t). The presence of a scalar field can therefore be detected on the laser frequency.

III. Experimental setup

A first test of detection was carried out at SYRTE, using an ultra-stable cavity made of a spacer in ultra-low expansion (ULE) glass, but this recent experiment did not reveal any ultra-light dark matter in the explored mass range [5].

In the project presented here, it is planned to realize the scheme of the experiment shown in Fig. 1, with a silicon cavity spacer and a laser for which the phase noise will be reduced at high frequency.

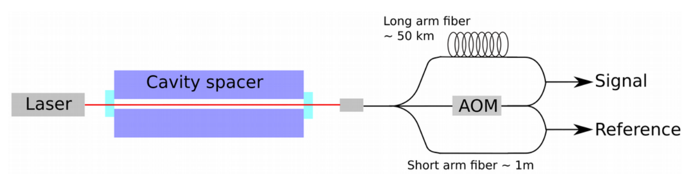

Figure 1: A laser is stabilized on an ultra-stable cavity, and the transmitted light is injected into a three-arm fibered interferometer. The reference is given by the interferometric signal from the AOM – "short" arm comparison, while the signal possibly perturbed by dark matter will be given by the AOM- "long" arm interferometric signal.

Among the ultra-stable cavities designed at FEMTO-ST, we dispose of a cryogenic cavity made of a single-crystal silicon, with a very high quality factor (1000 times higher than the ULE) [6]. This 14 cm long cavity (Fig. 2), cooled to 17 K by a specially designed cryogenic system, is going to provide an ultra-stable laser that meets the state of the art [7], with a relative frequency stability of $\sigma_y(\tau)=3\times10^{-17}$. By taking advantage of this remarkable relative frequency stability and of the mechanical resonances of the cavity spacer, it will be possible to detect oscillations of δl(t) 10 to 10,000 times smaller than the previous experiment, depending on m_φ, and it will improve the knowledge of the coupling parameters between the dark scalar field and the fundamental constants α and m_e.

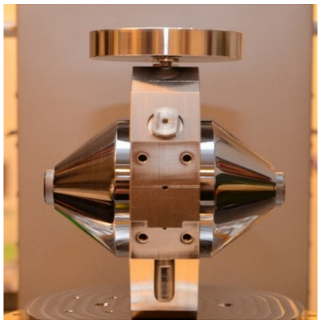

Figure 2: 17 K mono-crystalline silicon cavity at FEMTO-ST, in its mount. The cavity specially cut in the [111] cristalline axis present a mechanical quality factor of 5×10^7.

IV. Conclusions

We are aiming to build an experiment of detection of ultra-light dark matter, based on the interaction between an ultra-light scalar field and an ultra-stable silicon cavity. This experiment will consist on the observation of the frequency oscillations of an ultra-stable laser locked on a silicon cryogenic Fabry-Pérot cavity.

Beyond the demonstration of the contribution of time & frequency metrology in fundamental physics, this project has two major advantages compared to the large detectors usually used for fundamental research (LHC, giant neutrino detectors, gravitational wave detectors): it is competitive while having a moderate cost and an implementation relatively fast.

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