Optomechanics and astroparticle physics; an (im)possible union

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In recent year with the advent of optomechanics, physics has gained a new powerful tool for small displacement and small forces sensing. It is based on two key ingredients, a resonant optical cavity and a micro-fabricated mechanical resonator. By coupling the two by radiation pressure a powerful tool, capable of sensing extremely small signals at sensitivity limit imposed by Heisenberg uncertainty principle, can be constructed. Here we will try to exploit it's extraordinary sensitivity for detection of radiation pressure exerted by hypothetical particles that could be produced in the Sun's interior.

1 Introduction

In recent years, with development of micro-fabricating techniques a new field in physics has started its rapid growth. The field is cavity optomechanics. It offers a plethora of possibilities due to coupling of mechanical resonator to the light by radiation pressure. The mechanical degree of freedom can be provided by variety of designs as nanomechanical beam, silica toroidal micro-cavities, silicon nitride membranes etc, and the other ingredient, the resonating cavity can be either inside the mechanical element, or outside as in the case of Fabry - Perot cavity. The properties of mechanical and optical degrees of freedom can be relatively simply controlled and modified accordingly to the requests posed in front of them. A notable example is light by light control that can be achieved by tailoring the interaction of light with mechanical resonances. It is an optomechanical analogue of the electromagnetically induced transparency (EIT) [3], a well know effect that has been first observed in atomic systems. The optomechanical analogue is known as optomechanically induced transparency (OMIT) and has been demonstrated both in optical [4] and microwave domain [5]. In EIT, and by analogy also in the case of OMIT an intense control beam (pump) modifies the optical response of an opaque medium making it transparent in a narrow bandwidth. Concomitant with the transparency window there is also a variation of the refractive index that induces a significant slow down of the group velocity of the probe beam which can be used to delay, stop, store and retrieve both classical and quantum information. In OMIT the internal resonance of the atom is replaced by the interaction of optical and mechanical degrees of freedom which occurs when the control beam is tuned to the lower motional sideband of the cavity resonance. It can be exploited in a variety of technical applications with obvious advantages over atomic systems since its properties can be tailored at will, and due to lower resonance frequencies longer delay times can be achieved. Besides controlling light by light, also the properties of mechanical system could be controlled by the laser beam. The mechanical response of the vibrational mode is modified by its interaction with light [6]. Both the mechanical frequency and the susceptibility are modified and the selected resonance mode becomes less sensitive to a thermal noise. This effect is known also as (resolved) sideband cooling. The exceptional tailoring possibilities and sensitive readout make these systems extraordinary sensors for small forces and displacement sensing limited only by Heisenberg uncertainty principle, making them interesting for various applications. One of the fields where it can find its place is, surprisingly, astroparticle physics.

One of the best known, and most studied, celestial bodies is the Sun, but nevertheless some of the questions related to the processes that happen inside still remain unanswered. This leaves a window for production of yet experimentally not observed Weakly Interacting Slim Particles (WISPs). Some types of these particles as for example axions are Dark Matter candidates, and the others, as Chameleons [7], could be an answer to the Dark Energy problem. The Chameleons due to their peculiar interaction with matter that is proportional to the density of matter offer a possibility of using kinetic detection together with an appropriate sensor. The kinetic detection exploits the fact that the Chameleons are reflected from a solid surface, thus changing their momentum which is compensated by momentum conservation law by the change in the momentum of the surface itself. A good sensor for the kinetic detection could be a thin membrane, with a readout sensitive to small displacements, caused, in this case, by the radiation pressure of solar Chameleons. If a thin silicon nitride membrane is placed inside a Fabry-Perot optical cavity, a setup sensible to movements caused by radiation pressure is obtained, thus making the detection of Chameleon flux possible. In the following section the experimental setup and the measuring technique will be presented.

2 Experimental setup

The experimental setup is based on the so called membrane in the middle setup 1, where a thin semitransparent silicon nitride membrane is placed in the middle between two high reflectivity mirrors that form a resonant Fabry-Perot cavity. If the membrane is tilted with

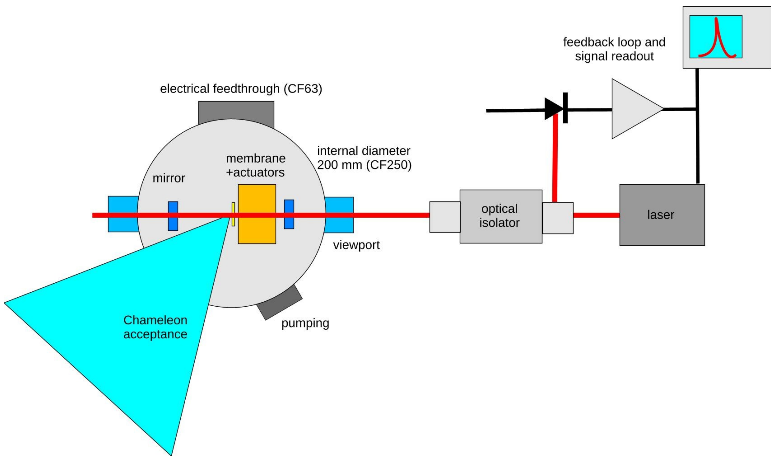

Figure 1: The simplest version of the membrane in the middle setup. The displacement readout is obtained directly from the feedback loop.

respect to the optical axis, the cavity modes become distorted and degenerate modes are split, avoided crossings are created, and the new cavity modes are superposition of the standard TEM_{mn} modes [2]. The new structure of the modes is shown in the following picture 2, where the cavity resonant frequency strongly depends on the linear position of the membrane

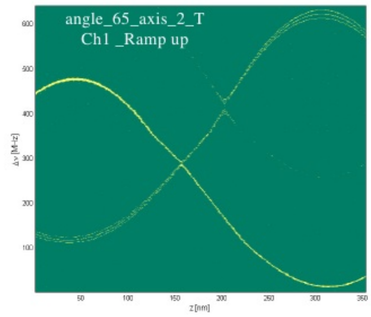

Figure 2: Cavity modes modified by a presence of a thin membrane. Avoided crossings and degenerate mode splitting can be seen.

along the optical axis. By positioning it where the derivative with respect to the position is highest, highest sensitivity is obtained. Once appropriately positioned the laser is locked to the cavity instantaneous resonant frequency, and a buildup of optical power in the cavity is obtained. It is sufficient to observe the Pound Drever Hall feedback signal, and an information on the movement of the membrane in the cavity can be extracted. The origin of the observed movement could be the radiation pressure of the solar Chameleons hitting the membrane [8]. This so called DC mode of detection is only one of the possibilities, otherwise in the AC mode height of the mechanical resonance peak can be observed since the height is proportional to the displacement. The sensitivity in the latter case can be enhanced by cooling the mechanical modes of the membrane either by placing it in a low temperature environment or by cooling it optically with resolved sideband cooling technique. The two modes can be also combined to reach mechanical resonance's ground state.

If this sensor is successfully applied an upper limit to the solar Chameleon flux could be inferred. An estimate could be obtained starting from the sensitivity of an setup constructed in the Camerino Quantum Optics Laboratory [1]. There a displacement sensitivity of $10^{-15}\frac{m}{\sqrt{HZ}}$ has been obtained. By using the cited displacement sensitivity together with an active surface of $25mm^2$, that is the maximum area of the membrane that is commercially available, a force sensitivity $s_F = 10^{-13}\frac{N}{\sqrt{Hz}}$ can be inferred. This corresponds to an solar Chameleon flux equal to $10^{-2}\frac{W}{m^2}$.

3 Conclusion

This measurement would be the first of its kind and would place a bound on the solar Chameleon flux. Furthermore, it could be improved by placing the sensor in front of an X-ray telescope that would focus the Chameleon flux on the membrane. If some of the cooling schemes are applied the sensibility can have a further improvement and by placing a chopper in the Chameleon beam, and having a Chameleon reflector other improvement factors can be expected.

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