MIR: an experiment for the measurement of the dynamical Casimir effect

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Abstract. In this paper we report the status of the experiment MIR (Motion Induced Radiation), aimed at the experimental verification of the dynamical Casimir effect. The stringent theoretical requirements to observe the effect are satisfied in a scheme in which the conductivity of a semiconductor inside a superconducting microwave resonant cavity is varied in time. Free carriers in the semiconductor are periodically excited and recombine at 5 GHz. In this process vacuum and thermal photons are parametrically amplified in a time interval of 200-500 ns.

1. Introduction
The study of the quantum vacuum has seen, in the recent years, an increase in the number of dedicated experiments, following the pioneering results of Lamoreaux on the Casimir effect [1]. The interest on this subject is motivated by the possibility of attaining a more cogent verification of Quantum Electrodynamics (QED), giving at the same time results in other fields of fundamental physics research. Casimir effect experiments can, for example, shed light onto the field of non Newtonian forces at small separation [2], while experiments which sense optical properties of vacuum under external fields [3] are able to search for new small mass particles. We are interested in the Casimir effect in the presence of accelerated boundaries, which is best known as the dynamic Casimir effect [4]. While in the static Casimir effect [5] the action of the vacuum results in a force acting between two bodies, in this experiment we try to reveal directly the presence of a non-empty vacuum by using a specifically designed device to amplify the virtual vacuum photons and to produce real electromagnetic radiation. The ‘amplifier’ is nothing else than a boundary undergoing an oscillation, and hence radiating energy due to the dissipative action against the vacuum photons. The most obvious realization of this amplifier would be a single mirror moving with periodic motion at a frequency $\Omega$. Unfortunately this system produces an undetectable number of photons $N$, approximately given by [6]: $N \sim \Omega T(v/c)^2$ where $T$ is
the observation time, $v$ the maximum velocity and $c$ the speed of light. Using for the parameters the utmost values $\Omega \sim \text{GHz}$ and $(v/c) \sim 10^{-8}$, for an observation time $T = 1$ s the expected number of photons of frequency $\Omega$ would be much less than 1. Such a small number of photons is undetectable, but it can be increased by realizing the moving boundary as part of a resonant cavity with quality factor $Q$. If the resonant frequency $\nu$ of the cavity fulfills the parametric resonance condition, i.e. $2\nu = \Omega$, the number of photons would then be $QN$ [4, 7], which might be in the range of detectability. In our approach the cavity is a high-$Q$ superconducting niobium cavity inside which the moving boundary is realized with a time variable mirror. Lozovik [8] and Yablonovitch [9] suggested to change the reflectivity of a semiconductor by using short intense laser pulses: following this idea we developed a scheme where a semiconductor switches from complete transparency to total reflection at a well defined frequency by means of an amplitude modulated laser beam [10]. This is depicted in Figure 1.

The semiconductor is illuminated by a train of laser pulses, with a repetition frequency twice the resonance frequency of the cavity. Each pulse has enough energy to produce in the semiconductor a plasma reflecting the electromagnetic radiation at frequency $\nu$ [11]. If the recombination time of the semiconductor is short enough, at the end of each pulse the plasma disappears. In this way we will have achieved an effective motion of the boundary, which satisfies the parametric resonance condition. If the number of consecutive pulses is sufficient, a measurable signal will appear in the resonant cavity.

A complete parametrization of our set-up is currently under study by V.V. Dodonov [12]. In his calculation all the parameters describing the apparatus are taken into account. The most critical ones are those concerning the behaviour of the semiconductor and the duration of the process of parametric amplification. The reference values used in the following come from Dodonov’s calculations.

2. Experimental set-up

A detailed description of the apparatus and of the detection technique has been given in [10], here only a brief summary is given.
2.1. Resonant cavity and the cryogenic system

The core of the apparatus is a superconducting niobium cavity, shown in figure 2. We tested several different cavity shapes; in figure 2 we show a rectangular one with dimensions $9 \times 1 \times 8 \text{ cm}^3$, optimised for a large dynamic Casimir effect signal [13]. One of the walls of the cavity can be removed and contains the groove for positioning the semiconductor slab. The cavity resonance frequency is approximately $\nu = 2.35 \text{ GHz}$ and the $Q$ value is in excess of $10^6$ with the semiconductor inserted. The resonance frequency can be varied in order to match the laser repetition rate by controlled insertion of a sapphire slab into the cavity.

The energy stored in the cavity mode is detected by a loop antenna connected to an heterodyne receiver; the antenna position is adjustable and is controlled by two computer driven cryogenic motors. The cavity and the first stage of amplification of the receiver are kept in contact with the bottom of a 50 l liquid helium cryostat. Inside the chamber (shown in figures 2 and 3) He gas at a pressure of 1 mbar allows a better thermal stabilisation of the components in the presence of heat sources (amplifier bias, laser pulses over the semiconductor surface). The cryostat can be operated in the $1 - 8 \text{ K}$ temperature range.

2.2. Semiconductor

There are two theoretical requirements which optimise the photon production in our apparatus: the recombination time $\tau$, which should be of the order of 20 ps, and the mobility $\mu$, whose required value is in the range $3000 - 5000 \text{ cm}^2/(\text{V s})$. As the combination of these two characteristics is not at all common in semiconductor materials, we had to test a lot of GaAs samples grown with different methods before finding a valuable procedure. Starting from semi-insulating GaAs with $\tau \sim 1 \text{ ns}$ and the required mobility, it is possible to reduce $\tau$ in a well defined way while keeping $\mu$ rather constant. This is done by irradiating the semi-insulating GaAs sample with fast neutrons (MeV energy range). The dose determines the recombination time, and a dose of $\sim 10^{15} \text{ neutrons/cm}^2$ results in a $\tau \sim 20 \text{ ps}$. Irradiation is performed at the laboratorio ENEA in Rome, and high precision measurement (about 1 ps resolution) of the recombination time is performed with the THz pump and probe technique, at cryogenic temperature, by the group of Prof. Krotkus at the University of Vilnius. This measurement
provides also an estimate of the mobility, which degrades only slightly with respect to the value measured before irradiation, as obtained also in [14].

2.3. Laser

The laser must deliver a train of a few thousands pulses (macro-pulse of 200 – 500 ns duration) with single pulse energy of the order of 100 µJ energy and a few picoseconds duration. Laser wavelength must be around 800 nm wavelength to excite carriers across the GaAs bandgap. The time interval between consecutive pulses must be about 200 ps, corresponding to a frequency of 5 GHz. These parameters are not available in commercial laser systems, and for this reason the light source was realised in-house.

In figure 3 (right side) we show the Nd:YVO$_4$ laser generating a stable cw ($\lambda=1064$ nm) mode-locking train of 6 ps pulses at approximately 5 GHz. This part, called the main oscillator, is pumped by a 1-W laser diode emitting at 808 nm [15, 16, 17]. The seed is injected into a pulse picker system, which selects a number of pulses thus generating the macro-pulse to be fed into a two stage optical amplifier [17]. The pre-amplifier stage comprises a couple of Nd:YVO$_4$ slabs, each side-pumped by a pulsed 150 W peak power laser diode array in a grazing incidence, total internal reflection configuration. Nd:YAG flash-lamp pumped rods are used for the final power amplification stage, for a total single pass gain of 90 dB. Second-harmonic conversion allows synchronous pumping of an optical parametric oscillator, obtaining up to 40 mJ. A further amplification stage to reach the final required value of energy/pulse is currently under development.

3. Expected sensitivity and background effects

The energy stored in the cavity after excitation decays exponentially in time, with a time constant \( \tau_U = 1/(\pi \Delta \nu) \), where \( \Delta \nu \) is the linewidth of the cavity. The decay signal travels to an heterodyne receiver, that is shown in figure 4.

We use a cryogenic amplifier kept at liquid helium temperature to increase the sensitivity of the measurement. In fact, the sensitivity of the receiver is primarily determined by the noise temperature \( T_e \) of the first stage of amplification, which has a nominal value \( T_e = 5 \) K. With such a low noise temperature, the system sensitivity is limited by the temperature and the length of the cable which connects the input of the amplifier to the cavity. This is the reason why the
Figure 4. Detailed scheme of the electronics of the MIR experiment. A microwave cavity, equipped with a weakly coupled input antenna (WCA) and a critically coupled antenna (CCA), is placed inside a liquid helium cryostat. A directional coupler connects the CCA to the receiver. The cryogenic amplifier CA is followed by a post amplifier PA; the mixer provides frequency down-conversion of the signal while a filter between the two amplifiers A1 and A2 rejects noise outside the cavity bandwidth. All the components following the cryogenic amplifier are at room temperature.

The cable is anchored to the bottom of the liquid helium vessel and is kept as short as possible. The results obtained with different cavities indicate that the actual noise temperature of the system varies between 7 and 10 K.

We measure the noise temperature of the receiver with the variable temperature load method, which has been described in detail elsewhere [18]. The calibration procedure with a 50 Ω load allows us to obtain the precise value of the gain $G$ of the receiver and the overall noise temperature $T_e$, as shown in figure 5. The inserted table shows the gain $G$ and the noise temperature $T_e$ obtained by fitting the data with equation $P/B = k_B G (T + T_e)$, where $P$ is the noise power within the measurement bandwidth $B$ of the spectrum analyser, $k_B$ is the Boltzmann constant and $T$ the temperature of the calibration load. When we connect a cavity in place of the resistor we measure the value represented by the encircled dot in Fig. 5. This noise level can be converted, dividing it by the measured gain, in a noise density in input to the amplifier of $(2.0 \pm 0.2) \cdot 10^{-22}$ W/Hz, which corresponds to approximately 100 microwave photons at equilibrium.

The parametric amplification process described in this paper can be characterised by a gain $G_V$ which can be estimated from the parameters of the apparatus [12, 13]: the total number of photons produced is $N = G_V (1 + 2N_{th})$, where $N_{th}$ is the number of thermal photons in the mode considered and $(1 + 2N_{th})$ is the thermal factor [19]. Since our receiver is capable to detect a hundred photons, a gain $G_V$ of about 100 must be reached to see the amplified vacuum photons. The contribution to $N$ of the vacuum photons $G_V$ for our apparatus has not been measured yet, but it should not be critical [12, 13]. It will be measured by charging the cavity before the parametric excitation, but in principle it can be measured also using the thermal photons present at equilibrium in the cavity at different temperatures in the range 1 – 8 K. To have an estimate of the number of photons distributed in the cavity mode TE$_{101}$, we have to consider that the photon wavelength in a microwave cavity is comparable to the cavity dimensions. In this case the number of thermal photons $N_{th}$ at equilibrium at temperature $T$ is

$$N_{th} = \frac{1}{e^{\frac{h \nu}{k_B T}} - 1} \simeq \frac{k_B T}{h \nu},$$

where $h$ is the Planck constant and $\nu$ the cavity resonance frequency. For example, at 4 K a
Figure 5. Left: scheme of the apparatus for the noise and calibration measurement at LHe temperature. Measurements are performed with either the cold cavity or the variable temperature resistor connected to the receiver electronics. Right: noise power density of the receiver measured with a load resistor in place of the cavity plotted as a function of the temperature. The continuous line is a linear fit of the experimental data. The encircled value corresponds to the measured noise power density peak of a reentrant cylindrical cavity.

A thermal contribution of 33 photons is expected. A number of other procedures are also under study to disentangle a real signal from a systematic effect. These include detuning of laser frequency out of the parametric resonance, variation of the thickness and the recombination time of the semiconductor and possible new shapes of the resonant microwave cavity.

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