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3D SPECKLE COOLING IN A MICROWAVE CLOCK

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Abstract – **Sub-Doppler laser cooling is studied in an optically polished microwave cavity used as a reflecting cell. Light potential wells due to the speckle field in the cell make Sisyphus cooling mechanisms possible. For a 1 s capture time, about 10^8 cesium atoms are cooled at temperatures in the microkelvin range from thermal vapor. These results are discussed and compared with the basic theoretical model involving two laser beams lin ⊥ lin polarized. For a microwave clock using such cold atoms, the pulsed operation is precised and the main frequency shifts are evaluated. The short term relative frequency stability is expected to be lower than $10^{-12}\ \tau^{-1/2}$.**

Keywords - **Atomic clocks, laser cooling, frequency stability.**

I. INTRODUCTION

BNM-SYRTE is involved in the development of high frequency performances compact clocks based on laser cooled cesium atoms for industrial applications. HORACE is an original device where all the interactions – atomic cooling and preparation, microwave interrogation, detection – are located in the same place and separated using a time sequence.

Previous studies have demonstrated atomic laser cooling in different cavities made in copper or Spectralon [1], and several cavity geometries have been tested [2,3]. Microwave properties of a spherical microwave resonator have been studied in [4]. In this paper we present the results of laser cooling in this reflecting spherical cavity.

We first describe the physics package and give the main properties of the experimental set-up. Then the laser cooling properties are presented. We start from the background given in [5], then explain our set-up conditions, and from experimental results we deduce physical parameters about the cold atoms obtained in Horace. Finally we give an estimation of the frequency performance expected for Horace as a microwave clock.

II. A MINIATURE DEVICE

The main feature for Horace is to reduce the volume of the physics package, which basically consists of an optical bench and a microwave cavity surrounding a quartz bulb under vacuum at 10^{-8} Torr. This cavity is optically polished with $\lambda/14$ roughness in order to store the laser light and create an isotropic light field for atomic cooling. This microwave cavity is resonant at 9.192 GHz on a TE_{011} mode for the clock interrogation. Thermal cesium atoms are continuously present in the volume enclosed by the cavity. Cesium pressure vapor is maintained by a temperature-controlled reservoir located at about 10 cm above the cavity (see figure 1). Under operating conditions, the reservoir temperature is -15°C.

To avoid any light field imbalance and to keep a good quality factor for the microwave resonance, the different holes in the cavity have to be as small as possible. The light coming from the cooling beam and the pumping beam is sent to the cavity through six multimode fibers. The cooling beam is generated from an injected master-slave system laser. The resulting laser linewidth is about 150 kHz and the optical power is about 100 mW. The pumping beam is a DBR with 5 MHz linewidth and 5 mW effective power. The optical frequency and intensity of each beam is independently adjusted with computer-controlled AOMs.

Owing to the fact that atomic cooling occurs in a closed reflecting cavity, we cannot have direct information about the cold atoms cloud by imaging methods, like for any classical optical molasses experiment. To study the cloud shape, two experimental techniques have been used. They are direct linear absorption and time of flight detection technique [6].

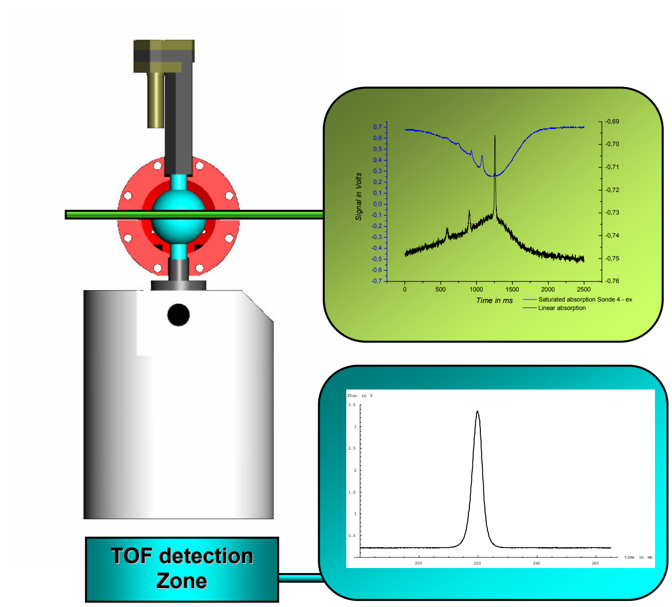

Fig. 1. Horace physics package (to scale). The overall vertical dimension is about 30 cm. Upper part : the laser beam sent through the spherical cavity probes the cesium density in the cavity. Lower part : once the cooling beams switched off, the cold atoms cloud reaches the TOF detection zone after free fall under gravity. TOF signal gives two physical parameters for the cold atoms : the curve width scales as the temperature and the curve integral as the number.

III. COOLING PROPERTIES

Actually the laser field in the microwave cavity is a 3D speckle field. At a macroscopic scale, intensity gradients limit the atoms trapping region. Sub-Doppler temperatures are reached in Horace, despite the fact we use multimode fibers with no control of light polarization and with intensity imbalances greater than 20%. Using an original time sequence for the cooling process, we have estimated from TOF measurements a cloud of 3.10^8 atoms at a temperature of 4 µK, making the assumption of a cloud size of 10 mm.

A. Principle

Sisyphus cooling in a speckle field has already been demonstrated experimentally at ENS-LKB [5]. They showed that the friction coefficient and the diffusion coefficient depend on the size of the speckle grain, leading to the following expression of the temperature :

$$\frac{k_B T}{\hbar\delta'} \propto 1 + \left[\frac{d/\lambda}{\delta/\Gamma}\right]^2 \qquad (1)$$

where $\delta' = \delta s_0$, s_0 being the saturation parameter at resonance, δ the detuning from the resonance, Γ the natural width of the $|6P_{3/2},F=5>$ level, λ the wavelength of the $|6S_{1/2}, F=4> \rightarrow |6P_{3/2},F=5>$ transition, and d the size of the speckle grain.

In the classical lin ⊥ lin configuration where Sisyphus effect has been demonstrated first [7,8], the light intensity is uniform and spatial modulation of polarization is periodic over a macroscopic scale. In the case of the speckle field, the random and strong modulation of the laser intensity and the presence of many polarization components in the light potential wells allow transitions between potential curves. This phenomenon is similar to Sisyphus cooling obtained in the lin ⊥ lin case.

Nevertheless, their results cannot be directly applied to our case. The ENS experiment leaded to a 3D speckle field indeed, but they kept a lin ⊥ lin configuration for the lasers. This has to be compared to the 3D speckle field obtained in HORACE where no control of the polarization is realized. We will see that in spite of those differences, some of their results can be compared to ours.

B. A Sisyphus phase in two steps

Experimentally the cooling time sequence has been determined by optimizing the number of atoms detected with the time of flight method. As shown on figure 2, we distinguish two phases in this sequence. A first phase captures the atoms at high intensity and low detuning. A second phase consists of decreasing the intensity and increasing the detuning simultaneously to reach the smallest temperatures. Typically we start from 73 µK during the capture phase, and achieve at 4 µK at the end of the Sisyphus phase. TOF signals plotted on figure 3 justify the time sequence we use.

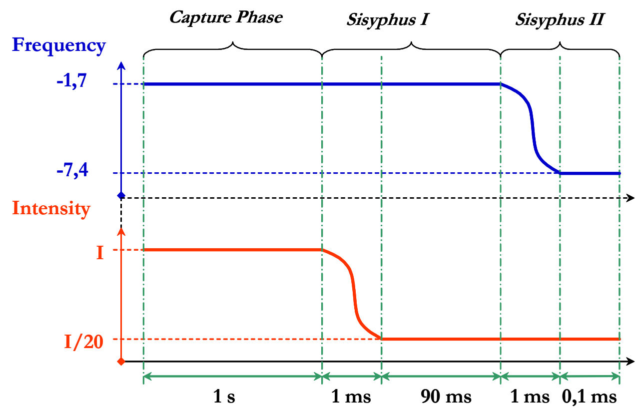

Fig. 2. Horace cooling time sequence. Intensity and detuning of the cooling laser are varied separately with two independent phases. For each phase, the times that optimize the TOF detection are indicated on the graph.

The first one (curve C) is obtained at the end of the capturing phase. The second one (curve S1) is obtained at the end of a Sisyphus phase realized in one step (intensity decreased and detuning increased simultaneously) where the different parameters (intensity, detuning, phase time) have been optimized in order to maximize the number of atoms. Finally, the third one (curve S2) is obtained at the end of the time sequence presented on figure (2).

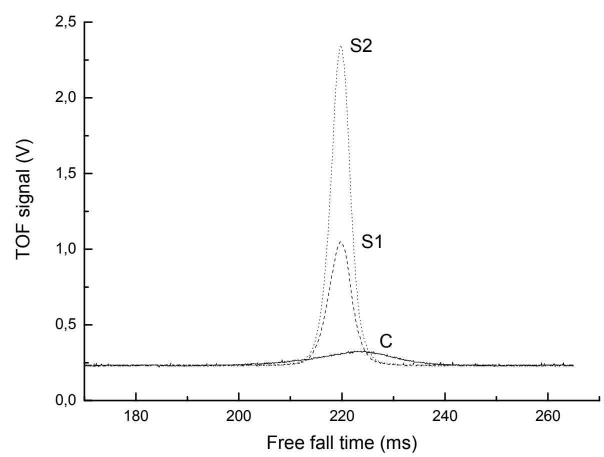

Fig. 3. Comparison of TOF signals. S2 is obtained after a Sisyphus cooling with two separate steps; S1 with one step; C after the Capture phase only.

One can see that a Sisyphus phase in two steps is more efficient in our device, since more than a factor two is found between S1 and S2 considering the number of atoms detected in the TOF. Besides, one can notice that a Sisyphus phase in two steps allows us to reach the smallest temperatures. Table I summarizes the results associated to the three curves presented on figure 3.

TABLE I

	Atoms detected by TOF	Maximum temperature (μK)
Capturing phase (C)	$N_{d,c} = 1{,}9.10^6$	73
Sisyphus phase in one step (S1)	$N_{d,S1} = 4{,}8.10^6$	6
Sisyphus phase in two steps (S2)	$N_{d,S2} = 10^7$	4

Temperatures and number of atoms detected at the end of the different phases of the cooling sequence

The temperatures presented above have been calculated from the TOF measurements by the estimation of the rms momentum according to the following velocity distribution [7]:

$$\frac{1}{\left[1+\left(p/p_C\right)^2\right]^b} \qquad (2)$$

The parameter b calculated in the fit by a LorentzB is typically equal to 3.6 in our case. The momentum distribution plotted on figure 4 is correlated to Sisyphus cooling according to the theoretical paper [7].

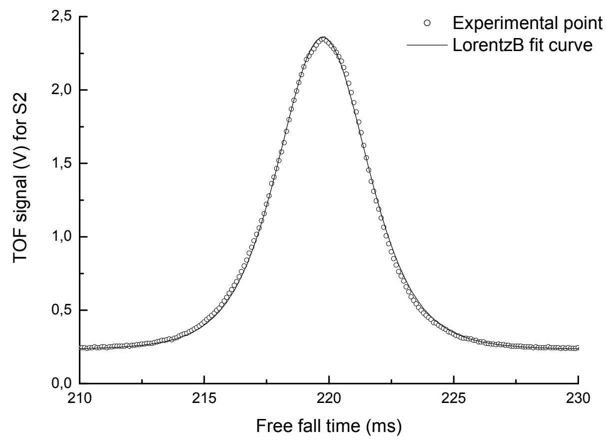

Fig. 4. Theory of Sisyphus cooling predicts LorentzB momentum distribution. The agreement between the experimental data and the fit function confirms Sisyphus effects in Horace.

C. Characterization of the cold atoms cloud

All measurements presented here have been done with the cooling time sequence presented in part *B*. Owing to the random intensity polarization modulation and to the fact that there is no correlation between polarization and intensity, Sisyphus mechanisms are less efficient than the lin ⊥ lin molasses. We are thus expecting a longer atomic thermalization time [5]. We studied the variation of the temperature of the atoms (plotted on figure 5) and their number (plotted on figure 6) versus the Sisyphus I time.

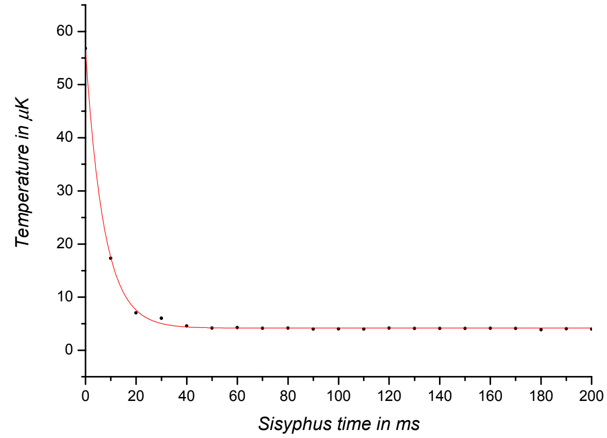

Fig. 5. TOF distribution width (ie Atoms temperature without size correction) versus Sisyphus I time.

Considering the variation of the temperature versus Sisyphus I time, we find a thermalization time of the atoms in the wells $\tau_{th} \sim 7$ ms as shown on figure 5. The temperature remains constant for longer Sisyphus times. Our value lies in the range of previous measurements which indicates we are in an intermediate configuration. The experiments carried out at LKB [5] gave $\tau_{th} \sim 20 - 80$ ms (depending of detuning and intensity), and $\tau_{th} \sim 1$ ms in the lin ⊥ lin configuration [8].

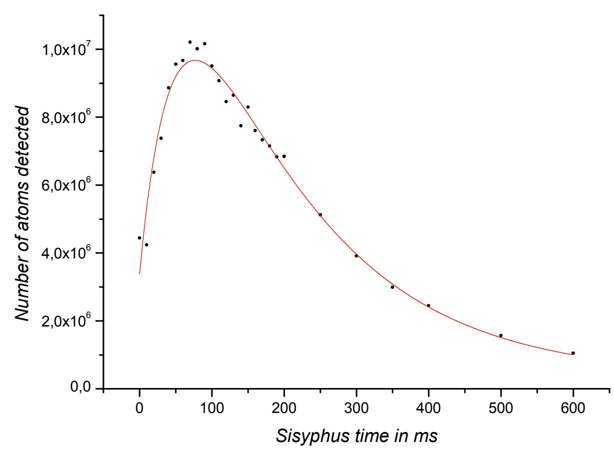

Fig. 6. TOF distribution area (ie atoms number) versus Sisyphus I time.

Considering the variation of the number of atoms detected versus the Sisyphus I time on figure 6, we see an increase from 0 ms to about 100 ms that should correspond to the actual time for the atoms to get trapped in the potential wells. The data curve are fitted with the function :

$$\left[1-\exp(-t/\tau)\right]\exp(-t/\tau_{at}) \qquad (3)$$

where $\tau_{at} \sim 180$ ms is the lifetime in the wells. This value is in good agreement with the loading time of the cold atoms from figure 7. This is well understood since the lifetime of the atoms in the wells is determined essentially by the collisions with the cesium atoms in the thermal vapor. However, the time constant $\tau \sim 70$ ms in the first part of the plot disagrees with the thermalization time obtained from figure 5. During this time indeed, we can suspect the cold cloud spatial distribution to be modified by the Sisyphus phase in which the temperature remains constant. Therefore, the first part of the graph is biased and cannot lead us to a value for the thermalization time.

Considering the loading time $\tau_{at} \sim 180$ ms presented on figure 7 and resulting of the fit of the data with

$$A\left[1 - \exp(-t/\tau_{at})\right] \tag{4}$$

we can estimate the detected fraction in the probe beam by considering the loss of atoms along the free fall (238 mm long) during about 220 ms. This fraction is then given by

$$F_x = \exp(-t/\tau_{at}) \approx 27\% \tag{5}$$

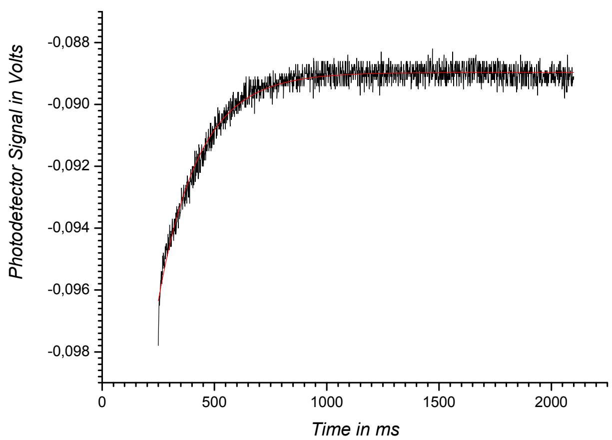

Fig. 7. Loading time measurement. The exponential fit to experimental data gives a characteristic loading time equal to 180 ms.

In order to give an estimation of the number of atoms cooled in the cavity, we need to make some assumption about the size of the cloud. A realistic value is obtained by considering the case of a Gaussian distribution. The spatial extension can be related to the TOF width measurement according to :

$$\beta = h\left[1 + \Delta t\sqrt{\frac{g}{8h\ln 2}}\right]^2 - h \tag{6}$$

where h is the free fall height and Δt is FWHM for the Gaussian distribution. This gives β_{max}, the maximum weight of the cloud taken at *1/e*. On figure 4, the measured $\Delta t \sim 3.8$ ms leads to $\beta_{max} \sim 7$ mm.

Assuming a cloud radius of 5 mm at a given temperature, we can estimate the fraction F_g of atoms truncated by a Monte-Carlo simulation. Consequently, taking into account the fraction of atoms lost by truncation and by collisions with the thermal vapor, we can finally give the number of atoms cooled in the cavity:

$$N_0 = N_d \frac{F_x}{F_g} \tag{7}$$

This has been applied to the number of atoms detected at the end of the capture phase, and at the end of the Sisyphus phase. The results are summarized in table II.

TABLE II

Estimations of the number of atoms cooled inside the cavity at the end of the capturing phase, and the Sisyphus phase

	Temperature of the cloud	Fraction of atoms truncated	Number of atoms estimated inside the cavity
At the end of the capturing phase (C)	$T_C \sim 73$ µK	$F_{g,c} = 1.1$ %	$N_{0,c} = 6.10^8$
At the end of the Sisyphus phase (S2)	$T_{S2} \sim 4$ µK	$F_{g,c} = 12.5$ %	$N_{0,S2} = 3.10^8$

IV. Towards a compact atomic clock

Pulsed clock principles. Horace as a clock will be operated so that cold atoms are kept at the same place from one cycle to the following. The best cycle time is about 20 ms.

Three interrogation methods are possible: Rabi, Ramsey or Maser-like [9]. The methods with a single Rabi π–pulse and two Ramsey $\pi/2$–pulses have already been studied for Horace [10]. A detection beam tuned to the 4-4 or 4-5 transitions sent through the cavity after the atomic interrogation would give access to the clock levels populations and hence a measurement of the clock signal.

Expected frequency performances. Numerical calculations have been performed in the case of Ramsey interrogation method [10]. For 10^8 atoms cooled in the cavity, the short term frequency stability is limited by the Dick effect at about $5.10^{-13}\tau^{-1/2}$. As for the clock frequency shifts, the main contributions have been roughly estimated and are given in table III.

Effects	**Relative frequency shifts**
First order Doppler effect	10^{-15}
Microwave leaks	0
Microwave switch	10^{-13}
Cavity pulling	$< 10^{-14}$
Cold collisions	$< 10^{-12}$
Light shift	$< 10^{-15}$

TABLE III

V. Conclusion

We have shown that 3D speckle cooling in our device gives access to Sisyphus temperature range. We have measured about 3.10^8 cold atoms below 4 µK. The cloud size is estimated at 10 mm, located at the center of the cavity where the magnetic induction is the least perturbed. From numerical calculations, the short term frequency stability is expected at the level of $5.10^{-13}\tau^{-1/2}$.

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