Characterization of a quantum gas microscope with a subwavelength resolution based on AC Stark Shifts

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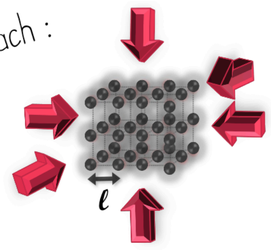
Motivation

The AUFRONS (Ultra cold atoms in nanostructured optical potentials) project aims at building near field optics / Ultra cold atoms hybrids to achieve stronger coupling between solid state systems and cold atoms. Our first experimental target is to reduce the 2D lattice spacing to enter more deeply into anti-ferromagnetic quantum phases [1,3]. Experimental methods to manipulate atoms in the close vicinity of surfaces are essential to push forward the capabilities of cold atom/nanophotonic platforms.

Common approach : Far field

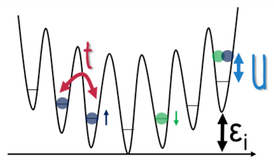


Optical Lattice : laser interferences

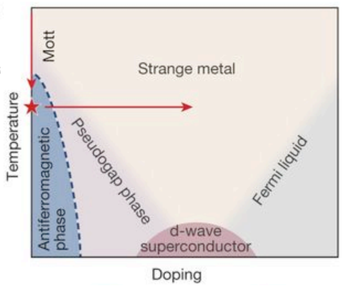
[1,2]

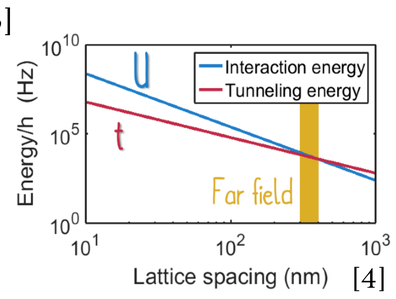
Hubbard Hamiltonian :

$$\hat{\mathcal{H}} = -t \sum_{\langle i,j\rangle,\sigma} \left(\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + \text{h.c.}\right) + U \sum_{i} \hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow} + \sum_{i} \varepsilon_i \hat{n}_i$$



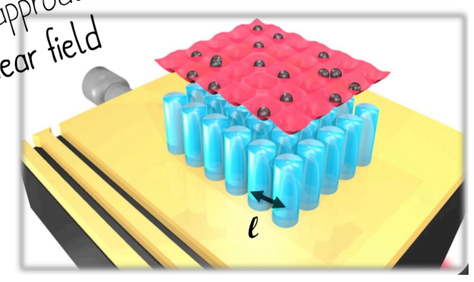
Antiferromagnetic phase [3]





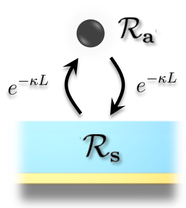
[4]

Our approach : Near field



Doubly Dressed State trapping

- Casimir-Polder forces [5]



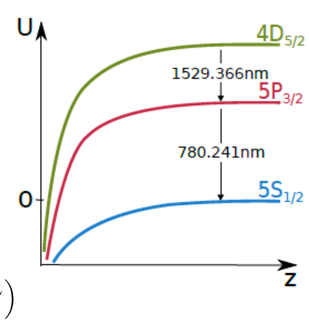
Atomic reflection operator (polarisability)

Surface reflection operator (surface modes)

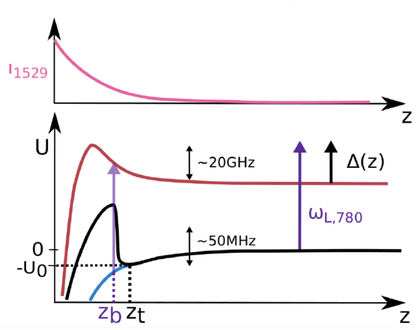
- Interaction potential [6]

$$U(\mathbf{r}) = \frac{\hbar}{2\pi}\int_0^{\infty} d\xi \,\text{Tr}\ln\left(\mathbf{1} - \mathcal{R}_a e^{-\kappa L}\mathcal{R}_s e^{-\kappa L}\right)$$

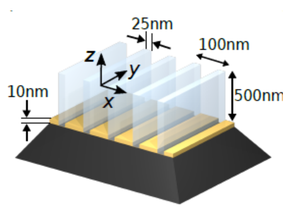
- Short range energy shifts [7]

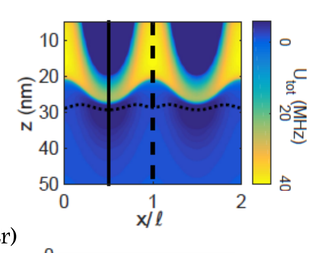


- Plasmonic resonance enhancement

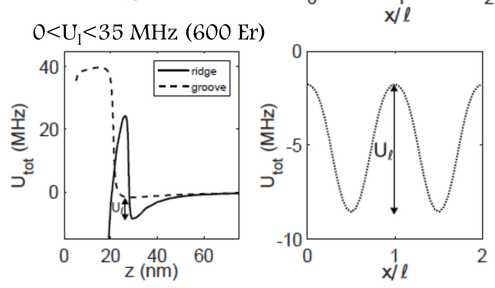


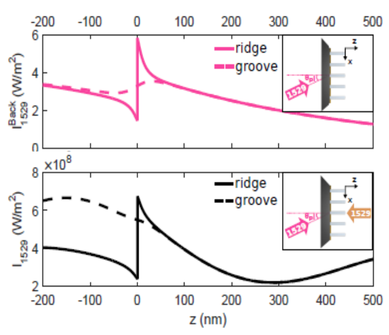
Sub-wavelength 1D structuration [8]





0<U$_l$<35 MHz (600 Er)

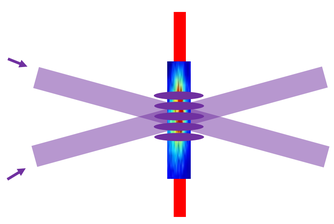


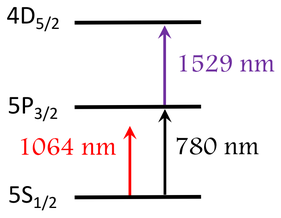


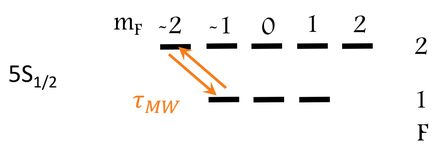
→ Need subwavelength imaging

Experimental setup

- Dipole trap with a ^{87}Rb BEC at 1064 nm
- Lattice at 1529 nm with period i_{1529} and amplitude v_0
- Imaging/Repumper beam at 780 nm
- Atomic density control with micro-wave pulses between m_F states

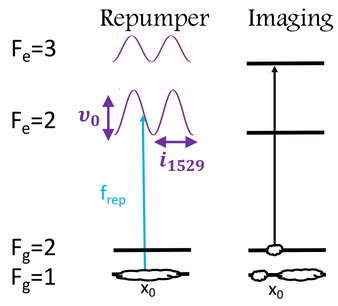




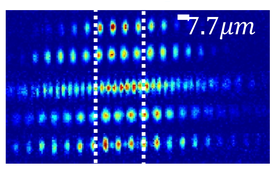


Method 1: 780 nm repumper + 1529 nm

Experimental sequence



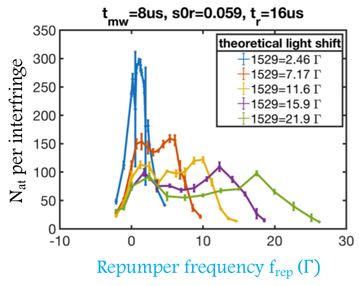
Scan f_{rep} and integrate the atom number at the center of the cloud

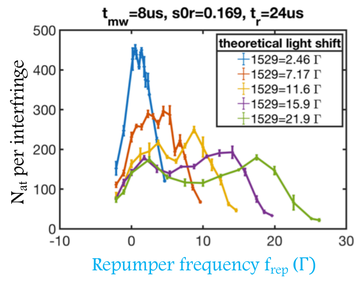


At the light shift middle position (3-level model) for $s_{0r} \ll 1$, $t_r \gg 1/\Gamma$, $\Gamma/2\pi\nu_0 \ll 1$:

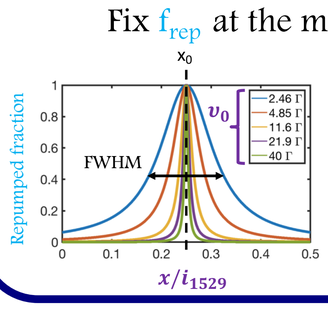
$$FWHM_{rep} = \frac{\Gamma}{2\pi\nu_0}\frac{i_{1529}}{\pi}\left(\frac{\Gamma s_0 t_r}{4\ln(2)} - 1\right)^{1/2}$$

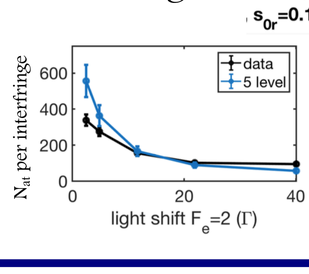
slope

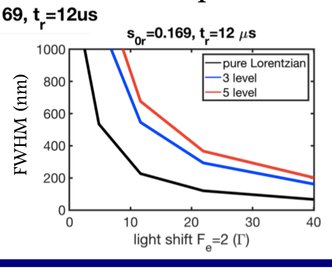


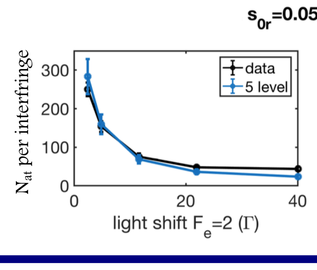


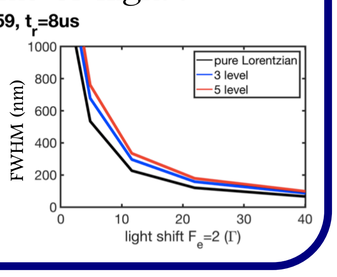
Fix f_{rep} at the middle of the light shift (data) and compare (3/5-level models*) with time-of-flight :





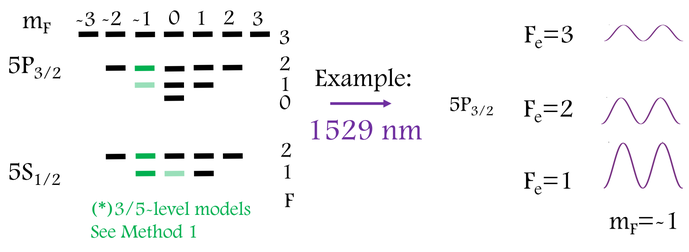






Dressed excited state

Light shifts smaller than the hyperfine structure:



(*)3/5-level models See Method 1

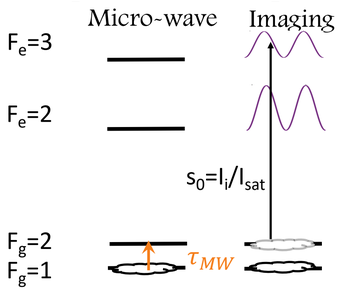
$$\Delta E_{|F,m_F>} = U_0\left(\alpha^{(0)} + \alpha^{(2)}\frac{3m_F^2 - F(F+1)}{F(2F-1)}\right)$$

Light shifts larger than the hyperfine structure:

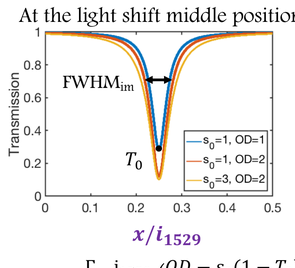
- $|F, m_F\rangle$ not a good basis, most of the m_F states mixe.
- The transition $|F_g = 2, m_F = -2\rangle \rightarrow |F_e = 3, m_F = -3\rangle$ remains closed.

Method 2: 780 nm imaging + 1529 nm

Experimental sequence



At the light shift middle position



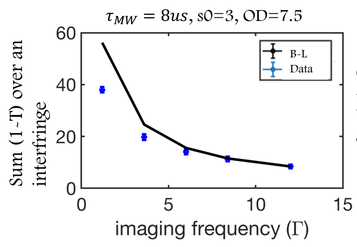
$$FWHM_{im} = \frac{\Gamma}{2\pi\nu_0}\frac{i_{1529}}{\pi}\left(\frac{OD - s_0(1-T_0)/2}{-\ln((1+T_0)/2)} - 1\right)^{1/2}$$

Imaging assuming Beer-Lambert's law

$$OD = -(1 + 4\delta(x)^2)\ln(T(x)) + s_0(1 - T(x))$$

- $\delta(x)$: detuning
- OD: optical density homogenous over the light shift

Integrate 1-T at the middle of the light shift



OD is a free parameter: Estimated with cloud's width and atom number in TOF.

→ Subwavelength resolution in transmission demonstrated. Ongoing quantitative analysis based on small cloud scattering dynamics.

→ Possible alternative : measure the scattered photon number (dark ground imaging).

Perspectives

~ Large clouds:
Role of dipole-dipole interactions in sub-wavelength structures.
See **V. Mancois's poster** on 18/11/2020.

~ Ground state lattice:
Test this imaging method to resolve the ground state sites. Implemented soon !
See **J.B. Gerent 'poster** on 16/11/2020.

~ Doubly dressed state trapping with 3 lasers 1064+780+1529 without surface

References

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[4] Gullans M. et al., Phys. Rev. Lett. 109, 235309 (2012)
[5] Casimir H.B.G. and Polder D., Physical Review, 73 (1948)
[6] Lambrecht A. and al., New Journal of Physics, 8 (2006)
[7] Chang, D. E., *et al* Nature Communications, 5 :13 (2014)
[8] M. Bellouvet et al., Phys. Rev. A 98, 023429 (2018)

Collaborations

Fabrication :
INRIM Turin (L. Boarino)

Nano-structured optical mode calculations :
LP2N Bordeaux (P. Lalanne and K. Vynck)

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