The role of dispersion forces for matter-wave binary holography experiments

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Introduction

- Lithography of arbitrary structures down to nanometre scale has applications in semiconductor industry, quantum electronics, nanophotonics and others.
- Recently proposed method: sending metastable He through a holography masks [1]
- However, these first calculations used a simple scalar wave approach, which did not take into account the dispersion force interaction between the atoms and the mask material
- We address this issue and illustrate the impact to the proposed method

Matter-wave lithography

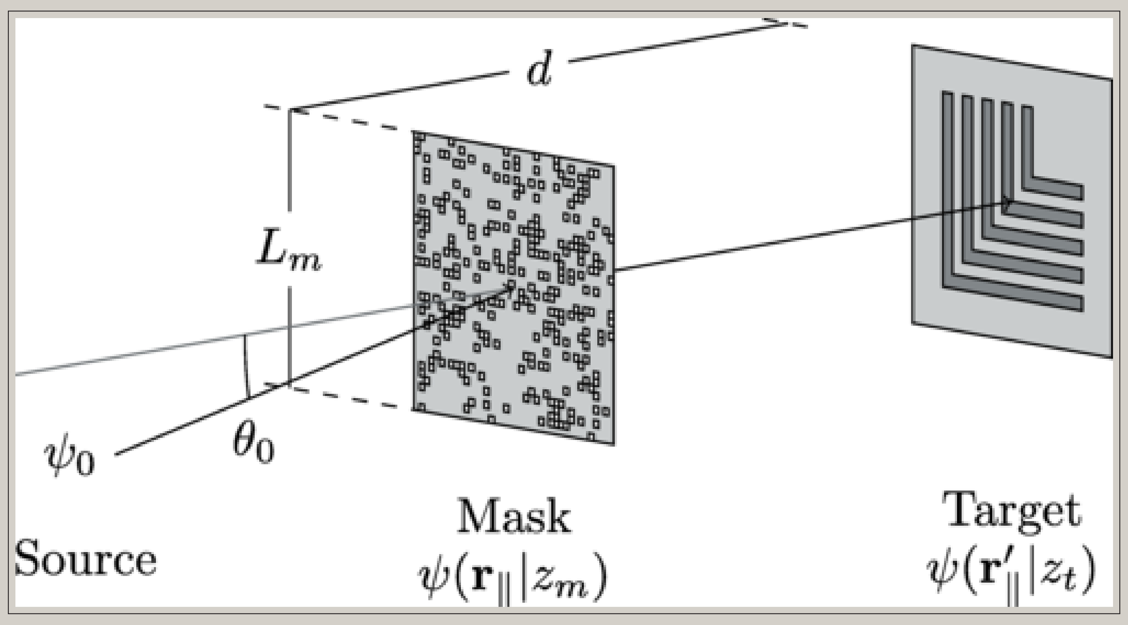


Figure 1: Sketch of the experimental setup for lithography with matter waves. The incoming beam, initialised at the source, is diffracted at a mask and creates a target pattern on the screen. Picture taken from Ref. [1].

- Lithography: Experimental technique to create nano-structured patterns
- State of the art: EUV $14\,\mathrm{nm}$ energy $(E = \hbar\omega) \approx 80\,\mathrm{eV}$
- Matter waves:
  - proposed resolution $< 1\,\mathrm{nm}$
  - transferred energy $(E = mv^2/2) \approx \mathcal{O}(\mathrm{meV})$
  - But: Matter waves interact with dielectric objects (mask)

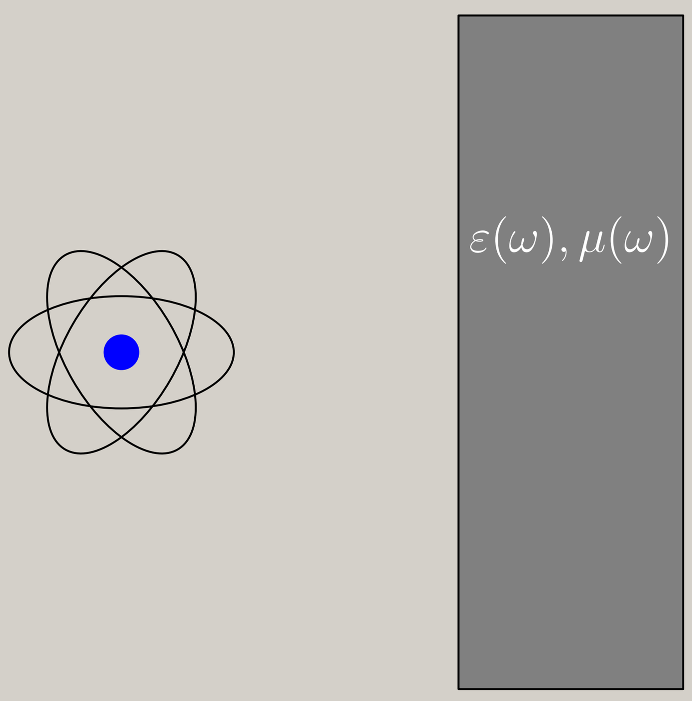
Macroscopic QED

- Ground state of the electromagnetic field: $\langle\hat{\mathbf{E}}\rangle = 0$, but $\langle\hat{\mathbf{E}}^2\rangle \neq 0$ $\rightarrow$ vacuum fluctuations
- Energy shift due to second order perturbation of field-matter interaction
- Field quantisation: $\hat{\mathbf{E}}(\mathbf{r}) = \int_0^\infty \mathrm{d}\omega\, \hat{\mathbf{E}}(\mathbf{r},\omega) + \text{h.c.}$

$$\hat{\mathbf{E}}(\mathbf{r},\omega) = i\sqrt{\frac{\hbar}{\pi\varepsilon_0}}\frac{\omega^2}{c^2}\int \mathrm{d}^3r'\, \sqrt{\Im\chi(\mathbf{r}',\omega)}\mathbf{G}(\mathbf{r},\mathbf{r}',\omega)\cdot\hat{\mathbf{f}}(\mathbf{r}',\omega)$$

Casimir–Polder interactions

- Consideration: neutral particle α near dielectric object ε
- In presence of electric field: Induced dipole $d = \alpha\cdot E$ and Displacement fields $D = \varepsilon\cdot E$ leading to Coulomb forces
- Casimir–Polder potential [2]



$$U_{\mathrm{CP}}(r_{\mathrm{A}}) = \frac{\hbar\mu_0}{2\pi}\int_0^\infty \mathrm{d}\xi\,\xi^2\,\mathrm{Tr}\left[\alpha(\mathrm{i}\xi)\cdot\mathbf{G}^{(S)}(r_{\mathrm{A}},r_{\mathrm{A}},\mathrm{i}\xi)\right]$$

- He atoms and SiN_x membrane [3]

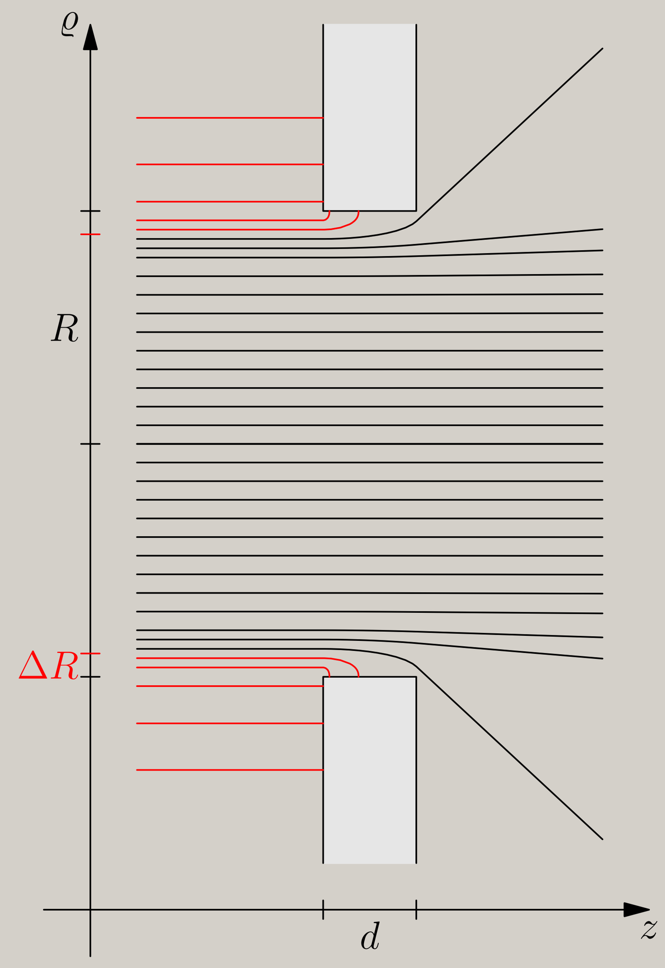
$$U_{\mathrm{CP,app}}(r) = -\frac{9C_3}{\pi}\int\frac{\mathrm{d}^3s}{|s-r|^6}$$

with the volume element d^3s covering the membrane
- Impact of CP forces on interference pattern: transmission function

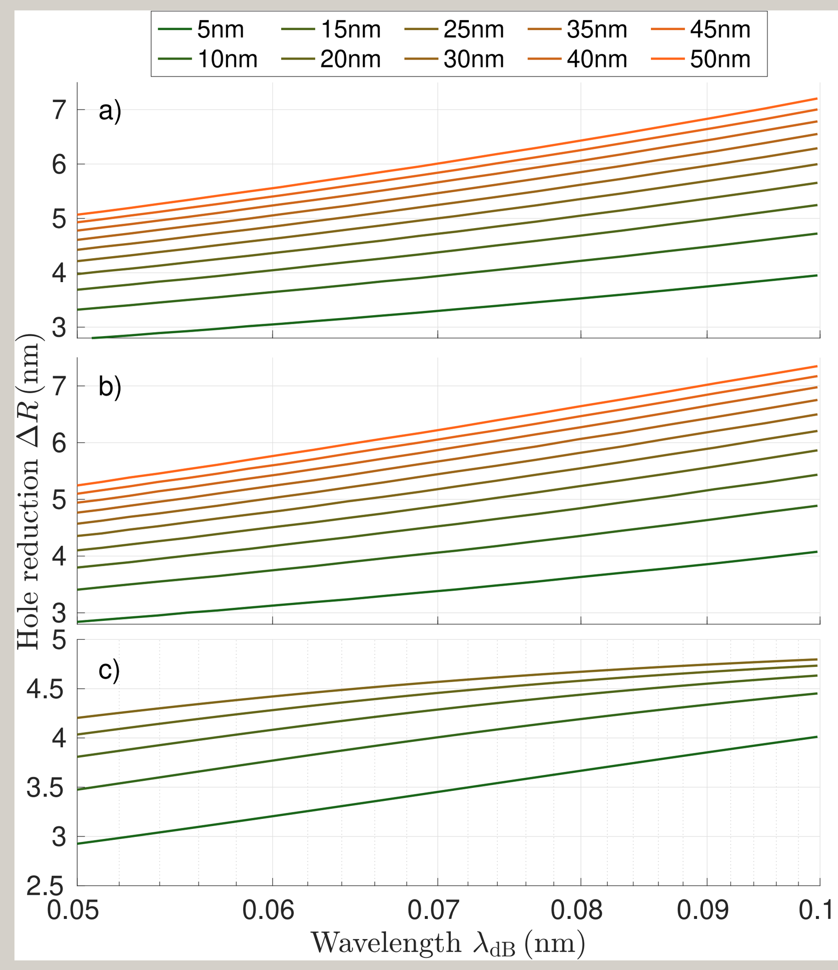
$$t(\varrho) = \Theta[\varrho-(R-\Delta R)]\,\mathrm{e}^{\mathrm{i}\varphi(\varrho)}$$

with: Pore reduction ΔR, Phase shift $\varphi(\varrho)$

Results for the pore reduction



(a) Deflection of particles bypassing a pore, transmitted trajectories (black), absorbed particles (red).



(b) Pore reduction for metastable He and silicon nitride membranes of different thicknesses (colour lines) and pore radii: 25 nm (a), 10 nm (b) and 5 nm (c).

Figure 2: Results of the pore reduction calculations

- Estimated via Newtons equation of motion $m\ddot{r} = -\nabla U(r)$ with the initial condition $\varrho(0) = R - \Delta R$ and finale point $\varrho(\tau) = R$

Results of the phase and impact on interference pattern

- Phase shift (integration along the particle's trajectories)

$$\varphi(\varrho) = -\frac{1}{\hbar}\int U\left[r(t)\right]\mathrm{d}t$$

- In eikonal approximation [straight lines $z = v_z t = ht/(m\lambda_{\mathrm{dB}})$] [3]

$$\varphi(\varrho) = -\frac{m\lambda_{\mathrm{dB}}}{2\pi\hbar^2}\frac{3C_3 d}{4R^3\left(\lambda-1\right)^3\left(\lambda+1\right)^2} \times\left[\left(\lambda-1\right)^2 K\left(\frac{2\sqrt{\lambda}}{\lambda+1}\right) - \left(\lambda^2+7\right)E\left(\frac{2\sqrt{\lambda}}{\lambda+1}\right)\right],$$

with $\lambda = \varrho/R$ and the elliptic integrals $K(x)$and $E(x)$

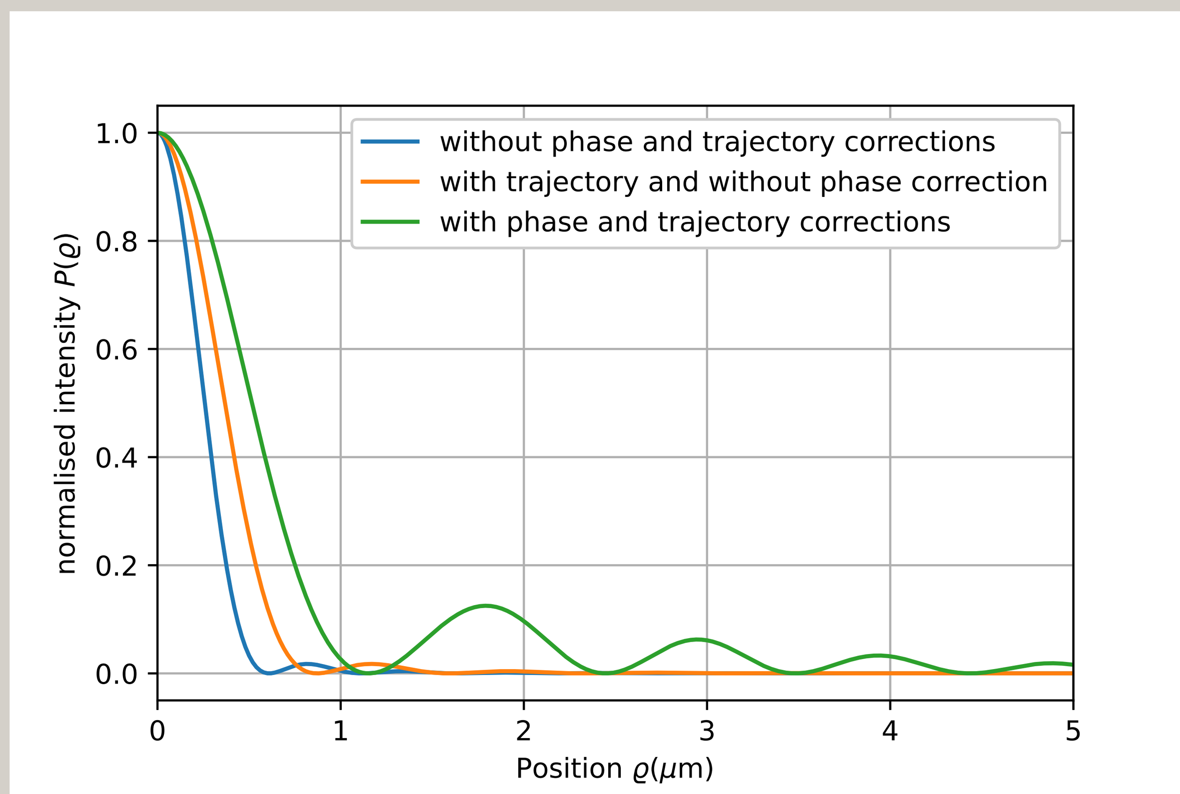


Figure 3: Impact of pore reduction and phase shift onto the diffraction at a hole.

- Lower transmittance rate
- Stronger population of higher diffraction orders
- Stronger diffraction of higher diffraction orders

References

[1] Torstein Nesse, Ingve Simonsen, and Bodil Holst. Nanometer-resolution mask lithography with matter waves: Near-field binary holography. *Phys. Rev. Applied*, 11:024009, 2019.

[2] S. Y. Buhmann. *Dispersion Forces I: Macroscopic quantum electrodynamics and ground-state Casimir, Casimir–Polder and van der Waals forces.* Springer, Heidelberg, 2012.

[3] JF and Bodil Holst. An atom passing through a hole in a dielectric membrane: Impact of dispersion forces on mask-based matter-wave lithography. *submitted to J. Phys. B*, 2021.

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