# Matter-wave interferometery of a free-falling nanoparticle

#### James Bateman (M. Rashid, D. Hempston, J. Vovrosh, & H. Ulbricht)

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Frascati, 28-30 April 2014

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Overview •	Schematic, theory, & decoherence	Experimental progress 0000	
Overview			Southampton
Interference	of 10 <sup>6</sup> amu particles wi	th optically resolval	ole fringes

- 1 Schematic, theory, & decoherence
- 2 Experimental progress
- 3 Summary & outlook

Near-field interferometry of a free-falling nanoparticle from a point-like source, Bateman, Nimmrichter, Hornberger, & Ulbricht, arXiv:1312.0500

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"Macroscopicity of Mechanical Quantum Superposition States" Nimmrichter, Hornberger, PRL **110**, 160403 (2013)

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Overview O	Schematic, theory, & decoherence	Experimental progress	

(a) Nanoparticle in dipole trap  $10^6$  amu (10 nm sphere) localised to < 30 nm



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Matter-wave interferometery of a free-falling nanoparticle

Overview O	Schematic, theory, & decoherence	Experimental progress 0000	

- (a) Nanoparticle in dipole trap  $10^6$  amu (10 nm sphere) localised to < 30 nm
- (b) Phase grating 177 nm period ns, mJ, trippled Nd:YAG



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- (a) Nanoparticle in dipole trap  $10^6$  amu (10 nm sphere) localised to < 30 nm
- (b) Phase grating 177 nm period ns, mJ, trippled Nd:YAG
- (c) Glass slide Fixed fall time  $\approx$  300 ms Near-field (Fresnel) Scaled Talbot effect



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- (d) Optical detection High NA with fitting to PSF



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# Talbot Effect

- Near-field (Fresnel)
- Periodic reconstruction
- Far-field
  - $\rightarrow$  diffraction orders



Colloquium: Quantum interference of clusters and molecules Hornberger, Gerlich, Haslinger, Nimmrichter, and Arndt, DOI: 10.1103/RevModPhys.84.157

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Overview	

Summary & outlook

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# Talbot Effect

- Near-field (Fresnel)
- Periodic reconstruction
- Far-field
  - $\rightarrow$  diffraction orders
- Plane-wave
  - $\rightarrow$ same period as grating
- Point-source
  - ightarrow geometrical scaling



Colloquium: Quantum interference of clusters and molecules Hornberger, Gerlich, Haslinger, Nimmrichter, and Arndt, DOI: 10.1103/RevModPhys.84.157

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Overview	Schematic, theory, & decoherence	Experimental progress	Summary & outlook
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Initial thermal state of 200kHz harmonic trap

$$w_0(x,p) = \frac{1}{2\pi\sigma_x\sigma_p} \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{p^2}{2\sigma_p^2}\right)$$

- $\sigma_x \sim 10$ nm
- $\sigma_p/m \sim 10 {
  m mm/s}$
- Wigner  $\rightleftharpoons$  Charateristic

$$w_0(x,p) \rightleftharpoons \chi_0(s,q) = \exp\left(-\frac{\sigma_x^2 q^2 + \sigma_p^2 s^2}{2\hbar^2}\right)$$

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- $\sigma_x \sim 10 {\rm nm}$
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- Fall for  $t_1 = 160$ ms
- Shearing → *locally* well-defined momentum

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$$\chi_1(s,q) \approx \frac{\sqrt{2\pi\hbar}}{\sigma_p} \exp\left(-\frac{\sigma_x^2 q^2}{2\hbar^2}\right) \delta\left(s - \frac{qt_1}{m}\right)$$

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- Grating interaction

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$$\chi_1(s,q) \rightarrow \sum_n B_n(s/d) \chi_1(s,q+nh/d)$$

where  $B_n(\xi) = J_n(\phi_0 \sin \pi \xi)$  or  $J_n(\phi_0 \pi \xi)$ 

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Initial thermal state of 200kHz harmonic trap

- $\sigma_x \sim 10 {\rm nm}$
- $\sigma_p/m \sim 10 {
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- Wigner  $\rightleftharpoons$  Charateristic
- Fall for  $t_1 = 160$ ms
- Shearing → locally well-defined momentum
- Grating interaction
- Fall for  $t_2 = 120$ ms
- Spatial distribution  $\int w(x,p)dp = \mathcal{F}[\chi(0,q)](x)$

$$w_0(x,p) = \frac{1}{2\pi\sigma_x\sigma_p} \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{p^2}{2\sigma_p^2}\right)$$

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Schematic, theory, & decoherence  $\circ\circ\circ\circ\circ\circ\circ$ 

Experimental progress

Summary & outlook

#### Phase-space description: Spatial distributions



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#### Phase-space description: Spatial distributions



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#### Phase-space description: Spatial distributions



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#### Decoherence via Blackbody radiation

- $\blacksquare$  Typical blackbody wavelength:  $\gtrsim 10 \mu m$
- Glass (dashed) absorbs; silicon (solid) is highly transparent

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#### Decoherence via Blackbody radiation

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## Decoherence via Blackbody radiation



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- Choose trap wavelength 1550nm:
- $\rightarrow$  fiber laser technology
- $\rightarrow$  some issues: free space/high power/imaging

Summary & outlook

# Dipole Trapping at 1550nm

Refracting optics: aspherics/objectives

- Designed for visible ( $\lambda \lesssim 1 \ \mu$ m)
- Significant aberrations at 1.5μm

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Schematic, theory, & decoherence

Experimental progress •000 Summary & outlook

# Dipole Trapping at 1550nm

Refracting optics: aspherics/objectives

- Designed for visible ( $\lambda \lesssim 1 \ \mu$ m)
- Significant aberrations at 1.5μm

Reflecting optics: parabolic mirror

- Inherently achromatic
- Single-point diamond turning
- 15nm roughness (λ/100)
- $\mathbf{I} < 1 \mu m$  form accuracy
- NA = 0.995
- Working distance =  $900 \mu m$





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Positio	n detection		

- Sense position and apply feedback [1,2]
- $\blacksquare$  Centre-of-mass cooling to  $\sim 10 \text{mK}$  for  $\sim 100 \text{nm}$  particle [2]

Li, Kheifets, Raizen, Nat. Phys. **7** 527 (2011)
 Gieseler, Deutsch, Quidant, Novotny, PRL **109** 103602 (2012)

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Overview	Schematic, theory, & decoherence	Experimental progress	
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## Position detection

- Sense position and apply feedback [1,2]
- $\blacksquare$  Centre-of-mass cooling to  $\sim 10 \textrm{mK}$  for  $\sim 100 \textrm{nm}$  particle [2]

Transmission imaging

- $\bullet \ \partial_{\mathbf{x}}\phi\sim 1/f$
- $\blacksquare \ \partial_z \phi \sim 1/z_R$
- $E_{\text{Ref}} \gg E_{\text{Sca}}$



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Position	detection			
<ul><li>Sense</li><li>Centre</li></ul>	e position and ap re-of-mass coolir	oply feedback $_{ m ng}$ to $\sim 10 { m mk}$	[1,2] $\zeta$ for $\sim$ 100nm par	ticle [2]
Transmiss $\partial_x \phi \phi$ $\partial_z \phi \phi$ $E_{\text{Ref}}$	ion imaging ~ 1/f ~ 1/z <sub>R</sub> ≫ E <sub>Sca</sub>	Input light		Dz Dz
Reflection $\partial_x \phi \phi$ $\partial_z \phi =$ $E_{\text{Ref}} \phi$	imaging $\sim 1/f$ $= 1/\frac{1}{2}\lambda$ $\sim E_{Sca}$	Input light Refle	cted light	
<ul><li>[1] Li, Kheifets, Ra</li><li>[2] Gieseler, Deutsc</li></ul>	izen, Nat. Phys. <b>7</b> 527 (201 h, Quidant, Novotny, PRL	11) 109 103602 (2012)	< □ > < @ >	<=> <=> <=> <=> < = <=> < =

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## Position detection $\rightarrow$ feedback cooling

Done:

- Trap signal
- Intensity modulation  $\checkmark$



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[2] Gieseler, Deutsch, Quidant, Novotny, PRL 109 103602 (2012)

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## Position detection $\rightarrow$ feedback cooling

#### Done:

- Trap signal ✓
- Intensity modulation  $\checkmark$

To do:

- Close loop with FPGA
- Repeat for transverse
- Pump down & cool



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## Position detection $\rightarrow$ feedback cooling

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### Particle source

Requirements:

- Pure Silicon
- Produce in UHV

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Overview	

# Particle source

#### Requirements:

- Pure Silicon
- Produce in UHV
- Approach (see also [1]):
  - Nd:YAG ablation (ns; mJ; 532nm)
  - Sub-200nm particles (limited by SEM resolution)

To do:

- Size selection
- Capture in UHV...





Matter-wave interferometery of a free-falling nanoparticle



Summary & outlook

# Summary & outlook

So far

- Theory including decoherence
- Use silicon, not glass
- 1550nm  $\implies$  reflective optics
- Position sensing via back-scattering
- Crude particle source

To do

- Feedback cooling ( $\checkmark$ )
- Capture Si in UHV
- ... then grating and imaging

