Non-Interferometric Phase Imaging of Atoms

P.J. Fox, L.D. Turner, T.R. Mackin, A. Barty, D. Paganin,
K. Nugent, M.R. Walkiewicz and R.E. Scholten

School of Physics, University of Melbourne, Victoria, Australia, 3010
Tel +61-3-83445457 Fax +61-3-93474783
E-mail: r.scholten@physics.unimelb.edu.au
Website: http://www.ph.unimelb.edu.au

Phase measurement of atom waves is extremely useful for applications in gravity wave detection, gravitational gradient measurement, investigations of atomic interactions and tests of fundamental quantum mechanics. Phase is normally measured with interferometry, but while this is quite easy for optical waves, it is more difficult to achieve with atoms [1]. It is possible, however, to measure phase shifts using non-interferometric techniques [2, 3, 4].

The phase of a wavefront can be defined in terms of the direction of propagation of energy. In the case of optical waves, the phase of the wavefront ϕ is related to the gradient of the intensity along the optical axis $\partial I/\partial z$ through the *Transport of Intensity Equation* (TIE) [2]:

$$-k\frac{\partial I(\vec{r}_\perp)}{\partial z} = \nabla_\perp \cdot (I(\vec{r}_\perp)\nabla_\perp \phi(\vec{r}_\perp)) \tag{1}$$

where k is the wavenumber, and $\vec{r}_\perp$, $\nabla_\perp$ are the position vector and two-dimensional gradient operator acting in the plane perpendicular to the optical axis. In the absence of any intensity zeroes, this equation is invertible and produces a unique solution for the phase [3].

This has an analogue for quantum mechanical waves, where instead of intensity, the probability amplitude is used [5]. If there exists a wavefunction with amplitude $\sqrt{\rho}$ and phase S such that $\psi = \sqrt{\rho}\ \exp(\imath S/\hbar)$, then the TIE can be written as:

$$-\hbar k\frac{\partial \rho(\vec{r}_\perp)}{\partial z} = \nabla_\perp \cdot (\rho(\vec{r}_\perp)\nabla_\perp S(\vec{r}_\perp)). \tag{2}$$

Using fluorescence detection with a CCD camera, the intensity profile, and hence probability intensity of an atomic beam, can be determined at two different planes. The difference between these two profiles can be used to calculate the intensity gradient and the phase, as shown in Fig. 1. We present measurements of the change in the phase of an atomic beam modulated by a far off-resonant laser beam. The atoms moving through the laser field experience a force, and hence phase shift due to dipole interactions. The recovered phase change is then related to the intensity profile of the laser.

The resolution of this technique is determined by the enclosed area between the two detection planes. This is similar to the resolutions of a split arm interferometer, which is limited by the area enclosed by the arms of the device. This allows very sensitive measurements to be made by increasing the seperation between the detection planes. Future investigations with this

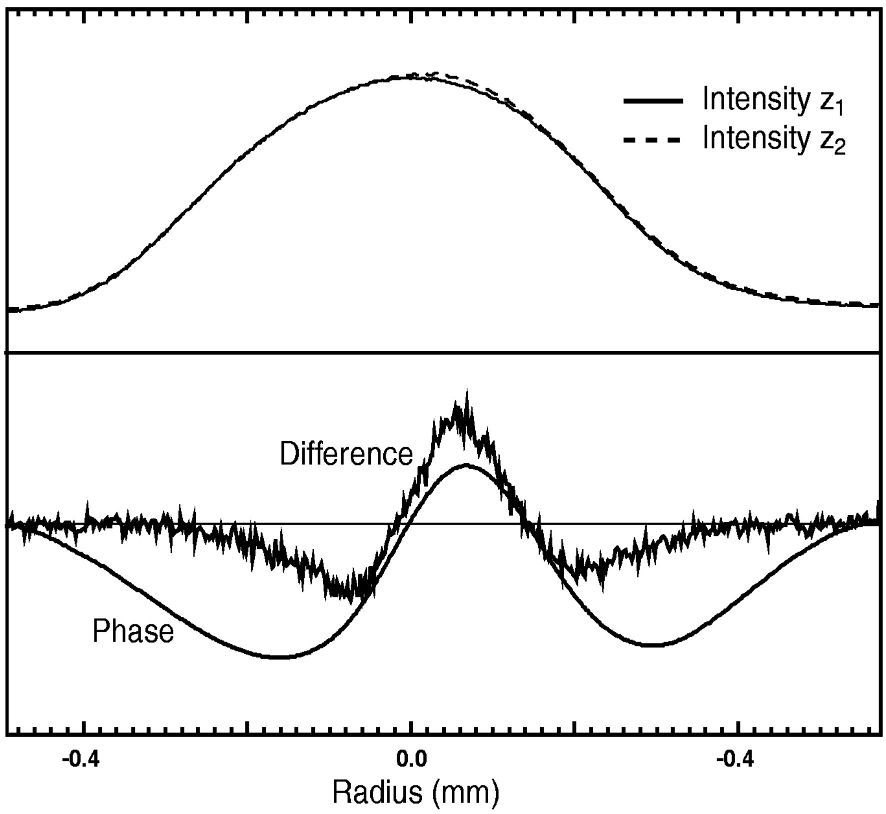

Figure 1: Demonstration of atomic beam phase measurement for atoms with velocity 200 m/s, after travelling through a gaussian laser beam (I = 400mW, ω_0 = 0.17mm) red detuned 40GHz. Top trace shows intensity profile at two planes z_1 and z_2, seperated by 6cm, along the atomic beam. Bottom trace shows difference between the two intensities, and the calculated phase profile.

technique will look at the application to measuring rotations, atom-atom interactions, gravitational gradients, and also study topological phase effects, such as the Aharonov-Bohm and Aharonov-Casher effects.

[1] PR Berman (ed), *Atom Interferometry*, Academic Press, San Diego (1997)
[2] KA Nugent, TE Gureyev, DF Cookson, D Paganin and Z Barnea, *Phys Rev Lett* **77**, 2961 (1996)
[3] D Paganin and KA Nugent, *Phys Rev Lett* **80**, 2586 (1998)
[4] A Barty, KA Nugent, D Paganin and A Roberts, *Opt Lett* **23**, 817 (1998)
[5] KA Nugent and D Paganin, *Phys Rev A*, Accepted for publication February 2000