Phase shifts due to atom-surface interaction

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Several atom optics experiments have studied how atom-surface interactions affect the propagation of atom waves. However, none of these experiments directly measure the *phase shift* of atom waves due to interaction with a surface. For example, experiments with atoms transmitted through a cavity [1, 2], atoms diffracted from a material grating [3–6], atoms reflecting from surfaces [7–10], atoms reflecting from evanescent waves near surfaces [11–13], and atoms trapped near surfaces [? ?] all monitor how surfaces affect the atom probability density, $|\psi|^2$, in various trajectories. Even with interferometers that use nanostructures [14–18], the predicted phase shifts due to interaction with a surface are not directly observable because there is no absolute reference phase for the interference fringes.

Here we compare the interference patterns of four separate atom interferometers and detect a phase difference that we attribute to atom-surface interactions. The interferometers shown in Fig. 1 are obtained by far-field diffraction of a single atom beam by nanofabricated gratings. A single one of these diamond-shaped interferometers has been used for numerous experiments [19], but this is the first use of multiple atom interferometers formed by the same nanostructures.

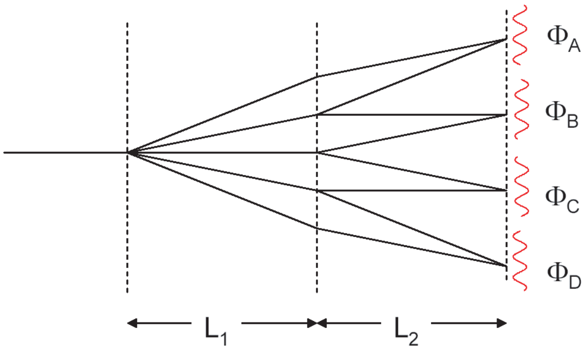

FIG. 1: Diagram of four interferometers. The atom beam (solid line) gets diffracted at each grating (dashed lines). Interference fringes from the four interferometers have observed phases with values Φ_A, Φ_B, Φ_C, Φ_D.

We show theoretically then experimentally that the phase outputs of the interferometers (Φ_A, Φ_B, Φ_C and Φ_D) each depend in a unique way on the strength of atom-surface interactions.

Because the free standing gratings used in our experiment have approximately 55-nm wide slots, atoms that are transmitted through the slots must pass closer than 28 nm from a surface. So we consider the non-retarded Casimir-Polder (also known as van der Waals) interaction potential [20, 21] given by

$$V(r) = \frac{C_3}{r^3} \tag{1}$$

for atoms a distance r from the walls of each slot. This is the same starting point as recent work on diffraction from similar nanostructures by [3–6]. We now show how the observable phase of each interferometer, denoted by $\Phi_{A(BCD)}$, depends on the phase shifts ϕ_n in each n^{th} far-field diffraction order.

It was shown in [3–6] how the complex amplitudes in each diffraction order depend on C_3. Here we explicitly describe the component of atom-wave amplitude in the n^{th} far-field diffraction order in terms of a real amplitude $|a_n|$ and a phase ϕ_n due to diffraction:

$$\psi_n = |a_n| e^{i\phi_n} e^{i(\mathbf{k_n}\cdot\mathbf{r}-\omega t)}. \tag{2}$$

The real amplitudes are related to intensity of each diffraction order. Several experiments [3–6] have measured $|a_n|$ but this is the first experimental evidence for ϕ_n.

Using the methods described in [5] we have plotted the values of a_n and ϕ_n as a function of C_3 in Fig. 2. The value of C_3 for sodium atoms and silicon nitride grating bars was measured to be 2.7±0.8 meVnm^3 and theoretically predicted to be 3.5 meVnm^3 [6].

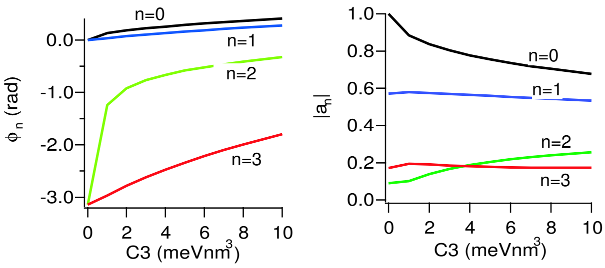

FIG. 2: The amplitude (left) and phase (right) in each diffraction order depends on the van der Waals interaction strength given by C_3. Predictions are shown for a 100-nm period grating with 55-nm wide windows.

The predictions in Fig. 2 are also sensitive to the assumed values of grating period (d_g = 100nm), grating window size (w = 55nm), grating bar wedge angle ($\alpha = 3.5^o$), grating thickness (t = 130nm) and atom beam velocity ($v = 1000$m/s). The grating geometry is described in [3–6, 22], and the grating fabrication is described in [23, 24].

The π phase difference between ϕ_2 and ϕ_0 when $C_3 = 0$ is understood from physical optics. A purely absorbing or transmitting grating with no phase profile (i.e. a *ronchi rule* with a real transmission function) makes diffraction orders with relative

$$\psi_n = \frac{\sin(nk_g w)}{(k_g w)} \tag{3}$$

where $k_g \equiv 2\pi/d_g$ is the grating wave number [25]. The sign of ψ_2 is opposite ψ_0 if the open fraction w/d_g is less than 1/2. For non-zero C_3, however, the transmission function becomes complex as described in [3, 5] and ϕ_2 can have a continuous range of values as plotted in Fig. 2

The skew interferometer (labelled by Φ_A in Fig. 1) has two paths that are formed by diffraction into the $+2, -1$ orders and $+1, +1$ orders respectively. The interference pattern in the plane of the third grating has intensity

$$I_A(x_3) = \langle I_A \rangle \left[1 + C_A \cos(\Phi_A)\right], \tag{4}$$

where k_g is the grating wavenumber ($k_g = 2\pi/d_g$) and Φ_A is the observable phase that depends on $\phi_2 - \phi_1$. The third grating is simply used as a mask to transmit or block the maxima of these fringes.

The four separate interferometers shown in Fig. 1 have observable fringe phases predicted to be

$$\begin{aligned} \Phi_A &= \phi_g + 3\phi_{\Delta L} + \phi_2 - \phi_1 & (5)\\ \Phi_B &= \phi_g + \phi_{\Delta L} + \phi_1 - \phi_0 & (6)\\ \Phi_C &= \phi_g - \phi_{\Delta L} + \phi_0 - \phi_1 & (7)\\ \Phi_D &= \phi_g - 3\phi_{\Delta L} + \phi_1 - \phi_2 & (8) \end{aligned}$$

where

$$\phi_g = k_g(x_1 - 2x_2 + x_3) \tag{9}$$

and

$$\phi_{\Delta L} = (L2 - L1)\lambda_{dB}\pi/d_g^2 \tag{10}$$

are phases due to geometry that are described in [19, 26, 27]. ϕ_g is known as the *grating phase* and is exactly common to all interferometers. $\phi_{\Delta L}$ is due to any mismatch in the lengths L_1 and L_2 shown in Fig. 1.

All four interferometers are formed by the recombination of paths with ±1 order diffraction at the second grating. Due to symmetry the phase shifts into these orders are expected to be equal (i.e. $\phi_1 = \phi_{-1}$) except in the case of non-normal beam incidence or asymmetric grating bars. Hence, the only difference in diffraction phase amongst all four interferometers is expected to be from diffraction by the first grating. All four values of Φ are shown in Fig. 3 for a few different values of C_3.

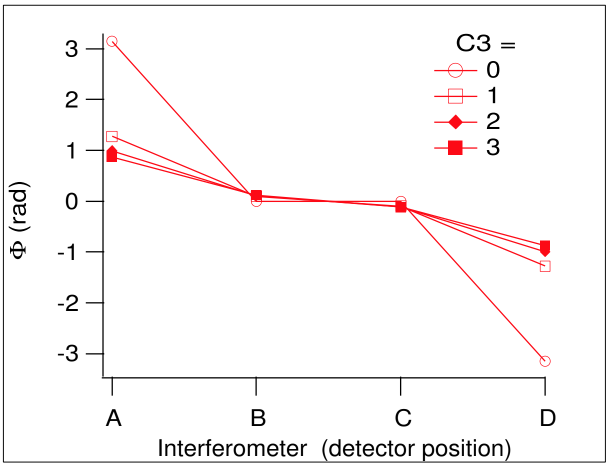

FIG. 3: Predicted interference fringe phases Φ_A, Φ_B,Φ_C,Φ_D, for the four interferometers shown in Figure 1. Differences in phase are entirely due to van der Waals interactions with the first grating structure.

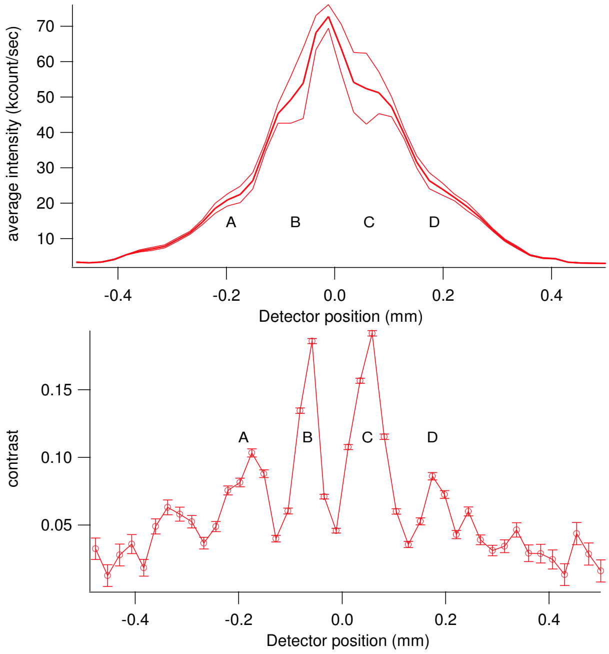

FIG. 4: (Top) Measured atom beam intensity $\langle I \rangle$. (Bottom) Measured interference fringe contrast C. Fringes from the four interferometers (A,B,C,D) are distinguishable by the 50-μm diameter hot wire detector.

To demonstrate that the four interferometers make distinguishable interference patterns, we show the intensity $\langle I \rangle$ and the contrast C as a function of detector position in Fig. 4.

The phase of the interference fringes in each interferometer Φ_A, Φ_B, Φ_C, and Φ_D is shown in Fig. XXX.

Control experiments for this include

- symmetry
- moving 3g
- moving 2g
- moving 1g
- changing L
- changing velocity
- changing the coating on 1g

By adjusting ΔL we can arrange that $\Phi_B = \Phi_C$. Then

$$\Phi_A - \Phi_B = \phi_2 - \phi_1 - 3(\phi_1 - \phi_0) \tag{11}$$

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$$\Phi_A - \Phi_B = \phi_2 - 4\phi_1 + \phi_0 \tag{12}$$

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[1] A. Anderson, H. E. A. Haroche, S. and, J. W., and D. Meschede, Phys. Rev. A **37**, 3594 (1988).

[2] C. I. Sukenik, M. G. Boshier, D. Cho, V. Sandoghdar, and E. A. Hinds, Phys. Rev. Lett. **70**, 560 (1993).

[3] R. E. Grisenti, W. Schollkopf, J. P. Toennies, G. C. Hegerfeldt, and T. Kohler, Phys. Rev. Lett. **83**, 1755 (1999).

[4] R. Bruhl, P. Fouquet, R. E. Grisenti, J. P. Toennies, G. C. Hegerfeldt, T. Kohler, M. Stoll, and D. Walter, Europhys. Lett. **59**, 357 (2002).

[5] A. Cronin and J. Perreault, Phys. Rev. A **70**, 043607 (2004).

[6] J. Perreault, A. Cronin, and T. Savas, arXiv:physics/0312123 (2003).

[7] A. Anderson, S. Haroche, E. A. Hinds, W. Jhe, D. Meschede, and L. Moi, Phys. Rev. A **34**, 3513 (1986).

[8] J. J. Berkhout, O. J. Luiten, I. D. Setija, T. W. Hijmans, T. Mizusaki, and J. T. M. Walraven, Physical Review Letters **63**, 1689 (1989).

[9] F. Shimizu, Physical Review Letters **86**, 987 (2001), times Cited: 25.

[10] F. Shimizu and J. Fujita, Journal of the Physical Society of Japan **71**, 5 (2002), times Cited: 4.

[11] J. V. Hajnal, K. G. H. Baldwin, P. T. H. Fisk, H. A. Bachor, and G. I. Opat, Optics-Communications. **73**, 331 (1989).

[12] R. Kaiser, G. Labeyrie, A. Landragin, N. Vansteenkiste, C. Westbrook, J. Von-Zanthier, and A. Aspect, Laser-Physics **6**, 409 (1996).

[13] N. Westbrook, C. I. Westbrook, A. Landragin, G. Labeyrie, L. Cognet, V. Savalli, G. Horvath, A. Aspect, C. Hendel, K. Moelmer, et al., Physica-Scripta-Volume-T **T78:**, 7 (1998).

[14] D. W. Keith, C. R. Ekstrom, Q. A. Turchette, and D. Pritchard, Phys. Rev. Lett. **66**, 2693 (1991).

[15] O. Carnal and J. Mlynek, Phys. Rev. Lett. **66**, 2689 (1991).

[16] O. Nairz, M. Arndt, and A. Zeilinger, American Journal of Physics **71**, 1084 (2003).

[17] B. Brezger, L. Hackermuller, S. Uttenthaler, J. Petschinka, M. Arndt, and A. Zeilinger, Phys. Rev. Lett. **88**, 100404 (2002).

[18] T. Kohno, F. Shimizu, J. Fujita, and K. Shimizu, Journal of the Physical Society of Japan **72**, 461 (2003), times Cited: 0.

[19] P. R. Berman, ed., *Atom Interferometry* (Academic Press, 1997).

[20] H. B. G. Casimir and D. Polder, Nature **158**, 787 (1946).

[21] H. B. G. Casimir and D. Polder, Physical Review **73**, 360 (1948).

[22] R. E. Grisenti, W. Schollkopf, J. P. Toennies, J. R. Manson, T. A. Savas, and H. I. Smith, Phys. Rev. A **61**, 033608 (2000).

[23] T. A. Savas, S. N. Shah, M. L. Schattenburg, J. M. Carter, and H. I. Smith, Journal of Vacuum Science and Technology B **13**, 2732 (1995), tN816 J VAC SCI TECHNOL B.

[24] T. A. Savas, M. L. Schattenburg, J. M. Carter, and H. I. Smith, J. Vac. Sci. Tech. B **14**, 4167 (1996).

[25] E. Hecht, *Optics* (Addison Wesley Longman, 1998).

[26] C. Champenois, M. Buchner, and J. Vigue, European Physical Journal D **5**, 363 (1999).

[27] R. Delhuille, A. Miffre, B. V. de Lesegno, M. Buchner, C. Rizzo, G. Trenec, and J. Vigue, Acta Physica Polonica B **33**, 2157 (2002).