Phase shifts due to atom-surface interaction

Alexander D. Cronin*
Department of Physics, University of Arizona, Tucson, AZ 85721
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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.

We show theoretically then experimentally that the phase outputs of the interferometers ($\Phi_A$, $\Phi_B$, $\Phi_C$ and $\Phi_D$) 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

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

(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 $\phi_n$ 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 $\phi_n$ due to diffraction:

$$\psi_n = |a_n| e^{i\phi_n} e^{ik_n r - \omega t}.$$  

(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 $\phi_n$.

Using the methods described in [5] we have plotted the values of $a_n$ and $\phi_n$ 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].

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

The \(\pi\) phase difference between \(\phi_2\) and \(\phi_0\) 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

\[
\psi_n = \frac{\sin(nk_g w)}{(k_g w)}
\]

where \(k_g \equiv 2\pi/d_g\) is the grating wave number [25]. The sign of \(\psi_2\) is opposite \(\psi_0\) 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 \(\phi_2\) can have a continuous range of values as plotted in Fig. 2.

The skew interferometer (labelled by \(\Phi_A\) 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

\[
I_A(x_3) = \langle I_A \rangle \left[ 1 + C_A \cos(\Phi_A) \right],
\]

where \(k_g\) is the grating wavenumber \((k_g = 2\pi/d_g)\) and \(\Phi_A\) 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

\[
\Phi_A = \phi_g + 3\phi_{\Delta L} + \phi_2 - \phi_1
\]

\[
\Phi_B = \phi_g + \phi_{\Delta L} + \phi_1 - \phi_0
\]

\[
\Phi_C = \phi_g - \phi_{\Delta L} + \phi_0 - \phi_1
\]

\[
\Phi_D = \phi_g - 3\phi_{\Delta L} + \phi_1 - \phi_2
\]

where

\[
\phi_g = k_g(x_1 - 2x_2 + x_3)
\]

and

\[
\phi_{\Delta L} = (L_2 - L_1)\lambda dB\pi/d_g^2
\]

are phases due to geometry that are described in [19, 26, 27]. \(\phi_g\) 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 \(\pm 1\) 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 \(\Phi\) are shown in Fig. 3 for a few different values of \(C_3\).

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 \(\Phi_A, \Phi_B, \Phi_C\), and \(\Phi_D\) 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 $\Delta L$ we can arrange that $\Phi_B = \Phi_C$. Then

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

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

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* Electronic address: cronin@physics.arizona.edu


