

# Observation of atom wave phase shifts induced by van der Waals atom-surface interactions

John D. Perreault and Alexander D. Cronin  
*University of Arizona, Tucson, Arizona 85721*  
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The development of nanotechnology and atom optics relies on understanding how atoms behave and interact with their environment. Isolated atoms can exhibit wave-like (coherent) behaviour with a corresponding de Broglie wavelength and phase which can be affected by nearby surfaces. Here an atom interferometer is used to measure the phase shift of Na atom waves induced by the walls of a 50 nm wide cavity. To our knowledge this is the first direct measurement of the de Broglie wave phase shift caused by atom-surface interactions. The magnitude of the phase shift is in fair agreement with that predicted by quantum electrodynamics for a non-retarded van der Waals interaction. This experiment also demonstrates that atom-waves can retain their coherence even when atom-surface distances are as small as 10 nm.

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The generally accepted picture of the electromagnetic vacuum suggests that there is no such thing as empty space. Quantum electrodynamics tells us that even in the absence of any free charges or radiation the space between atoms is actually permeated by fluctuating electromagnetic fields. An important physical consequence of this view is that the fluctuating fields can polarize atoms resulting in a long range attractive force between electrically neutral matter: the van der Waals (vdW) interaction [1]. This microscopic force is believed to be responsible for the cohesion of nonpolar liquids, the latent heat of many materials, and deviations from the ideal gas law. The vdW interaction can also affect individual atoms or groups of atoms near a solid surface. For example, nearby surfaces can distort the radial symmetry of carbon nanotubes [2] and deflect the probes of atomic force microscopes [3]. Atom-surface interactions can also be a source of quantum decoherence or uncontrolled phase shifts, which are an important considerations when building practical atom interferometers on a chip [4]. For the case of an atom near a surface the vdW potential takes the form  $V(r) = -C_3r^{-3}$ , where  $C_3$  describes the strength of the interaction and  $r$  is the atom-surface distance [1].

Previous experiments have shown how atom-surface interactions affect the *intensity* of atom waves transmitted through cavities [5–7], diffracted from material gratings [8–12], and reflected from surfaces [13–15]. However, as we shall see, none of these experiments provide a complete characterization of how atom-surface interactions alter the *phase* of atom waves. In order to monitor the phase of an atom wave one must have access to the wave function itself ( $\psi$ ), not just the probability density for atoms ( $|\psi|^2$ ). In this Letter an atom interferometer is used to directly observe how atom surface interactions affect the phase of atom waves. This observation is significant because it offers a new measurement technique

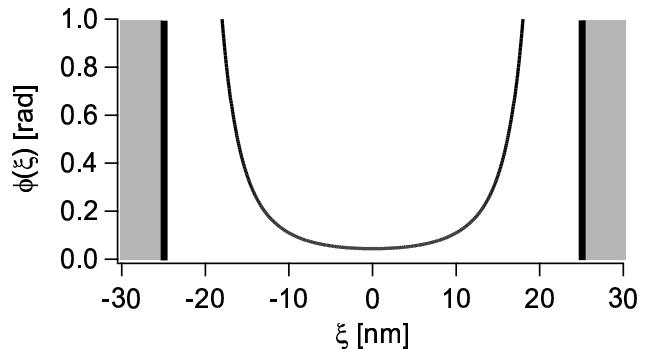


FIG. 1: Accumulated phase  $\phi(\xi)$  of an atom wave as a function of position due to a vdW interaction with  $C_3 = 3 \text{ meV nm}^3$ . The atom wave has propagated through a 150 nm long cavity at a velocity of 2 km/s. The grey rectangles indicate the location of the cavity walls which are 50 nm apart. Notice how there is a non-zero constant phase offset  $\phi_o \sim 0.05 \text{ rad}$ .

for the vdW potential and is of practical interest when designing atom optics components on a chip [16, 17].

When an atom wave propagates through a cavity it accumulates a spatially varying phase due to its interaction with the cavity walls

$$\phi(\xi) \equiv \phi_o + \delta\phi(\xi) = -\frac{lV(\xi)}{\hbar v}, \quad (1)$$

where  $l$  is the interaction length,  $V(\xi)$  is the atom-surface potential within the cavity,  $\hbar$  is Planck's constant, and  $v$  is the particle velocity [11]. Equation 1 also separates the induced phase  $\phi(\xi)$  into constant  $\phi_o$  and spatially varying  $\delta\phi(\xi)$  parts. A plot of the phase  $\phi(\xi)$  from Eqn. 1 is shown in Fig. 1 for the cavity geometry and vdW interaction strength in our experiment. If these cavities have a width  $w$  and are oriented in an array with spacing  $d$ , then the atom wave far away will have spatially separated

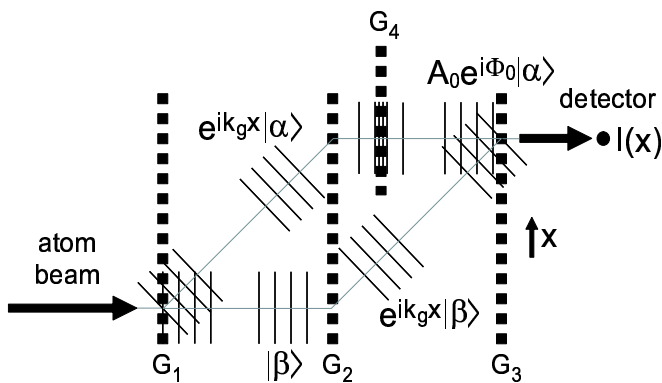


FIG. 2: Experimental setup for vdW induced phase measurement. A Mach-Zehnder atom interferometer with paths  $\alpha$  and  $\beta$  is formed using the zeroth and first order diffracted beams of gratings  $G_1$  and  $G_2$  which have a period of 100 nm. The atom wave interference pattern is read out using grating  $G_3$  as an amplitude mask. The phase fronts (groups of parallel lines) passing through grating  $G_4$  are compressed due to the attractive vdW interaction, resulting in a phase shift  $\Phi_0$  of beam  $|\alpha\rangle$  relative to  $|\beta\rangle$ . This causes the interference pattern  $I(x)$  to shift in space at the plane defined by  $G_3$ .

components (diffraction orders) with amplitudes

$$\psi_n = A_n e^{i\Phi_n} = e^{i\phi_o} \int_{-w/2}^{w/2} e^{i\delta\phi(\xi)} e^{i2\pi\xi \frac{z}{d}} d\xi, \quad (2)$$

where  $A_n$  and  $\Phi_n$  are real numbers, and  $n$  is the diffraction order number [11]. Experiments which measure the intensity of atom waves (e.g. atom wave diffraction) are only sensitive to  $|\psi_n|^2 = |A_n|^2$  which is in part influenced by  $\delta\phi(\xi)$ . However, it is clear from Eqn. 2 that  $|\psi_n|^2$  reveals no information about  $\phi_o$  or  $\Phi_n$ . We have determined  $A_0$  and  $\Phi_0$  by placing this array of cavities (grating) in one arm of an atom interferometer. This new technique is sensitive to the *entire* phase shift  $\phi(\xi)$  induced by an atom-surface interaction, including the constant offset  $\phi_o$ .

The experimental setup for using an atom interferometer to measure the phase shift  $\Phi_0$  induced by atom-surface interactions is shown in Fig. 2. A beam of Na atoms travelling at roughly 2 km/s is generated from an oven and a position state of the atom wave is selected by two 10  $\mu\text{m}$  collimation slits spaced 1 m apart. A Mach-Zehnder type interferometer is formed using the zeroth and first order diffracted beams from three 100 nm period silicon nitride gratings [18]. The grating  $G_1$  creates a superposition of position states  $|\alpha\rangle$  and  $|\beta\rangle$  which propagate along separated paths  $\alpha$  and  $\beta$  respectively. The states are then recombined using grating  $G_2$  and form a spatial interference pattern at the plane of  $G_3$ . The third grating  $G_3$  is used as an amplitude mask to determine the phase and contrast of the interference pattern. A co-propagating laser interferometer (not shown in Fig.

2) was used to compensate for mechanical vibrations of  $G_1, G_2, G_3$ .

When grating  $G_4$  is inserted into the interferometer path  $\alpha$ , the interference pattern  $I(x)$  shifts in space along the positive x-direction. This can be understood by recalling de Broglie's relation  $\lambda_{dB} = h/p$  [19, 20]. The atoms are sped up by the attractive vdW interaction between the Na atoms and the walls of grating  $G_4$ . This causes  $\lambda_{dB}$  to be smaller in the region of  $G_4$ , compressing the atom wave phase fronts and retarding the phase of beam  $|\alpha\rangle$  as it propagates along path  $\alpha$ . One could also say that  $G_4$  effectively increases the optical path length of path  $\alpha$ . At  $G_3$  the beams  $|\alpha\rangle$  and  $|\beta\rangle$  then have a relative phase between them leading to the state

$$|\chi\rangle = A_0 e^{i\Phi_0} |\alpha\rangle + e^{ik_g x} |\beta\rangle, \quad (3)$$

where  $k_g = 2\pi/d$ . The diffraction amplitude  $A_0$  reflects the fact that beam  $|\alpha\rangle$  is also attenuated by  $G_4$ . The state  $|\chi\rangle$  in Eqn. 3 then leads to an interference pattern that is shifted in space by an amount that depends on  $\Phi_0$

$$I(x) = \langle \chi | \chi \rangle \propto 1 + C \cos(k_g x - \Phi_0), \quad (4)$$

where  $C$  is the contrast of the interference pattern. Inserting  $G_4$  into path  $\beta$  will result in the same form of the interference pattern in Eqn. 4, but with a phase shift of the opposite sign (i.e.  $\Phi_0 \rightarrow -\Phi_0$ ).

Grating  $G_4$  is an array of cavities 50 nm wide and 150 nm long which cause a potential well for the Na atoms due to the vdW interaction. The atoms transmitted through  $G_4$  must pass within 25 nm of the cavity walls since the open slots of the grating are 50 nm wide. At this atom-surface distance the depth of the potential well is about  $4 \times 10^{-7}$  eV. Therefore, as the atoms enter the grating they are accelerated by the vdW interaction energy from 2000 m/s to 2000.001 m/s and decelerated back to 2000 m/s as they leave the grating. This small change in velocity is enough to cause about a 0.3 rad phase shift which corresponds to a 5 nm displacement of the interference pattern. It is quite remarkable to note that the acceleration and deceleration happens over a time period of 75 ps implying that the atoms experience an acceleration of at least  $10^6$  g's while passing through the grating. This indicates that the vdW interaction is one of the most important forces at the nanometer length scale.

The experiment consists of measuring shifts in the position of the interference pattern  $I(x)$  when  $G_4$  is moved in and out of the interferometer paths. The interference data is shown in Fig. 3. When  $G_4$  is placed in path  $\alpha$  the fringes shift in the positive x-direction, whereas placing  $G_4$  in path  $\beta$  causes a shift in the negative x-direction. Therefore the absolute sign of the phase shift is consistent with an attractive force between the Na atoms and

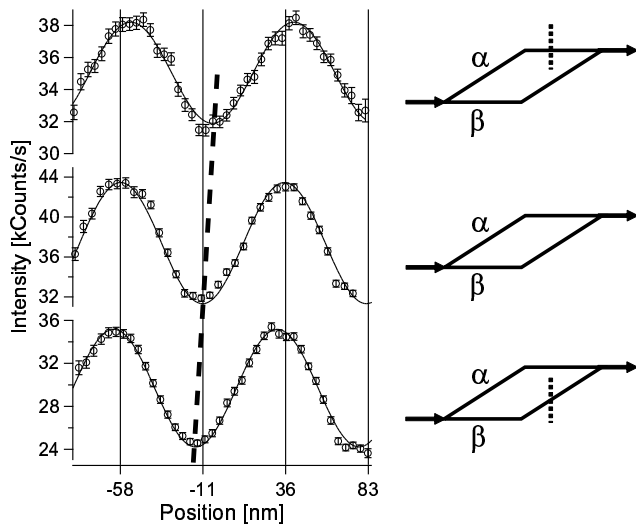


FIG. 3: Interference pattern observed when the grating  $G_4$  is inserted into path  $\alpha$  or  $\beta$  of the atom interferometer. Each interference pattern represents 5 seconds of data. The intensity error bars are arrived at by assuming Poisson statistics for the number of detected atoms. The dashed line on the plots is a visual aid to help illustrate the measured phase shift of 0.3 radians. Notice how the phase shift induced by placing  $G_4$  in path  $\alpha$  or  $\beta$  has opposite sign. The sign of the phase shift is also consistent with the atom experiencing an attractive potential as it passes through  $G_4$ .

walls of grating  $G_4$ . It is also observed that although the Na atoms are passing within 25 nm of the grating the atom waves retain their wave like behaviour (coherence) as evident by the non-zero contrast of the interference fringes.

The atom interferometer had a linear background phase drift of approximately  $2\pi$  rad/hr and non-linear excursions of  $\sim 1$  rad over a period of 10 min, which were attributed to thermally induced mechanical drift of the interferometer gratings  $G_1, G_2, G_3$  and phase instability of the vibration compensating laser interferometer. The data were taken by alternating between test ( $G_4$  in path  $\alpha$  or  $\beta$ ) and control ( $G_4$  out of the interferometer) conditions with a period of 50 seconds, so that the background phase drift was nearly linear between data collection cycles. A fifth order polynomial was fit to the phase time series for the control cases and then subtracted from the test and control data. All of the interference data was corrected in this way.

Grating  $G_4$  had to be prepared so that it was possible to obscure the test arm of the interferometer while leaving the reference arm unaffected. The grating is surrounded by a silicon frame, making it necessary to perforate  $G_4$ . The grating bars themselves are stabilized by  $1 \mu\text{m}$  period support bars running along the direction of  $\mathbf{k}_g$ . The grating naturally fractured along these support structures after applying pressure with a drawn glass capillary tube. Using this preparation technique  $G_4$  had a

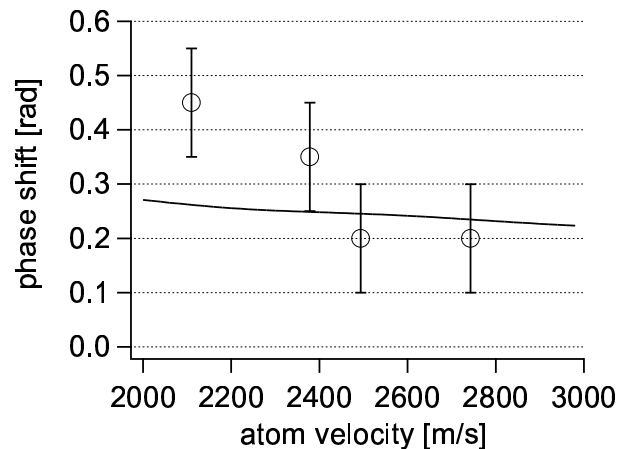


FIG. 4: Phase shift  $\Phi_0$  induced by grating  $G_4$  for various atom beam velocities. The phase shift data has been corrected for systematic offsets ( $\sim 30\%$ ) caused by the interference of other diffraction orders in the atom interferometer and the error bars reflect the uncertainty in the systematic parameters. The solid line is a prediction of the induced phase shift for vdW coefficient  $C_3 = 3 \text{ meV nm}^3$ , grating thickness 150 nm, and grating open fraction 0.5. The data agrees in magnitude with the prediction and reproduces the slight trend of decreasing phase shift with increasing velocity.

transition from intact grating to gap over a distance of about  $3 \mu\text{m}$ , easily fitting inside our interferometer which has a path separation of about  $50 \mu\text{m}$  for atoms travelling at 2 km/s.

Due to the preparation technique,  $G_4$  was inserted into the test arm with  $\mathbf{k}_g$  orthogonal to the plane of the interferometer. This causes diffraction of the test arm out of the plane of the interferometer, in addition to the zeroth order. However, the diffracted beams have an additional path length of approximately 2 nm due to geometry. Since our atom beam source has a coherence length of  $\lambda_{dB} \frac{v}{\sigma_v} = 0.1 \text{ nm}$ , the interference caused by the diffracted beams will have negligible contrast. Therefore, the zeroth order of  $G_4$  will be the only significant contribution to the interference signal.

In principle the amount of phase shift  $\Phi_0$  induced by the vdW interaction should depend on how long the atom spends near the surface of the grating bars. Therefore the observed phase shift produced by placing  $G_4$  in one of the interferometer paths should depend on the atom beam velocity in the way described by Eqs. 1 and 2. To test this prediction the experiment illustrated in Fig. 3 was repeated for several different atom beam velocities and the data are shown in Fig. 4. Systematic phase offsets of ( $\sim 30\%$ ) caused by the detected interference of additional diffraction orders generated by  $G_1, G_2, G_3$  in the atom interferometer (not shown in Fig. 2) have been corrected for in Fig. 4. The uncertainty in the phase measurements in Fig. 4 is given by the uncertainty in the systematic parameters. The measured phase shift

compares well to a prediction of the phase shift  $\Phi_0$  for the zeroth order of grating  $G_4$  which includes the vdW interaction. The value of  $C_3 = 3 \text{ meV nm}^3$  used to generate the theoretical prediction in Fig. 4 is consistent with previous measurements based on diffraction experiments [11]. It is important to note that if there was no interaction between the atom and the grating there would be zero observed phase shift.

The confirmation of atom-surface induced phase shifts presented here can be extrapolated to the case of atoms guided on a chip. Atoms travelling at 1 m/s over a distance of 1 cm will have an interaction time of 0.01 seconds. According to Eqn. 1, if these atoms are  $0.1 \mu\text{m}$  from the surface they will acquire a phase shift of  $10^4$  radians due to the vdW interaction. Similarly, if the atoms are  $0.5 \mu\text{m}$  from the surface they will have a phase shift of  $10^2$  radians. Therefore, a cloud of atoms  $0.1 \mu\text{m}$  from a surface will have a rapidly varying phase profile which could severely reduce the contrast of an interference signal. At some atom-surface distance the vdW interaction will significantly alter atom-chip trapping potentials, resulting in loss of trapped atoms or multimode behavior. Atom-chip magnetic wave-guides have a typical trap depth on the order of  $1 \text{ mK} \sim 10 \text{ neV}$  [17], which is comparable to the vdW interaction at an atom surface distance of  $0.05 \mu\text{m}$ . Since the vdW interaction increases as  $r^{-3}$  and the typical width of the trap ground state is  $0.1 \mu\text{m}$ , a wave-guide whose center is within  $0.1 \mu\text{m}$  of a surface will no longer trap atoms. Therefore, the vdW interaction places a limit on the spatial scale of atom interferometers built on a chip because bringing the atoms too close to a surface can result in poor contrast and atom intensity.

In conclusion the affect of atom-surface interactions on the phase of a Na atom wave has been observed directly for the first time. When the atom wave passes within 25 nm of a surface for 75 ps it accumulates a phase shift of  $\Phi_0 \approx 0.3 \text{ rad}$  consistent with an attractive vdW interaction. The slight velocity dependence of this interaction has also been confirmed. This experiment has also demonstrated the non-obvious result that atom waves can retain their coherence when passing within 25 nm of a surface. In the future one could use this experiment to make a more precise measurement of  $C_3$  at the 10 % level if the interference of unwanted diffraction orders are eliminated and the window size  $w$  of  $G_4$  is de-

termined with a precision of 3 %. This level of precision in measuring  $w$  is possible with existing scanning electron microscopes.

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