Observation of Atom Wave Phase Shifts Induced by Van Der Waals Atom-Surface Interactions

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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 wavelike (coherent) behavior 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 agreement with that predicted by Lifshitz theory for a nonretarded 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 vacuum 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 polarized atoms can also interact with their electrical image in a surface, resulting in an atom-surface vdW force [2]. For example, nearby surfaces can distort the radial symmetry of carbon nanotubes [3] and deflect the probes of atomic force microscopes [4]. Atom-surface interactions can also be a source of quantum decoherence or uncontrolled phase shifts, which are important considerations when building practical atom interferometers on a chip [5]. For the case of an atom near a surface the vdW potential takes the form $V(r) = -C_3 r^{-3}$, where C_3 describes the strength of the interaction and r is the atom-surface distance [1]. This form of the vdW potential is valid in the limit of atom-surface distances smaller than the principle transition wavelength of the atoms, typically $\lesssim 1$ μm.

Previous experiments have shown how atom-surface interactions affect the *intensity* of atom waves transmitted through cavities [6], diffracted from material gratings [7,8], and reflected from surfaces [9]. 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 (ψ), 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, as proposed in [10]. This observation is significant because it offers a new measurement technique for the vdW potential and is of practical interest when designing atom optics components on a chip [11,12].

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

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

where ξ is the position in the cavity, 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 [8]. Equation (1) also separates the induced phase $\phi(\xi)$ into constant ϕ_o and spatially varying $\delta\phi(\xi)$ parts. A plot of the phase $\phi(\xi)$ from Eq. (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 in the far field will have spatially separated components (diffraction orders) with complex amplitudes

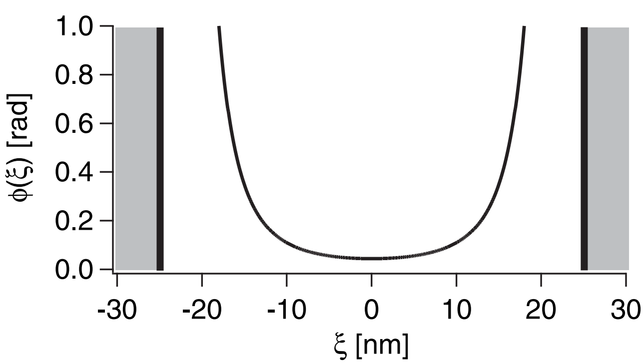

FIG. 1. Accumulated phase $\phi(\xi)$ of an atom wave as a function of cavity position ξ due to a vdW interaction with $C_3 = 3$ meV nm^3. The atom wave has propagated through a 150 nm long cavity at a velocity of 2 km/s. The gray rectangles indicate the location of the cavity walls which are 50 nm apart.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

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

where A_n and Φ_n are real numbers, and n is the diffraction order number [8]. For $n = 0$ the second exponential in the integrand is unity, and to leading order in $\phi(\xi)$, $\Phi_0 \approx \langle\phi(\xi)\rangle$ is the average phase over the grating window. 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 Eq. (2) that $|\psi_n|^2$ reveals no information about ϕ_o or Φ_n. We have determined A_0 and Φ_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 ϕ_o.

The experimental setup for using an atom interferometer to measure the phase shift Φ_0 induced by atom-surface interactions is shown in Fig. 2. The atom interferometer used is similar to the type described in [13] and described here briefly. A beam of Na atoms traveling at $v = 2$ km/s ($\lambda_{dB} = 0.08$ Å) is generated from an oven, and a position state of the atom wave is selected by two 10 μm 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 [14]. The three gratings G_1, G_2, G_3 are spaced 1 m from each other and produce a first order diffraction angle of about 80 μrad for 2 km/s sodium atoms. The grating G_1 creates a superposition of position states $|\alpha\rangle$ and $|\beta\rangle$ which propagate along separated paths α and β, respectively. The states are then recombined using grating G_2 and form a spatial interference pattern $I(x)$, with a 100 nm period, at the plane of G_3. The phase and contrast of the interference pattern are measured by scanning G_3 in the x direction with a piezoelectric stage and counting the transmitted atoms with a detector. The detector ionizes the transmitted atoms with a 60 μm diameter hot Re wire, and then counts the ions with a channel electron multiplier. A copropagating laser interferometer (not shown in Fig. 2) was used to monitor the positions of G_1, G_2, G_3 and to compensate for mechanical vibrations. Since the optical interference fringe period is $\Lambda = 3$ μm, relative uncertainty in the optical interferometer output intensity of $\Delta I/I \sim 2\pi\Delta x/\Lambda = 1/1000$ permits nanometer resolution in the position of G_3.

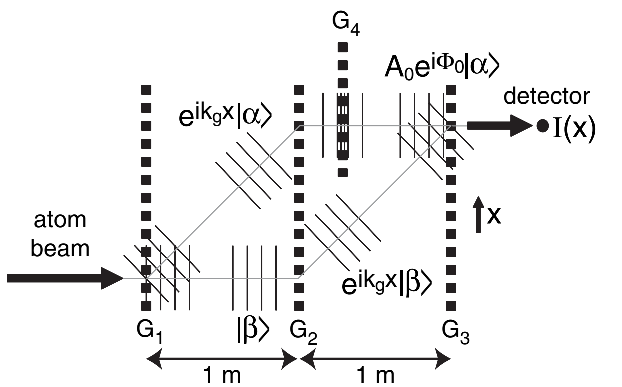

FIG. 2. Experimental setup for vdW induced phase measurement. A Mach-Zhender atom interferometer with paths α and β is formed using the zeroth and first order diffracted beams of gratings G_1 and G_2 which have a period of 100 nm. The atom wave interference pattern $I(x)$ is read out using grating G_3 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 Φ_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.

When grating G_4 is inserted into the interferometer path α, the interference pattern $I(x)$ shifts in space along the positive x direction. This can be understood by recalling de Broglie's relation $\lambda_{dB} = h/p$ [15]. The atoms are sped up by the attractive vdW interaction between the Na atoms and the walls of grating G_4. This causes λ_{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 α. One could also say that G_4 effectively increases the optical path length of path α. 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 $k_g = 2\pi/d$ is the grating wave number and d is the grating period. The diffraction amplitude A_0 reflects the fact that beam $|\alpha\rangle$ is also attenuated by G_4. The state $|\chi\rangle$ in Eq. (3) leads to an interference pattern which is shifted in space by an amount that depends on Φ_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 β will result in the same form of the interference pattern in Eq. (4), but with a phase shift of the opposite sign (i.e., $\Phi_0 \to -\Phi_0$).

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. Atoms transmitted through G_4 must pass within 25 nm of the silicon nitride 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 4×10^{-7} eV. Therefore, as the atoms enter the grating they are accelerated by the vdW interaction from 2000 m/s to at least 2000.001 m/s (depending on ξ) and decelerated back to 2000 m/s as they leave the grating. This small change in velocity is enough to cause a phase shift of $\Phi_0 = 0.3$ rad according to Eqs. (1) and (2), which corresponds to a 5 nm displacement of the interference pattern in the far field. 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 while passing through the grating. Therefore, 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 are shown in Fig. 3. When G_4 is placed in path α the fringes shift in the positive x direction, whereas placing G_4 in path β 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 the 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 wavelike behavior (coherence), as evident by the nonzero contrast of the interference fringes.

The atom interferometer had a linear background phase drift of approximately 2π rad/h and nonlinear excursions of ~ 1 rad over a period of 10 min, which were attributed to thermally induced position 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 α or β) and control (G_4 out of the interferometer) conditions with a period of 50 s, 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 were 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. A scanning electron microscope image of G_4 after it has been perforated can be found in [16]. The grating bars themselves are stabilized by 1 μm period support bars running along the direction of $\mathbf{k_g}$ as described in [13,14]. 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 transition from intact grating to gap over a distance of about 3 μm, easily fitting inside our interferometer, which has a path separation of about 80 μm for atoms traveling at 2 km/s.

Because of 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 $(v/\sigma_v)\lambda_{\mathrm{dB}} = 0.1$ 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 Φ_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

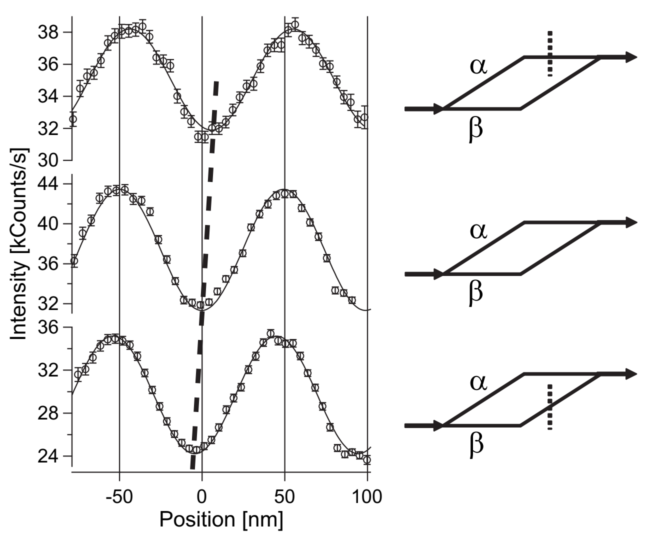

FIG. 3. Interference pattern observed when the grating G_4 is inserted into path α or β of the atom interferometer. Each interference pattern represents 5 s of data. The intensity error bars are arrived at by assuming Poisson statistics for the number of detected atoms. The dashed line in the plots is a visual aid to help illustrate the measured phase shift of 0.3 rad. Notice how the phase shift induced by placing G_4 in path α or β 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.

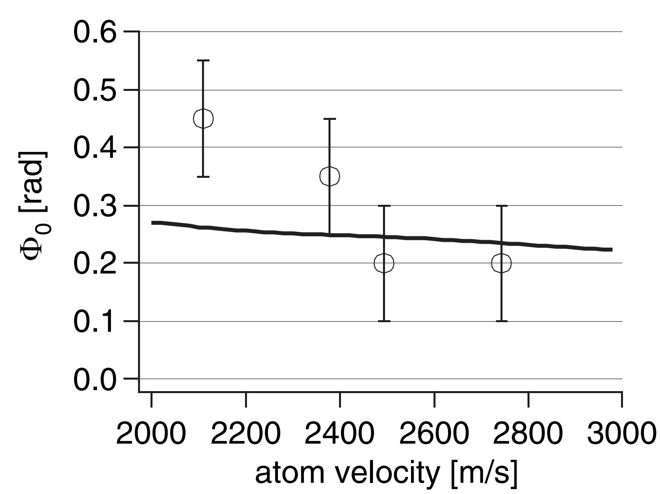

FIG. 4. Phase shift Φ_0 induced by grating G_4 for various atom beam velocities. The phase shift data have been corrected for systematic offsets ($\sim$30%) caused by the interference of other diffraction orders and beam overlap in the atom interferometer, and the error bars reflect the uncertainty in the systematic parameters. The solid line is a prediction of the induced phase shift for vdW coefficient $C_3 = 3$ meV nm^3, grating thickness 150 nm, and grating open fraction 0.5. The data agree in magnitude with the prediction and reproduce the slight trend of decreasing phase shift with increasing velocity.

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 overlap of the beams $|\alpha\rangle$ and $|\beta\rangle$ and 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. Uncertainty in the extent of beam overlap and amount of signal from additional diffraction orders led to the uncertainty of the phase measurements in Fig. 4. A more detailed discussion of systematic effects can be found in [16]. The measured phase shift compares well to a prediction of the phase shift Φ_0 for the zeroth order of grating G_4 which includes the vdW interaction. The value of $C_3 = 3$ meV nm^3 used to generate the theoretical prediction in Fig. 4 is consistent with Lifshitz theory and previous measurements based on diffraction experiments [8]. 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 traveling at 1 m/s over a distance of 1 cm will have an interaction time of 0.01 s. According to Eq. (1), if these atoms are 0.1 μm from the surface they will acquire a phase shift of 5×10^4 rad due to the vdW interaction. Similarly, if the atoms are 0.5 μm from the surface they will have a phase shift of 4×10^2 rad. Therefore, a cloud of atoms 0.1 μm 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 the loss of trapped atoms. Atom-chip magnetic traps are harmonic near their center and can have a trap frequency of $\omega = 2\pi \times 200$ kHz [12]. Given the vdW interaction we have observed, such a magnetic trap would have no bound states for Na atoms if its center was closer than 220 nm from a surface. 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 $\Phi_0 \approx 0.3$ rad consistent with an attractive vdW interaction. The slight velocity dependence predicted for Φ_0 by Eqs. (1) and (2) is consistent with the data. This experiment has also demonstrated the nonobvious 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 determined with a precision of 3%. This level of precision in measuring w is possible with existing scanning electron microscopes.

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