

Analysis of a Material Phase Shifting Element in an Atom Interferometer

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Abstract. The interaction of Na atoms with a surface was probed by inserting a nanofabricated material grating into one arm of an atom interferometer (IFM). This technique permits a direct measurement of the change in phase and coherence of matter waves as they pass within 25 nm of the grating bar surface. The practical concerns and challenges of making such a measurement are discussed here. Interference of spurious diffraction orders, IFM path overlap, and the partial obscuration of IFM beams are all important aspects of this experiment. The systematic effects that contribute to the measured phase shift and contrast are discussed.

Atomic diffraction from material grating structures [1] has been used as a tool to measure atom-surface interactions for noble gases [2] and alkali atoms [3, 4]. In these experiments the van der Waals (vdW) interaction [5] changed the relative intensities of the diffraction orders. More recently the atom wave phase shift Φ_0 induced by these grating structures¹ was measured directly using a sodium atom beam interferometer (IFM) [6]. The experimental setup is shown in Fig. 1. An interaction grating (IG), comprised of an array of 50 nm wide channels, is inserted into one arm of the IFM. The vdW interaction between the sodium atoms and IG causes a phase shift of about $\Phi_0 \sim 0.3$ radians. A number of systematic effects need to be understood before reporting this phase shift induced by the vdW interaction. This paper describes how the measured phase shift and contrast in [6] are influenced by these systematic effects and suggests some physical mechanisms for them.

In general there is a non-trivial relationship between the measured phase shift Φ_{meas} and induced phase shift Φ_0 , when the IFM paths are partially obscured by a phase shifting element. Therefore, care should be taken when interpreting the phase shift data. This notion of partial obscuration is shown in Fig. 2, which illustrates how the interference pattern can have different phases in different regions of space. The detected interference signal can be written as the average flux transmitted through each grating window of G_3 in Fig. 1

$$\begin{aligned} S(\theta) &= \sum_l \frac{1}{d} \int_{-w/2}^{w/2} dx \left[1 + C(x - ld) \cos \left(\frac{2\pi}{d}(x - ld) + \theta + \phi(x - ld) \right) \right] \langle I \rangle(x - ld) \\ &\approx \frac{1}{d} \sum_l \int_{-w/2}^{w/2} dx \left[1 + C_l \cos \left(\frac{2\pi}{d}x + \theta + \phi_l \right) \right] \langle I_l \rangle \end{aligned}$$

¹ The subscript of Φ_0 specifies this variable as the phase of the zeroth diffraction order induced by the IG. For reasons discussed in [6] only the zeroth diffraction order leads to significant interference contrast.

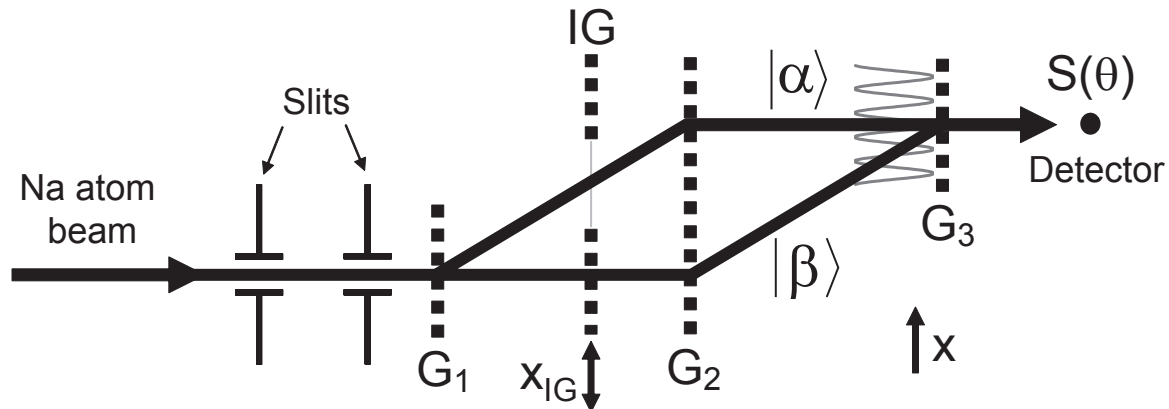


Figure 1. Experimental setup for using an atom interferometer (IFM) to measure the vdW induced phase shift. An IFM is formed using the zeroth and first order diffracted beams of gratings G_1 and G_2 . Placing the interaction grating (IG) in one of the interferometer paths causes the interference pattern at the third grating G_3 to shift in space. The IG has been perforated (light grey line) to allow the reference arm of the IFM to pass unaffected. The flux transmitted through G_3 is the detector signal $S(\theta)$.

$$= \frac{w}{d} \sum_l \left[1 + \text{sinc} \left(\frac{w}{d} \right) C_l \cos(\theta + \phi_l) \right] \langle I_l \rangle, \quad (1)$$

where the contrast (C_l), phase (ϕ_l), and average intensity ($\langle I_l \rangle$) of the interference pattern are assumed to be constant over each grating window l of G_3 . The grating window size w and period d in Eqn. 1 refer to grating G_3 .² The variable $\theta = 2\pi x_3/d$ accounts for the position of G_3 relative to the interference pattern phase ϕ_l . Equation 1 establishes a connection between the spatial interference pattern, shown just before G_3 in Fig. 1, and the signal $S(\theta)$ which is actually measured.

From Eqn. 1 it is clear that the detector signal $S(\theta)$ is a sum of cosines with varying phases ϕ_l and intensities $C_l \langle I_l \rangle$. When determining the measured phase Φ_{meas} of the signal it is only the relative phase and intensity of the terms in Eqn. 1 that are important. For the case of a half-plane phase shifting element (e. g. the IG in Fig. 2) the form for the detector signal implied by Eqn. 1 would be

$$S(\theta) \propto A \cos(\theta) + B \cos(\theta + \Phi_0) \equiv D \cos(\theta + \Phi_{meas}), \quad (2)$$

where constant offsets in the signal have been ignored. The intensity of the detector signal can then be given by

$$D = \sqrt{A^2 + B^2 + 2AB \cos(\Phi_0)}, \quad (3)$$

and the phase by

$$\Phi_{meas} = \tan^{-1} \left[\frac{B \sin(\Phi_0)}{A + B \cos(\Phi_0)} \right], \quad (4)$$

where A and B are the relative intensities of the unshifted and shifted interference patterns. The resulting phase and contrast measured by $S(\theta)$ can also be found for more complicated interference patterns by using Eqn. 2 in an iterative fashion.

² A more complete discussion of the grating structures and other experiments in which they are used can be found in a separate entry of the CAMS conference proceedings by A. D. Cronin.

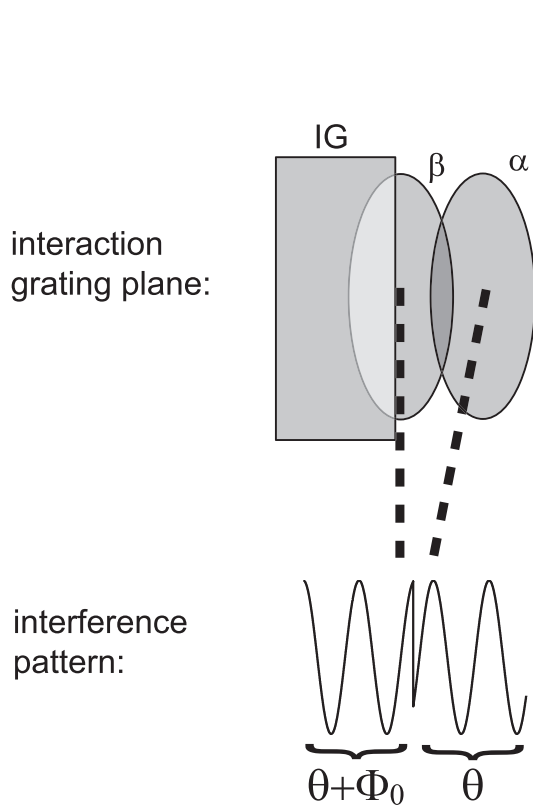


Figure 2. Partial obscuration of the interferometer beams α and β . In general the interaction grating (IG) may only induce a phase shift to part of the beam, resulting in an interference pattern that has different phases in different regions of space. As indicated by the dark grey region the beams can also have some overlap resulting in a more complicated interference pattern.

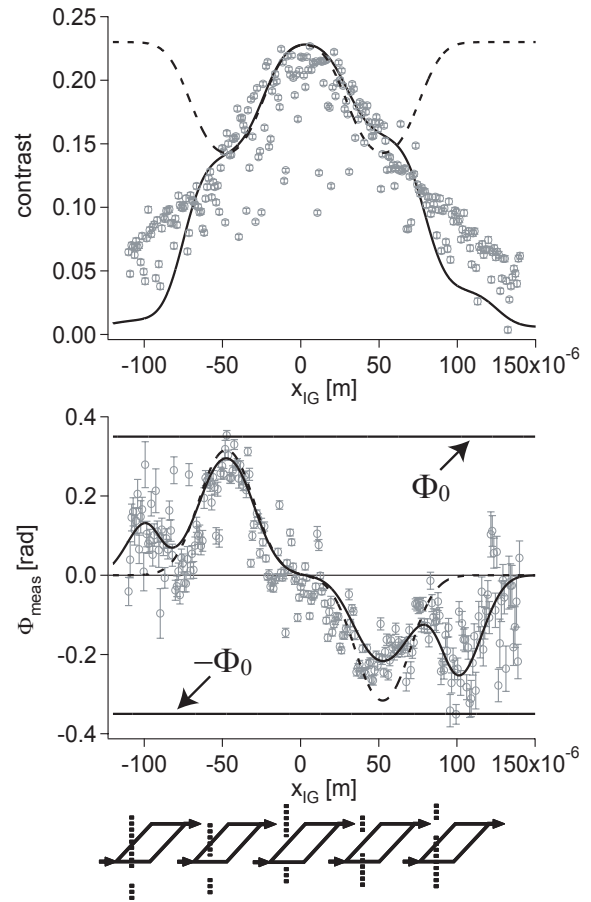


Figure 3. Measured phase and contrast as a function of interaction grating position x_{IG} . The naive model implied by Fig. 1 (dashed) fails to reproduce several features in the phase and contrast, which are explained when systematic effects are included (solid). The horizontal lines on the phase plot indicate the value for the induced phase Φ_0 and the diagrams below the x-axis show the position of the IG within the interferometer.

Figure 3 shows the measured phase and contrast of $S(\theta)$ when the interaction grating is placed at a given location x_{IG} inside the atom IFM. All phase measurements are relative to the situation where the IG is out of the IFM, and this reference phase was regularly measured. As one would expect the measured phase reaches a local extremum when the IG is completely obscuring one of the IFM paths. When the IG begins to obscure both of the IFM paths one would presume that the measured phase should return to zero again. However, the Φ_{meas} data deviate from this prediction. Likewise, the contrast should decrease when the IG attenuates one of the IFM paths, but then return to its nominal value when both paths are obscured. In addition, the beam overlap shown in Fig. 2 will tend to make the measured phase smaller than the induced phase because the overlapped portion will have no relative phase difference. These expectations are made quantitative by the use of Eqn. 2 and shown as the dashed line in Fig. 3.

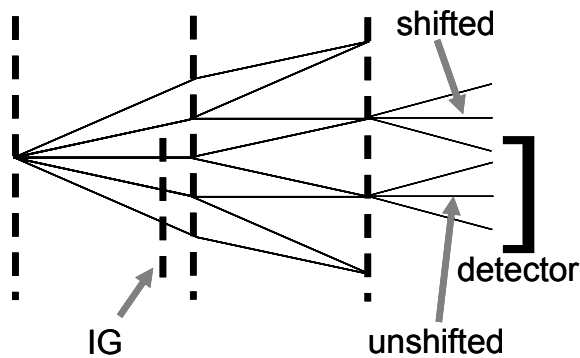


Figure 4. Explanation for the observed phase shift when both interferometer paths are obscured by the IG. The other diffraction orders can interfere leading to additional contributions to $S(\theta)$. It is possible for the IG to obscure both of the primary interferometer paths while only obscuring one of the secondary paths, leading to a phase shifted component.

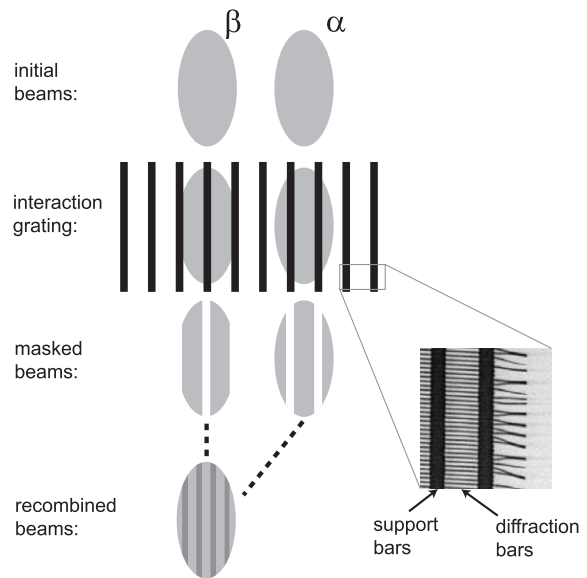


Figure 5. Explanation for contrast reduction when the IG obscures both interferometer paths. The IG support bars effectively operates like a mask. When the beams are recombined only the dark grey area will have significant contrast, leading to an overall reduction in the observed contrast in $S(\theta)$. The inset SEM image shows how the IG has been prepared with a sharp transition from gap to intact grating.

There are two striking failures of this naive prediction when compared to the experimental data: the appearance of a phase shift and significant loss of contrast when *both* IFM paths are obscured by the IG.

The appearance of the extra phase features can be understood by looking more carefully at the details of the IFM. Our IFM is formed by the zeroth and first order diffracted beams of the gratings G_1 and G_2 in Fig. 1. In reality there are more than just two paths that can interfere because of the other diffraction orders. This situation is depicted in Fig. 4. These additional interfering paths allow for the possibility of the IG to obscure both of the primary interferometer paths, while only obscuring one of the secondary interferometer paths. When this notion is combined with the finite size of the detector and diffraction caused by the third grating G_3 , a clear mechanism for the extra phase features is found.

A likely explanation for the unexpected reduction in contrast, when both interferometer paths are obscured by the IG, is shown in Fig. 5. The inset SEM image in Fig. 5 shows how the diffraction bars (which cause the atom-surface phase shift) are stabilized by much more widely spaced support bars. The support bars will imprint a spatial amplitude modulation on the two beams, shifted in space by different amounts with respect to the center of the beams. When the beams are recombined the region of overlap is effectively reduced, leading to an overall reduction in contrast. While there are some near-field diffractive effects caused by the support bars [7], numerical simulations have shown that the effective mask picture in Fig. 5 is still appropriate when considering the influence on $S(\theta)$. It is important to note that this effect only

reduces the contrast for an IFM that has *both* paths obscured by the IG. This also explains the relative prominence of the extra phase features, since the contrast of the primary interferometer is reduced compared to the secondary one as a result of this effect.

When the previously discussed systematic effects are incorporated into the coefficients A and B in Eqn. 2, much better agreement with the data is achieved. The solid line in Fig. 3 shows the prediction of a model which includes the influence of other interfering orders and the support bars. It is quite satisfying to see that the behavior of the measured contrast and phase is now understood even when the IG is blocking both of the primary interferometer paths. One can also see that the asymmetry of the phase profile is reproduced.

In conclusion the measured phase and contrast as a function of IG position are now understood to be influenced by a number of systematic effects. The primary physical mechanisms for the systematic effects are beam overlap, interference of additional diffraction orders, and an effective masking by the IG support bars. The inclusion of systematic effects leads to a relationship between the phase shift that is measured (Φ_{meas}) with our experiment and that which is actually induced (Φ_0) by the IG. This allows us to make quantitative comparisons to predictions for the phase shift Φ_0 and in turn the vdW coefficient C_3 [6].

Acknowledgments

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