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Photon Scattering from Atoms in an Atom Interferometer: Coherence Lost and Regained

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We have scattered single photons from interfering de Broglie waves in an atom interferometer and observed contrast loss and revivals as the separation of the interfering paths at the point of scattering is increased. Additionally, we have demonstrated that the lost coherence can be recovered by observing only atoms that are correlated with photons emitted into a limited angular range.

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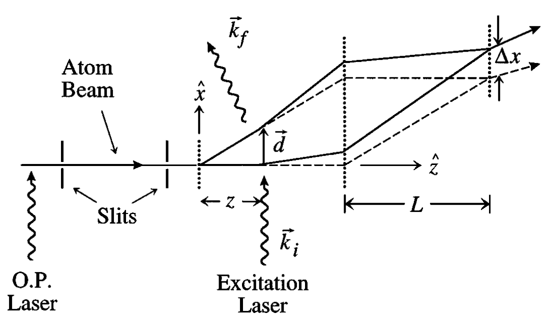
Wave-particle duality is perhaps the most striking example of complementarity in quantum mechanics. This duality is often addressed in the context of "which-way" *gedanken* experiments in interferometers, where attempts to measure which path the particle A traversed using some interaction with system M [1,2] invariably reduce the visibility of the interference fringes produced when the wave representing the particle recombines. In a *gedanken* experiment suggested by Feynman, a Heisenberg light microscope provides which-path information in a Young's two-slit experiment with electrons [2] or atoms [3,4]. Complementarity suggests that fringe contrast must disappear when the slit separation is greater than the wavelength of light, since, in principle, one could image the scattered photon to determine through which slit the atom passed. Indeed, photon scattering has been used to completely destroy atomic interference fringes for interfering path separations much larger than the photon wavelength [5].

We present here an experimental realization of this *gedanken* experiment, in which the loss of fringe contrast due to scattering single photons is measured as a function of the spatial separation d of the interfering paths at the point of scattering in a three-grating Mach-Zehnder atom interferometer [6] (see Fig. 1). We observe not only the loss of coherence expected from complementarity, but also several subsequent revivals of the fringe contrast that reflect the spatial resolution function of a single scattered photon [4]. Our experiment has the interesting property that the loss of coherence cannot be attributed to smearing of the interference pattern caused by momentum transferred in the scattering process, but, rather, is the result of random phase shifts between the two interfering paths. The average phase shift is also measured and compared with theoretical predictions.

Our experiment also addresses the questions: Where is the coherence lost, and how may it be regained? Elastic scattering of a photon *per se* is not a dissipative process and may be treated with Schrödinger's equation without any *ad hoc* dissipative term. The result of such a treat-



FIG, 1. A schematic, not to scale, of our atom interferometer. The original classical trajectories of the atoms (dashed lines) are altered (solid lines) due to scattering a photon (wavy lines). The atom diffraction gratings are indicated by the vertical dotted lines.

ment is that the atomic wave function becomes entangled with that of the scattered photon. Entanglement of one system A due to interaction with another system M is an important issue in contemporary quantum mechanics, particularly with regards to Einstein-Podolsky-Rosen type correlations and to understanding the measurement process and the loss of coherence between quantum and classical mechanics [7,8]. Here, selective observation of atoms which scatter photons in a restricted part of the accessible phase space results in fringes with regained contrast.

For our experimental configuration, the atom wave function at the third grating may be written $\psi(x) \propto u_1(x) + e^{i\phi_0}u_2(x)e^{ik_g x}$, where $u_{1,2}$ are (real) amplitudes of the upper and lower beams, respectively, $k_g = 2\pi/\lambda_g$, where λ_g is the period of the gratings, and ϕ_0 is a relative phase we may take to be zero. To describe the effects of scattering within the interferometer, we first consider an atom within the interferometer elastically scattering a photon with well-defined incident and final (measured) momenta, $\vec{k}_i$ and $\vec{k}_f$ with $|\vec{k}_{i,f}| = k$. With the scattering, the atomic wave function becomes

$$\psi'(x, \Delta k_x) \propto u_1(x-\Delta x) + u_2(x-\Delta x)e^{i(k_g x + \Delta\phi)}, \quad (1)$$

where Δk_x is the x component of $\Delta\vec{k} = \vec{k}_f - \vec{k}_i$. The resulting atomic interference pattern shows no loss in contrast but acquires a phase shift [9]

$$\Delta\phi = \Delta\vec{k} \cdot \vec{d} = \Delta k_x d\,, \quad (2)$$

where $\vec{d}$ is the relative displacement of the two arms of the interferometer at the point of scattering. In addition to this phase shift of the fringes, the fringe envelope shifts by $\Delta x = (2L - z)\Delta k_x/k_{\text{atom}}$ due to the deflection of the atom by the photon recoil momentum, where $k_{\text{atom}} = 2\pi/\lambda_{\text{dB}}$ and $2L - z$ is the distance from the point of scattering to the third grating.

If atoms are observed irrespective of the directions of the scattered photons $\vec{k}_f$, their interference pattern is given by an incoherent sum of interference patterns with different phase shifts [10] corresponding to different final photon directions (i.e., a trace over the photon states),

$$C' \cos(k_g x + \phi') = \int d(\Delta k_x) P(\Delta k_x) C_0 \times \cos(k_g x + \Delta k_x d)\,, \quad (3)$$

where $P(\Delta k_x)$ is the probability distribution of transverse momentum transfer and C_0 is the original contrast or visibility of the atomic fringe pattern. For the case of scattering a single photon, $P(\Delta k_x)$ (shown in the inset to Fig. 2) is given by the radiation pattern of an oscillating dipole [11]. The average transverse momentum transfer is $\hbar\overline{\Delta k_x} = 1\hbar k$ (the maximum of $2\hbar k$ occurs for backward scattering of the incoming photon and the minimum of $0\hbar k$ occurs for forward scattering). Because of the average over the angular distribution of the scattered photons,

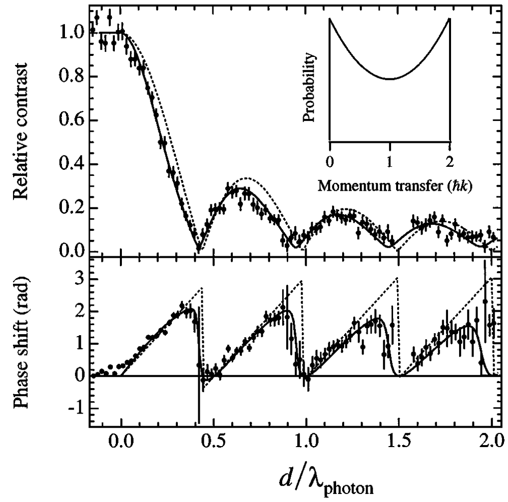


FIG. 2. Relative contrast C(laser on)/C(laser off) and phase shift of the interferometer as a function of d, where $d = z\lambda_{\text{dB}}/\lambda_g$ and $d < 0$ indicates scattering before the first grating.

through the waist is smaller than the lifetime of the excited state, hence the probability for resonant excitation in the two-state system shows weakly damped Rabi oscillations, which we observe by measuring the atomic deflection from the collimated atom beam as a function of laser power. To achieve one photon scattering event per atom, we adjust the laser power to the first maximum of these oscillations, closely approximating a π pulse.

To study the effects of photon scattering on the atomic coherence as a function of the separation d, the excitation laser beam is translated incrementally along the atomic beam axis z. The contrast and the phase of the interference pattern are determined at each point, both with and without the photon scattering.

In the first part of our experiment, we made no attempt to correlate the detected atoms with the direction of the scattered photon. The results of this study are shown in Fig. 2. First, we observe that, as expected, scattering the photons before and immediately after the first grating does not affect the contrast or the phase of the atomic interference pattern. For small beam separations, where $\overline{\Delta k_x} d$ ¿ π, the phase of the fringes increases linearly with d with slope 2π determined by the average momentum transfer of $1\hbar k$. The contrast decreases sharply with increasing beam separation d and falls to zero for a separation of about half the photon wavelength, at which point $\overline{\Delta k_x} d \approx \pi$. This would occur exactly at $d = \lambda/2$ if the scattered photon angular distribution were isotropic. As d increases further, a periodic rephasing of the interference gives rise to partial revivals of the contrast and to a periodic phase modulation. The fit, based on Eq. (3), includes "best fit" contributions from atoms that scattered 0 or 2 photons and is in good agreement with the data. The effects of velocity averaging are minimal for the narrow velocity distribution of our beam.

The effects of spontaneous scattering on the transverse momentum distribution of an atomic beam have been measured directly [12] using traveling wave excitation, and in conjunction with diffraction of an atomic beam passing through a standing light wave undergoing a single [13] or several [14] spontaneous emissions. These results are usually discussed using a simple classical argument: the recoil momentum from spontaneous emission produces random angular displacements that smear the far-field pattern, a viewpoint also applicable to two-slit *gedanken* experiments [3,4]. In [13], the modified momentum distributions are interpreted, using Fourier transforms, to yield an averaged spatial coherence function [15,16] for the range $d = (0.5 - 1.5)\lambda$. (Standing wave experiments cannot probe the important region $d < 0.5\lambda$.) In contrast, our experiment determines the coherence loss directly from the decrease in fringe visibility as d is varied without restriction. This decrease as well as the observed phase shift results from the relative quantum phase shift in the two arms of the interferometer, and cannot be simply understood as resulting from smearing of the interference pattern due to the recoil momentum. In our experiment, this recoil causes a deflection of the fringe envelope $\Delta x \sim 100-200$ fringes at our third grating, while the phase shift $\Delta\phi$ is at most only a few fringes. Furthermore, as the point of scattering is moved further upstream, the displacement of the fringe envelope actually increases slightly for a given $\vec{k}_f$, while the corresponding phase shift and the coherence loss both decrease monotonically, reaching zero when the scattering occurs at the first grating (i.e., the location of scattering in [14] and [13]).

We now describe a variant of our experiment in which the atoms observed are correlated with photons scattered into a restricted range of final directions. Under these conditions, we have demonstrated that the coherence lost as d increases may be partially regained. In principle, this could be achieved by detecting the atoms in coincidence with photons scattered in a specific direction. Such an approach is not feasible in our experiment for a number of technical reasons. However, we have performed an equivalent experimental realization of this type of correlation experiment made possible because the deflection of the atom Δx is a measurement of the final photon momentum projection, k_x, and hence Δk_x.

By using very narrow beam collimation in conjunction with small detector acceptance, we selectively detected only those atoms correlated with photons scattered within a limited range of Δk_x, resulting in a narrower distribution $P^0(\Delta k_x)$ in Eq. (3). This was achieved by using 10 μm slits and a third grating with a built-in 10 μm wide collimation slit which could be translated to preferentially detect atoms that received specific momentum transfers. (In contrast, for the first part of our experiment, we used 40 μm wide collimating slits and a 50 μm wide third grating to be sure that all momentum transfers were detected.)

We first took data with wide collimation slits and gratings to verify the experimental alignment and laser intensity. The experiment was then repeated with narrow slits, for three different positions of the third grating collimator (referred to as cases I–III) corresponding to different momentum transfer distributions accepted by the detector, $P_i^0(\Delta k_x), i = \mathrm{I,II,III}$, shown in the inset in Fig. 3. This figure also shows the contrast as a function of d for cases I and III, corresponding to forward- and backward-scattered photons, respectively. The contrast for case II is similar to case I and is not shown. The measured contrasts in this figure are normalized to the $d = 0$ (laser on) values [17]. The contrast falls off much more slowly than previously—indeed, we have regained over 60% of the lost contrast at $d \approx \lambda_{\mathrm{photon}}/2$.

The contrast falls off more rapidly for the faster beam velocity (case III, $v_{\mathrm{beam}} = 3200$ m/s) than the slower beam velocity (cases I and II, $v_{\mathrm{beam}} = 1400$ m/s) because the momentum selectivity is correspondingly lower. The final beam profile at the third grating is a convolution of the initial trapezoidal profile of the atomic

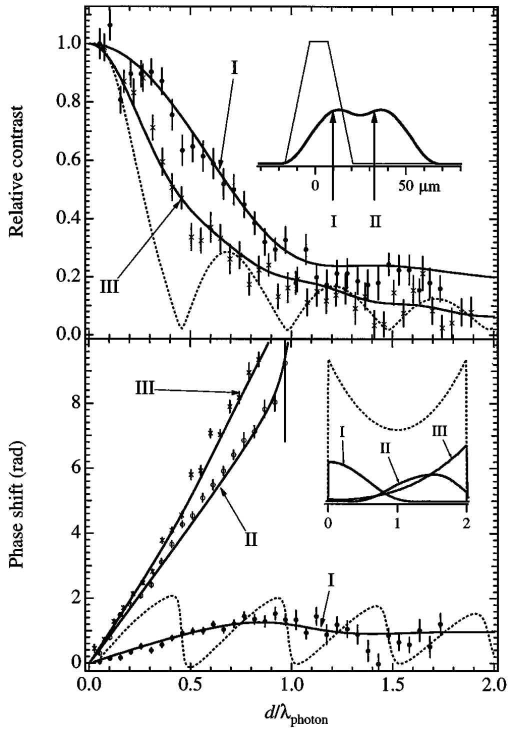


FIG. 3. Relative contrast and phase shift of the interferometer as a function of d for the cases in which atoms are correlated with photons scattered into a limited range of directions. The solid curves are calculated using the known collimator geometry, beam velocity, and momentum recoil distribution and are compared with the uncorrelated case (dashed curves). We do not attribute statistical significance to small deviations between these data and fits. The upper inset shows atomic beam profiles at the third grating when the laser is off (thin line) and when the laser is on (thick line). The arrows indicate the third grating positions for cases I and II. The lower inset shows the acceptance of the detector for each case, $P_i^0(\Delta k_x)$, compared to the original distribution (dotted line).

beam [18] and the distribution of deflections $\Delta x \propto \Delta k_x$ [11]. The initial and final profiles are shown in the upper inset of Fig. 3 for $v_{\rm beam} = 1400$ m/s. For a faster beam velocity, the different photon recoils are less separated in position at the detector, resulting in poorer selectivity.

The phase shift is plotted as a function of d for the three cases in the lower half of Fig. 3. The slope of case III is nearly 4π, indicating that the phase of the interference pattern is predominantly determined by the backward scattering events. Similarly, the slope of case I asymptotes to zero due to the predominance of forward scattering events. Case II is an intermediate case in which the slope of the curve, $\sim 3\pi$, is determined by the mean accepted momentum transfer of $1.5\hbar k$. The lower inset shows the transverse momentum acceptance of the detector for each of the three cases [i.e., the functions $P_i^0(\Delta k_x)$], which are determined using the known collimator geometry and beam velocity. The fits for the data in Fig. 3 are calculated using Eq. (3) and the modified distributions $P_i^0(\Delta k_x)$ and include effects of velocity averaging as well as atoms that scattered 0 or 2 photons, ignoring small contributions from other interfering pathways through the interferometer [19].

In summary, we have used an atom interferometer to measure the loss of atomic coherence caused by scattering of a single photon. Our results show that the decoherence that results from this process increases with the spatial extent of the atomic coherence at the point of scattering. Considering the different modes of the vacuum radiation field which photons may be scattered into as a reservoir, we would interpret our demonstration that the lost coherence can be regained as follows: The coherence was not truly destroyed, but only entangled with the final state of the reservoir.

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