

# Controlled decoherence in an atom interferometer

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We observe controlled decoherence in an atom interferometer, in which exposure to one environment changes the rate of decoherence in a subsequent environment.

## 1 Introduction

Interaction with an environment usually destroys quantum coherence. Here we show the opposite: adding an environment can protect coherence. We have demonstrated such a method for controlling spatial decoherence by adding an environment that interacts with spin.

In general, decoherence of a quantum system results from entanglement with an unmeasured reservoir, referred to as the environment. The rate of decoherence depends on the system-environment interaction, and therefore on the state of both the system and the environment. We have engineered two different environments: one which destroys coherence for atoms with a particular spin, and a second which causes only a little decoherence but changes the spin of atoms by optical pumping. The time-ordering of the two environments is important, because one environment prepares atoms in a decoherence-free state.

Using an atom's spin to control the rate of photon scattering – and thus the rate of spatial decoherence – is basically as simple as optical pumping. However, the dynamics of decoherence change when the same environment that causes decoherence also modifies the rate of decoherence. We use two separated environments to illustrate this point.

The system we are dealing with is a beam of atoms in an interferometer. Each atom can travel in a superposition of paths, and the spatial coherence between the paths is measured as atom fringe contrast [1,2]. The two engineered environments are resonant laser beams which spontaneously scatter photons from atoms in the interferometer as discussed in [3–6]. The setup is shown in Fig. 1.

First we review how entanglement with a single environment causes spatial decoherence for the atoms. Then we present the controlled decoherence experiment using two separated environments.

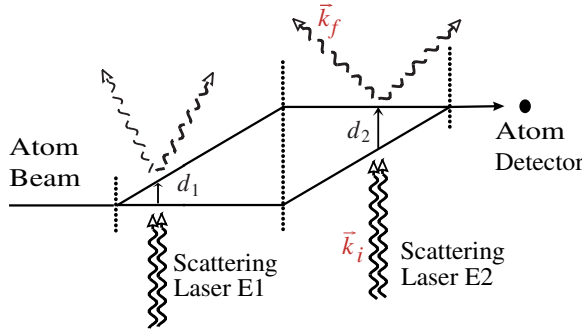
## 2 Decoherence from one environment

If an atom within a two-path atom interferometer, whose wavefunction is peaked at two positions which we label  $x$  and  $x + d$ , interacts with its environment (e.g. scatters a photon) the atom and environment become entangled:

$$\begin{aligned} |\psi\rangle_i &= (|x\rangle + |x + d\rangle) \otimes |e_0\rangle \\ &\xrightarrow{\text{interaction}} |x\rangle \otimes |e_x\rangle + |x + d\rangle \otimes |e_{x+d}\rangle, \end{aligned} \quad (1)$$

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**Fig. 1** The atom interferometer traverses two laser beams which constitute environments E1 and E2. The separation between the paths,  $d$ , varies and the laser beams are situated so that  $d_1 \ll \lambda_{ph} < d_2$ . Laser E1 optically pumps atoms into a dark state.

where  $|e_0\rangle$  is the initial wavefunction of the environment and  $|e_x\rangle$  is the post-interaction wavefunction of the environment given an atom at position  $x$ . If the environment is now observed to be in state  $|e_x\rangle$ , the (unnormalized) state of the atom becomes:

$$|\psi\rangle_e = |x\rangle + \beta_1(d)|x+d\rangle, \quad (2)$$

where

$$\beta_1(d) = \langle e_x | e_{x+d} \rangle. \quad (3)$$

If the two environment states are nearly identical then  $\beta_1(d) \approx 1$ ; very little which-way information is available in the measured state of the environment, and the atom is left in nearly the original superposition. If  $\beta_1(d) \ll 1$ , significant which-way information about the atom has been left in the environment, and the atom is highly likely (with probability  $1 - |\beta_1(d)|$ ) to be found in the final state corresponding to the measured environment state.

Whereas Eq. (2) gives the atomic state conditioned on an observation of the environment, if the environment is not observed, the final quantum state of the atom is found by averaging over all possible environment states. This is done by taking the trace of the atom+environment density matrix over the degrees of freedom of the environment. Applied to the atom interferometer, this procedure results in a reduction of contrast and a phase shift given by the complex factor  $\beta_1(d)$  for every photon scattered [3].

If there is a distribution in the number of photons scattered from individual atoms, then the interference signal is multiplied by

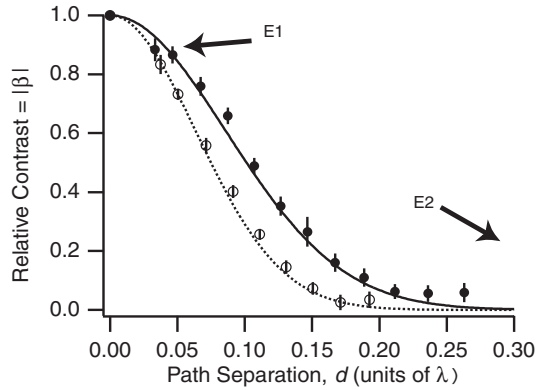
$$\beta(d) = \sum P_n \beta_1^n(d) \quad (4)$$

where  $P_n$  is the normalized probability of scattering  $n$  photons.  $\beta(d)$  is known as the decoherence function, and we have measured its modulus by studying contrast loss as a function of  $d$  and the average number of photons  $\bar{n}$  [3,4]. In the many-photon limit this measurement confirms several general models of decoherence [7–9]. In particular, decoherence from scattering  $\bar{n}$  photons reduces the contrast by the fraction

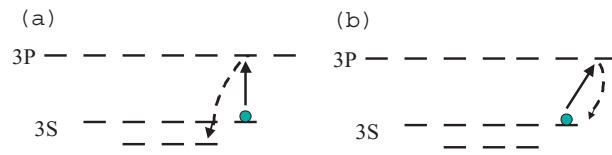
$$\frac{C}{C_0} = |\beta(d)| = e^{-\frac{1}{2}\bar{n}(\Delta k_{\text{RMS}} \cdot d)^2} \quad (5)$$

where  $d$  is the distance between components of the atom's wave function, and  $\Delta k_{\text{RMS}}$  is the spread in momentum kick from scattering a single photon. (A distribution in the number of photons scattered from each atom modifies this scaling only slightly.) Data from [4] are reproduced in Fig. 2 for the cases ( $\bar{n} = 4.8$ ) and ( $\bar{n} = 8.1$ ) and were obtained with a circularly polarized laser acting on a cycling transition (Fig. 3b).

To summarize, the laser beam constitutes a single environment with a variable  $d$ . The intensity of the laser (a parameter of the environment) can modify  $\bar{n}$ , and thus the decoherence given in Eq. (5).



**Fig. 2** Loss of contrast in the many-photon regime using a single environment with variable  $d$ . Over-laid are the theory curves generated from using parameters ( $\bullet \bar{n} = 4.8, \sigma_n = 1.8$ ) and ( $\circ \bar{n} = 8.1, \sigma_n = 3.5$ ) as determined by independent beam deflection measurements. The regimes of the two separate environments E1 and E2 from this work on controlled decoherence are denoted with arrows.



**Fig. 3** (a) Scattering photons in E1 causes atoms to decay into the dark state. (b) E2 drives the cycling transition.

### 3 Two separated environments

We now consider the effect of two separated environments E1 and E2. The naïve expectation is that decoherence from the two would compound, or multiply. However, data shown in Fig. 4 and summarized in Table 1 refute this.

The first environment is E1 which has  $d_1 \ll \lambda_{ph}$  so that it causes only a small amount of decoherence ( $\beta^{(E1)} \approx 1$ ) even though several ( $\bar{n} = 3$ ) photons are scattered. E1 has linearly polarized light which makes atoms to decay into the dark spin state, i.e. the lowest hyperfine manifold in Fig. 3a.

The second environment is E2 which has  $d_2 > \lambda_{ph}$  so that scattering  $\bar{n} = 3$  photons causes spatial decoherence ( $\beta^{(E2)} \ll 1$ ). The laser in E2 is circularly polarized, but only resonant with atoms in the original spin state, i.e. the upper hyperfine manifold of the 2S level in Fig. 3b. Before entering the interferometer all the atoms are prepared in this level (grey dot, Fig. 3).

The persistence of the fringe contrast shown in Fig. 4 is a direct measure of the spatial coherence for the atoms in the interferometer. In Fig. 4a, with both laser beams off, the relative contrast is defined to be 1. In Fig. 4b, only the laser for E1 is turned on, and it reduces the relative contrast to  $\beta^{(E1)} = .95$ . In Fig. 4c, only the laser for E2 is on, and it alone reduces the contrast to  $\beta^{(E2)} = .05$ . In Fig. 4d, both laser beams are on, but the contrast is only reduced to  $\beta^{(E1 \text{ and } E2)} = .93$ . From this we conclude that interaction with E1 controls the rate of decoherence in E2.

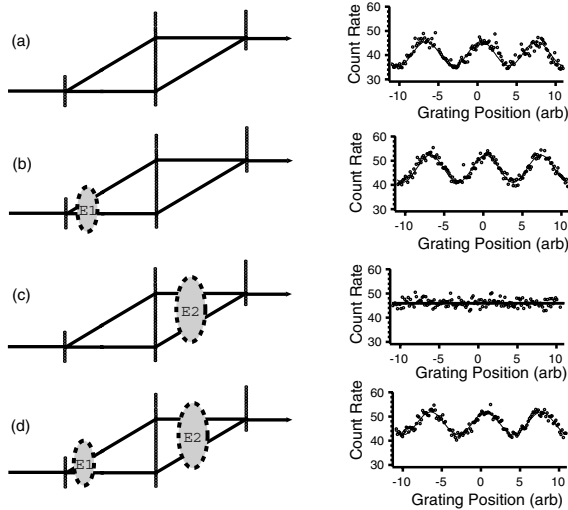
$$\beta^{(E1 \text{ and } E2)} = \beta^{(E1)} \times 1 \tag{6}$$

$$\approx 1. \tag{7}$$

This controlled decoherence is the main result of the paper.

We now return to the naïve expectation, which would have been correct if we neglected the atoms' internal structure. The naïve reasoning is simple, "since one environment is bad, two are worse". With a different choice of environments, E1' and E2' that do not change the atoms' spin we see the naïve expectation is true, and  $\beta^{(E1' \text{ and } E2')} = \beta^{(E2')} \times \beta^{(E2')}$ . We have studied this situation experimentally by using two circularly polarized laser beams E1' and E2' so atoms can return only to the original ground state (via the cycling transition). The results which confirm the naïve expectation are summarized in Table 2.

In conclusion, we observed controlled spatial decoherence by using the spin of atoms in an interferometer as a control bit to modify the system-environment interaction. Furthermore, spin can be changed by the same



**Fig. 4** The lasers corresponding to environments E1 (E2) are turned on (off) as depicted on the left column. Resulting atom interference fringe data are shown in the right column. E1 controls the rate of decoherence in E2, and thus the total amount of decoherence.

**Table 1** Measured relative contrast,  $\beta^{(\text{total})}$  due to E1, E2, or both. This table corresponds to Fig. 4, and demonstrates controlled decoherence. Parameters for E1 and E2 are given in the text. Statistical uncertainty for each measurement of  $\beta^{(\text{total})}$  is  $\pm .05$ .

laser E1	laser E2	$\beta^{(\text{total})}$
–	–	1 (by definition)
on	–	0.95
–	on	0.05
on	on	0.93

**Table 2** With both  $E1'$  and  $E2'$  acting on the cycling transition, decoherence from the two environments compounds. This is the naïve expectation. For these data, both  $E1'$  and  $E2'$  have a  $d \sim \lambda_{ph}/5$  and  $\bar{n} \sim 3$ . Statistical uncertainty for each measurement of  $\beta^{(\text{total})}$  is  $\pm .05$ .

laser $E1'$	laser $E2'$	$\beta^{\text{total}}$
–	–	1 (by definition)
on	–	0.16
–	on	0.09
on	on	0.02

radiation field which constitutes an environment, i.e. the optical pumping which modifies the rate of spatial decoherence can occur simultaneously with decoherence. This complicates the dynamics of decoherence so much that the order of coupling to two separated environments becomes important.

## References

- [1] D. W. Keith, C. R. Ekstrom, Q. A. Turchette, and D. E. Pritchard, An interferometer for atoms, *Phys. Rev. Lett.* **66**(21), 2693 (1991).
- [2] P. R. Berman (ed.), *Atom Interferometry* (Academic Press, 1999).
- [3] M. S. Chapman, T. D. Hammond, A. Lenef, J. Schmiedmayer, R. A. Rubenstein, E. Smith, and D. E. Pritchard, Photon scattering from atoms in an atom interferometer: coherence lost and regained, *Phys. Rev. Lett.* **75**(21), 3793 (1995).

- [4] D. K. Kokorowski, A. D. Cronin, T. R. Roberts, and D. E. Pritchard, From single- to multiple-photon decoherence in an atom interferometer, *Phys. Rev. Lett.* **86**(11), 2191 (2001).
- [5] D. A. Kokorowski, PhD thesis (2002).
- [6] D. E. Pritchard, A. D. Cronin, S. Gupta, and D. A. Kokoroski, Atom optics: old ideas, current technology and new results, *Ann. Phys.* **10**(1–2), 35–54 (2001).
- [7] E. Joos and H. D. Zeh, The emergence of classical properties through interaction with the environment, *Z. Phys. B* **59**(2), 223–245 (1985).
- [8] G. Z. Unruh, and W. H. Zurek, Reduction of a wavepacket in quantum Brownian-motion, *Phys. Rev. D* **40**, 1071–1094 (1989).
- [9] A. O. Caldeira and A. J. Leggett, Path integral approach to quantum Brownian-motion, *Physica A* **121**(3), 587–616 (1983).