Controlled Decoherence in Multiple Beam Ramsey Interference

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The transition between quantum and classical systems is usually ascribed to decoherence effects, which become increasingly important for larger size systems and tend to obscure the quantum behavior [1]. Quantum decoherence effects also come into play in the famous Gedanken experiments on the wave-particle duality of matter. For example, in the double slit experiment with electrons, a wavepacket passes simultaneously through both slits and forms an interference pattern manifesting the wave nature. When a photon is scattered on one of the interfering paths, the interference pattern is destroyed and the particle behavior takes over, as suggested by complementarity [2].

Here, we report on the study of controlled decoherence in a four-path atomic interference experiment. While in two-beam interference experiments the observation of a path always destroys the fringe signal, we demonstrate that the scattering of a photon on one of the paths in the multiple path arrangement cannot only lead to a decrease, but, under certain conditions also to an increase of the fringe contrast [3]. In both cases the scattering of a photon leads to an irreversible loss of observable information at the atom detector. The information is stored in the photon and allows in principle a detection of the path of the atom, i.e. it leads to an increased possible which-path information.

Our experimental setup employs a multiple path generalization of a Ramsey experiment performed in a cesium atomic beam apparatus. In a first optical pulse, cesium atoms are optically pumped into a dark coherent superposition of the magnetic sublevels $m_F = -3, -1, 1, 3$ of the $F = 3$ hyperfine ground state. After time T, the coherent superposition is probed with a second optical pulse, which again projects the atoms onto a dark state. We observe a sharp Airy-function like interference signal in the number of atoms remaining dark in the second pulse [4]. Between the Ramsey pulses the path in $m_F = 3$ can be observed by the following pulse sequence. With a microwave π-pulse the $m_F = 3$ component is transferred into $F = 4$, $m_F = 4$. Then, an optical pulse of variable length tuned to a closed cycling transition is used to scatter photons, which is followed by a second microwave π-pulse to transfer this path back into $F = 3$, $m_F = 3$. When we compensate for the phase shift due to the double microwave transfer, the fringe contrast decreases when scattering photons from the path in $m_F = 3$, as shown in Fig 1a. In Fig. 1b we did not compensate for the phase due to the double microwave transfer. In this case, the path in $m_F = 3$ is phase shifted by π relatively to the other paths. As shown in Fig. 1b, the fringe contrast *increases*, when scattering photons off this path. For longer pulse lengths, the fringe signal with and without a π-phase shift of the path in $m_F = 3$ is very similar,

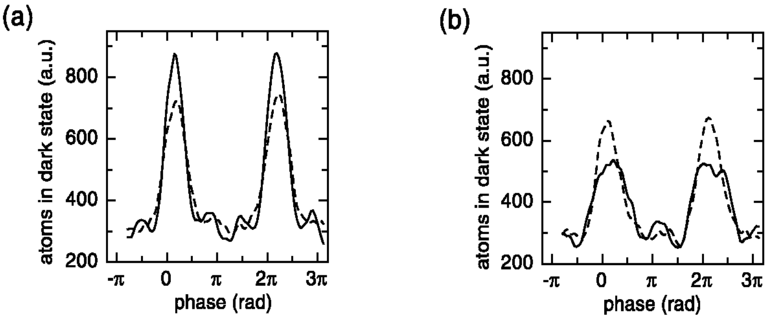

Figure 1: (a) Interference spectra for a spacing $T = 60\ \mu s$ between the Ramsey interactions as a function of the phase of the second Ramsey pulse. The solid line was recorded without scattering of photons. The dashed line with reduced contrast was measured with an applied $9\ \mu s$ long optical pulse scattering photons off the $m_F = 3$ path. (b) Interference spectra with an additional phase shift of π applied to the path in $m_F = 3$. Without scattering of photons, the fringe signal exhibits a small contrast (solid). When scattering photons, the interference contrast *increases* (dashed line).

which is an indication for the reduced information of the mixed quantum state. Fig. 2 shows the measured fringe contrast for different degrees of decoherence within the interferometer. The results are in agreement with quantum mechanical calculations and suggest that in multiple beam interference a single fringe contrast is not sufficient to quantify decoherence.

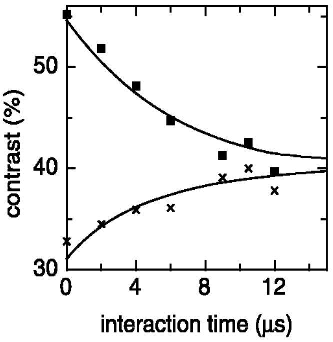

Figure 2: Michelson fringe contrast $c = (I_{max} - I_{min})/(I_{max} + I_{min})$ of multiple beam interference signals for different interaction times with the decoherence laser. Without any additional phase (squares) the fringe contrast decreases with increased pulse length. With a π phase shift in the $m_F = 3$ path (crosses) the contrast increases for larger pulse lengths.

[1] W. H. Zurek, *Physics Today* 44(10), 36(1991).

[2] See, e.g.: R. Feynman, R. Leighton, and R. Sands, *The Feynman Lectures on Physics*, Vol. III (Addison Wesley Reading, 1965). J. A. Wheeler, W. H. Zurek (eds.), *Quantum Theory and Measurement*, (Princeton University Press, New Jersey, 1983).

[3] M. Mei and M. Weitz, to be published.

[4] M. Weitz, T. Heupel, and T. W. Hänsch, *Phys. Rev. Lett.* 77, 2356(1996).