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Controlled Decoherence in Multiple Beam Ramsey Interference

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We have scattered photons from an interfering path of a multiple beam Ramsey interference experiment realized with a cesium atomic beam. It is demonstrated that in multiple beam interference the decoherence from photon scattering cannot only lead to a decrease but, under certain conditions, also to an increase of the Michelson fringe contrast. In all cases, the atomic quantum state loses information with photon scattering, as "which-path" information is carried away by the photon field. We outline an approach to quantify this which-path information from observed fringe signals, which allows for an appropriate measure of decoherence in multiple path interference.

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The wave-particle duality of matter describes one of the basic issues of quantum mechanics [1]. In a gedanken experiment suggested by Feynman [2], an electron wave packet passes simultaneously through two apertures and forms an interference pattern, which manifests the wave nature. However, if one is trying to determine the path of the electron by scattering a photon off the electron to probe the particle character, the quantum system is coupled to the environment and the interference pattern is destroyed, as suggested by complementarity. The existence of an interference pattern requires that the contributing paths are indistinguishable. This condition is so general that it also applies to higher order correlation interference experiments [3] and quantum-optical delayed-choice experiments [4–6]. Recently, neutral atoms have proven to be attractive candidates for experimental studies of the vanishing of two-beam interference patterns with observation [7–10]. As decoherence is believed to be responsible for the transition between quantum and classical systems [11], its study in larger quantum systems is of interest. Decoherence effects become increasingly important for quantum systems of larger size, and tend to obscure the quantum behavior in such systems [12,13].

Here, we report of an experiment studying quantum decoherence in an arrangement with more than two interfering paths. The experiment is based on four interfering internal states of the cesium atom in a multiple beam Ramsey setup. In all two-beam interference experiments considered so far, the observation of a path inevitably reduces the fringe contrast [1,4,14]. We demonstrate that, when using more than two interfering paths, the scattering of a photon off a path cannot only lead to a decrease but, under appropriate experimental conditions, also to an *increase* of the Michelson fringe contrast. Such a situation can occur, when the phase difference between adjacent paths is not constant for all paths. The results suggest that in the case of multiple beam interference more than the Michelson fringe contrast should be considered in order to quantify decoherence. We are aware that in all cases the scattering of photons leads to a loss of information contained in the atomic quantum state (yielding a nonzero entropy), as "which-path" information is carried away by the photon field. To obtain an appropriate measure for decoherence, we quantify the which-path information that could be gained from the emitted photons, which involves the analysis of more than a single output state of the interferometer. It is shown that the maximum possible path guessing likelihood [14,15] increases with a scattering of photons.

Let us begin by considering a general N-path interferometer with the interfering paths numbered by $1, \dots, N$. Assume that we are trying to detect particles traveling along path N, e.g., by scattering a photon on this path, which allows for partial "which-way" information. Before the photon scattering process (i.e., after the first beam splitter), the particle quantum state can be expressed as $|\psi\rangle = \sum_{n=1}^{N} c_n|n\rangle$. When no attempt is made to detect the path within the interferometer, the fringe signal is given as $|\langle\psi_{\text{out}} | \psi\rangle|^2 = |\sum_{n=1}^{N} c_n^2 e^{i(n-1)\varphi}|^2$, where $|\psi_{\text{out}}\rangle = \sum_{n=1}^{N} c_n e^{-i(n-1)\varphi}|n\rangle$. This assumes that the phase difference is constant between adjacent paths. One obtains a multiple beam interference signal with sharp principle maxima. If we now introduce a coupling to the environment such that it is possible to obtain knowledge about path N, this path can contribute only incoherently to the interference pattern. One expects that the fringe signal reduces to that of a $N - 1$ way interference pattern with, however, a smaller contrast due to an incoherent background from path N. A calculation of such a signal with partial coherence requires the use of the density matrix. Let us rewrite the particle wave function as $|\psi\rangle \equiv |\psi_{\text{part}}\rangle + c_N|N\rangle$, where $|\psi_{\text{part}}\rangle = \sum_{n=1}^{N-1} c_n|n\rangle$. While the density matrix of the pure quantum state is $\rho = |\psi\rangle\langle\psi|$, it is easy to show that the density matrix for the case of partial coherence of path N can be expressed as

$$\rho = |\psi_{\text{part}}\rangle\langle\psi_{\text{part}}| + a(c_N|N\rangle\langle\psi_{\text{part}}| + c_N^*|\psi_{\text{part}}\rangle\langle N|) + |c_N|^2|N\rangle\langle N|, \tag{1}$$

where the parameter a quantifies the remaining coherence between states $|\psi_{\text{part}}\rangle$ and $|N\rangle$. Here, $a = 1$ corresponds to a signal with full coherence and $a = 0$ to the case of a complete vanishing of all density matrix diagonal elements related to the Nth path, corresponding to complete possible which-path information on this path. The interference signal $I(\varphi) = \langle\psi_{\text{out}}|\rho|\psi_{\text{out}}\rangle$ can be written as

$$I(\varphi) = I_{\text{part}}(\varphi) + aI_{N\leftrightarrow\{N-1\}}(\varphi) + |c_N|^4, \tag{2}$$

where $I_{\text{part}}(\varphi)$ corresponds to the interference of the $N - 1$ paths $(1, \ldots, N - 1)$, $I_{N\leftrightarrow\{N-1\}}(\varphi)$ corresponds to the signal arising from the interference of path N with paths $1, 2, \ldots, N - 1$, and $|c_N|^4$ describes a background arising from path N alone. Figure 1a shows a calculated fringe signal for $N = 4$ paths and different couplings to the environment. Further, Fig. 1b shows the situation of an experiment performed with the phase of path N shifted by π. In that case, all interference terms with path N change sign, and the prefactor a to $I_{N\leftrightarrow\{N-1\}}(\varphi)$ is negative. When no photons are scattered, $a = -1$ and the signal has a small amplitude and a minimum at zero phase, corresponding to an inverted contrast. If we are trying to keep track of path N, this path will contribute incoherently, and one obtains the same signal as in situation 1a with $a = 0$. This corresponds to the at-first-sight counterintuitive situation of a higher interference contrast with increased decoherence.

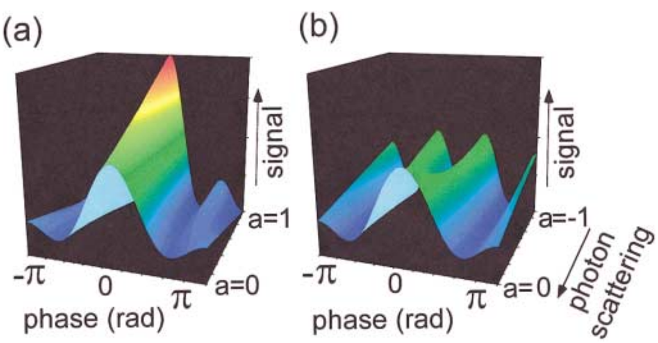

FIG. 1 (color). Expected interference signals for a which-path experiment performed with a quadruple-path interferometer (a) without and (b) with an additional π phase shift in one path.

In our experiment, four interfering paths are represented by the magnetic sublevels $m_F = -3, -1, 1, 3$, respectively, of the $F = 3$ hyperfine component of the cesium electronic ground state, as shown in Fig. 2. Cesium atoms from a thermal beam enter an interaction region with a homogeneous 0.54 G magnetic bias field. The atoms are irradiated with two superimposed resonant optical beams of opposite circular polarization tuned to the $F = 3 \rightarrow F' = 3$ component of the cesium $D1$ line directed along the magnetic field. In the first Ramsey pulse, the atoms are optically pumped into a nonabsorbing dark coherent superposition of four magnetic ground state sublevels. The atomic wave function is given by Eq. (1) with $|n\rangle$ describing a ground state of magnetic quantum number $m_F = 2(n - 1) - 3$, and the weights c_n being such that the absorption amplitudes into the upper electronic states cancel. The coherent superposition is probed after a time T with a second Ramsey pulse projecting the atoms onto the dark state. With no additional phase ($\varphi = 0$), the atoms by this time are still dark for the light field and the pulse leaves the atoms in this state (in $F = 3$). When the phase of this second pulse is varied, an atom is in general not dark for the modified light field, and can be optically pumped into the upper hyperfine ground state, which is not detected. The atoms remain dark only if the phase of the pulse roughly equals an integer multiple of 2π. The number of atoms remaining in the dark state after the two Ramsey pulses is read out by applying a detection laser pulse resonant with the $F = 3 \rightarrow F' = 2$ transition and collecting the fluorescence on a photomultiplier tube. As a function of the phase of the second Ramsey pulse, we observe an Airy-function-like interference signal [16].

Between the Ramsey pulses, the path in $m_F = 3$ can be coupled to the environment by the following sequence. With a microwave π pulse it is transferred into the state $F = 4, m_F = 4$. We then apply a σ^+-polarized optical pulse of variable length resonant with the closed cycling

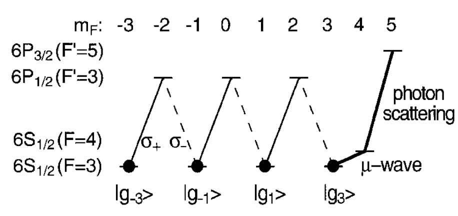

FIG. 2. Scheme of relevant levels of the cesium atom.

$F = 4 \rightarrow F' = 5$ component of the cesium $D2$ line to scatter photons, and finally a second microwave π pulse to bring this path back into the original level. Experimentally, it proved to be of importance to add additional σ^--polarized repumping light tuned to the $F = 4 \rightarrow F' = 4$ component of the cesium $D2$ line during (and also slightly after) the first optical Ramsey pulse. This ensures that the intermediate state $F = 4, m_F = 4$ is completely empty before the microwave pulse sequence. The double microwave transfer, which is applied for all recorded spectra, induces a phase shift of π for the path in $m_F = 3$. For some of the experimental runs, we have compensated for this effect by introducing an additional π phase shift for the second microwave pulse to maintain constant phase difference between adjacent paths.

Figure 3a shows typical interference patterns measured with constant phase difference between paths. The solid line was recorded without an attempt to keep track of an interfering path. One observes a sharply peaked four-way interference signal with two side peaks between the principle maxima. When scattering photons off the path in $m_F = 3$, we measure a fringe signal as shown by the dashed line. As expected, the signal loses contrast. Further, the widths of the principle maxima increase and the signal resembles more a three-way interference pattern. For the data shown in 3b we did not compensate for the π phase shift. Without scattering of photons (solid line), the contrast decreases significantly compared to the corresponding situation in 3a, as the fourth path is now severely out of phase. With scattering photons off the path in $m_F = 3$, the interference contrast *increases,* as shown by the dashed line. An analysis of the experimental signals shows that the experimental fringe patterns are slightly broader than the theoretical ones, a fact which we attribute mainly to stray magnetic fields. In addition, the finite efficiency of the microwave π pulses (roughly 70%), being limited by a spatially inhomogeneous distribution of the microwave field, causes deviations mainly for the signal with $a = -1$. Based on a simple theoretical model, one finds that the finite transfer efficiency can to first order be accounted for by assuming effective values for the parameter a ($|a| \leq 1$). At present, we can experimentally exploit effective values for a between roughly -0.4 and 1.

For a quantitative analysis, let us examine the contrast c_M of the experimental fringe patterns using the common definition introduced by Michelson $c_M = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$, where $I_{\max}$ ($I_{\min}$) denote the maxima (minima) values of the interference signal. Figure 4a shows the contrast of interference patterns recorded using different interaction times with the photon scattering pulse. The data points were fitted with a theoretical model for the contrast derived from Eq. (1), which accounts for the finite π pulse efficiency, a background caused mainly by the repumping light provided during the first Ramsey pulse, and a technical broadening of the fringes modeled by a Gaussian curve. When there is no phase shift of the path in $m_F = 3$, the contrast decreases with larger scattering of photons off this path (solid curve). This is similar to what is observed in two-beam atom interferometers, although the contrast does not reduce to zero here for large couplings, as the three remaining beams can still interfere phase-coherently. On the other hand, if the path in $m_F = 3$ is phase shifted by π, the interference contrast increases with a larger number of photons scattered on this path (dashed curve). Qualitatively speaking, the destructive interference of this path with the others is being replaced by a more and more incoherent contribution of this path to the interference pattern. For a larger coupling to the environment, the contrast for the two different preparations converges to the same value, as also shown qualitatively in Fig. 3.

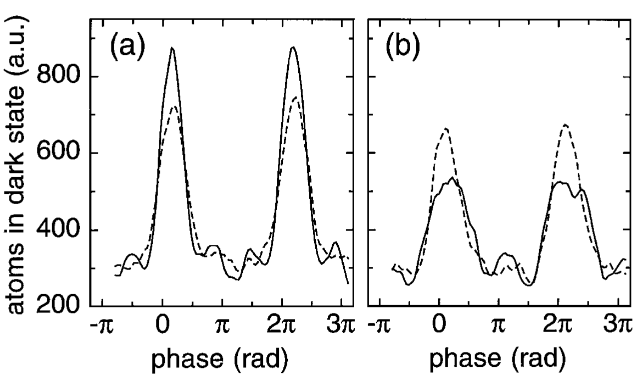

FIG. 3. Typical multiple beam interference fringes as a function of the phase of the second Ramsey pulse. (a) Signal without (solid line) and with an applied 9-μs-long optical pulse scattering photons from the path in $m_F = 3$ (dashed line). (b) In addition, a phase shift of π is applied to the path in $m_F = 3$. Again, both spectra without (solid line) and with (dashed line) scattering of photons are shown. The principle maxima are slightly shifted from 0 and 2π, since the frequency difference of the optical Ramsey beams does not exactly match the Zeeman splitting of the magnetic sublevels.

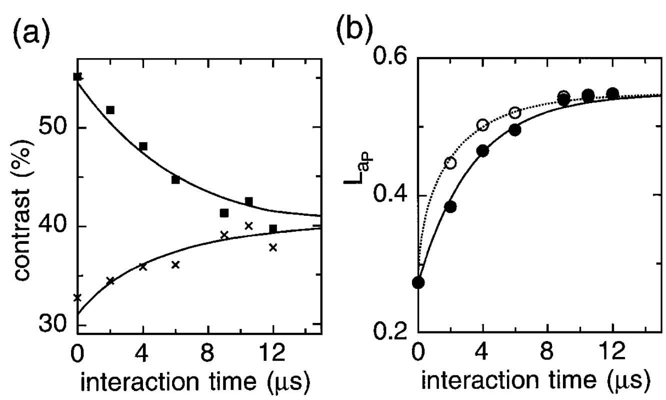

FIG. 4. (a) Contrast c_M of the interference signal for different lengths of the photon scattering pulse. The data points were measured without (squares) and with (crosses) a π phase shift of the path in $m_F = 3$. (b) Deduced path guessing likelihood in the detection basis (solid circles) and the theoretically optimum basis (open circles).

To quantify the decoherence of the atomic quantum state, we estimate the which-path information contained in the emitted photons. This approach is inspired from discussions on wave-particle duality in two-beam interferometers [1]. From information theory it is clear that the information lost when only considering the atomic degrees of freedom, i.e., performing a trace of the total density matrix over the photon degrees of freedom, equals the which-path information obtainable from the emitted photons. Such a trace operation yields the density matrix of Eq. (1). For a measure of the expected (maximum) which-path information, we follow earlier papers [10,14,15] and introduce the path guessing likelihood L that could be obtained when coupling a which-path detector to the quantum system. In a symmetric two-path interferometer, this likelihood is $1/2$ when not performing which-path detection and increases to 1 with full which-path detection. For the intermediate case of partial which-path detection, a relation between fringe contrast and path distinguishability has been developed for two-beam interferometers [14]. For our multiple beam arrangement, the optimum path guessing probability with no which-path detection equals $(c_n^2)_{\max}$, i.e., the maximum path weight. With $c_n^2 = 5/16$ for $m_F = -3$ and 3, and $c_n^2 = 3/16$ for $m_F = -1$ and 1, we obtain $(c_n^2)_{\max} = 5/16$. With scattering of photons on the path with $m_F = 3$, an obvious path betting strategy would be to choose the path with $m_F = 3$ when detecting a photon, and $m_F = -3$ otherwise. This results in a path guessing likelihood $L = (5/16)(1 + P_{\text{photon},3})$, where $P_{\text{photon},3}$ denotes the probability for an atom in the path with $m_F = 3$ to scatter a photon. One can show that $P_{\text{photon},3} = 1 - a^2$. This links the expected fringe pattern [Eq. (2)] to the maximum value for L.

We have attempted to deduce the modulus of a from our experimental fringe patterns. When comparing the signals (Fig. 3) with and without an applied π phase shift for the path in $m_F = 3$, one finds that, while the fringe signals differ considerably for no scattering of photons ($|a| = 1$), for a large scattering of photons (i.e., $|a| \ll 1$) the decoherence is so large that the fringe signal hardly changes when introducing this phase shift. We define

$$a_p = \frac{I_+(\varphi = 0) - I_-(\varphi = 0)}{[I_+(\varphi = 0) - I_-(\varphi = 0)]_{\max}} \tag{3}$$

as the presumed modulus of a at a given photon scattering laser pulse time, where I_+ and I_- correspond to the measured signals with and without an applied π phase shift of the path in $m_F = 3$ and $[I_+(\varphi = 0) - I_-(\varphi = 0)]_{\max}$ to this differential signal recorded with no scattering of photons. We have additionally accounted for a constant background K to the fringe signal, as estimated from the fringe contrast $c_{M,\max}$ measured with no scattering of photons and a constant phase between paths, and find

$$L_{a_p} = \frac{1}{1 + K}\left(c_3^2 + \frac{K}{N}\right)[1 + (1 - a_p^2)] \tag{4}$$

as an estimate for the *maximum* possible guessing probability for the described betting strategy, where $K = (N/2) \times [(1/c_{M,\max}) - 1]$. This approach relies on our model for the fringe pattern, as we presently do not perform full quantum tomography of the atomic state. The solid circles in Fig. 4b give the assumed value for L extracted from our data for different photon scattering pulse times. As expected, L_{a_p} increases with larger pulse lengths of the photon scattering laser. The strategy described so far would correspond to a which-path measurement in the detection basis of the photon vacuum state and an orthogonal state (with one or more photons). It has been pointed out that the basis in which L_{a_p} is maximized is in general given by a coherent superposition of the eigenstates of the detection basis [14]. It can be shown that such a strategy can yield a guessing probability L_{a_p} given by Eq. (4) with the term $1 - a_p^2$ replaced by $\sqrt{1 - a_p^2}$, and allows a determination of the path distinguishability. The open circles in Fig. 4b give the estimated L_{a_p} derived from our data using this formula. It is not clear how a measurement in this rotated basis could be performed experimentally when one of the basis states corresponds to a continuum state. However, this optimum case can be realized when decoding the which-path information in an additional internal atomic state [10]. Both data sets in Fig. 4b fit well with a theoretical model that is based on Eq. (2) with the parameter a taken to scale exponentially with the pulse time [11] (a similar model has been used to fit the data sets in Fig. 4a for the fringe constrast). The exponential behavior is understood in the following terms: the loss of coherence proceeds at a rate proportional to the remaining coherence between the path in $m_F = 3$ and those in $m_F \neq 3$.

An alternative interpretation of the described results is based on a quantum information science viewpoint. Studies of decoherence are of large interest for quantum computation, as such experiments aim towards complex entangled quantum systems [17]. The four paths of our Ramsey interference setup correspond to two-quantum bits, and the π phase shift on a path performed for some of the measurements equals the operation of a controlled-NOT gate. In the language of [13], the photon scattering corresponds to the coupling to an engineered reservoir, which results in an output quantum state that is independent of the operation of this gate. Our experiment represents a model system for the study of controlled decoherence in quantum systems, as, e.g., quantum logic gates.

To conclude, we have scattered photons of an interfering path in a multiple beam interference setup. The measurements show that partial decoherence cannot only lead to a decrease but also to an increase of the Michelson fringe contrast. This suggests that, in the case of more than two interfering paths, the Michelson contrast is not sufficient to quantify decoherence. An additional measure can be the path guessing likelihood, which quantifies the amount of which-path information contained in the emitted photons. For the future, it would be important to detect the photons scattered from the atoms with high quantum efficiency, which would allow for a direct verification of the presumed path guessing likelihood. Moreover, one could extend the experiment towards an increased number of interfering paths or other quantum systems of larger size.

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[1] N. Bohr, in *Albert Einstein: Philosopher-Scientist,* edited by P. A. Schilpp (Library of Living Philosophers, Evanston, 1949).
[2] R. Feynman, R. Leighton, and R. Sands, *The Feynman Lectures on Physics* (Addison-Wesley, Reading, MA, 1965).
[3] L. Mandel, Rev. Mod. Phys. **71**, S274 (1999).
[4] M. O. Scully and K. Drühl, Phys. Rev. A **25**, 2208 (1982).
[5] T. Hellmuth *et al.,* Phys. Rev. A **35**, 2532 (1987).
[6] Y.-H. Kim *et al.,* Phys. Rev. Lett. **84**, 1 (2000).
[7] T. Pfau *et al.,* Phys. Rev. Lett. **73**, 1223 (1994).
[8] J. F. Clauser and S. Li, Phys. Rev. A **50**, 2430 (1994).
[9] M. S. Chapman *et al.,* Phys. Rev. Lett. **75**, 3783 (1995).
[10] S. Dürr, T. Nonn, and G. Rempe, Phys. Rev. Lett. **81**, 5705 (1998).
[11] See, e.g., W. H. Zurek, Phys. Today **44**, No. 10, 36 (1991).
[12] M. Arndt *et al.,* Nature (London) **401**, 680 (1999).
[13] C. J. Myatt *et al.,* Nature (London) **403**, 269 (2000).
[14] B.-G. Englert, Phys. Rev. Lett. **77**, 2154 (1996).
[15] W. K. Wootters and W. H. Zurek, Phys. Rev. D **19**, 473 (1979).
[16] M. Weitz, T. Heupel, and T. W. Hänsch, Phys. Rev. Lett. **77**, 2356 (1996).
[17] See, e.g., A. M. Steane, Rep. Prog. Phys. **61**, 117 (1998).