Enhancing survival resonances with engineered dissipation

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We investigate a scheme that enhances survival resonances in a δ -kicked system through actively recycling lost atoms. The process causes atoms to dissipate into superpositions of momentum states with sustained survival when exposed to kicks of a dissipative optical standing wave. The recycling process causes momentum redistribution, which gives the atoms multiple chances to enter a long-surviving mode. The survival resonance peak height shows an improvement of a factor of 2.4. This technique can increase the sensitivity and precision of atomic interferometers based on survival resonances.

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I. INTRODUCTION

Dissipative processes occur when quantum systems are coupled to their environments. They are generally detrimental to quantum technologies since they can cause decoherence of superpositions and loss of quantum entanglement and information [1–3]. Fortunately, recent research shows that properly engineered dissipation can have the exact opposite effect, and drive a system toward a dark state that is decoupled from unwanted perturbations [4–8]. Such dark-state preparation is robust and can improve the performance of quantum technologies. An example of this is the so-called quantum error correction algorithm that harnesses engineered dissipation to generate entangled superpositions for performing quantum information processing and computation [9–12]. Alternatively, dissipation engineering has the potential for improving precision measurements by prolonging a system's coherence time beyond the limits of present technologies [13–15]. However, to date experimental investigations have focused solely on applications in quantum information processing.

This paper provides an experimental demonstration of using engineered dissipative processes to improve the initial state preparation in an atomic interferometer. The tailored dissipation leads the atoms originating from a thermal cloud to dissipate into a nonthermal distribution, which contains coherent superpositions of momentum states. The superposition states are ideally suited for precision measurements, and we observe that they improve the signal-to-noise ratio of an atomic interferometer by a factor of more than 2. The designed dissipation arises from combining survival resonances in the atom-optics δ -kicked rotor [16,17] with recycling of lost atoms through laser-cooling [18,19].

The aforementioned survival resonances have a close relationship to the widely studied quantum resonances (QRs) in the standard atom-optics δ -kicked rotor [20–22]. QRs provide a tool in atom interferometry, for example, due to their ability to transfer large momenta to atomic waves [22–25]. QRs are studied by kicking atoms temporally periodically with optical standing-wave pulses that modulate the phase of the atomic waves. On the other hand, survival resonances emerge when spatially periodic loss is added to each kick such that the standing-wave pulses act as absorption gratings, splitting initial atomic waves into a series of diffraction orders [26–28]. In practice, this can be realized by tuning the standing-wave light frequency close to an open atomic transition. Atoms are therefore lost in the vicinity of the standing-wave antinodes, due to photon scattering that optically pumps the atoms out of their initial electronic state.

II. LONG SURVIVING MODES

The probability that atoms survive is a meaningful observable when the kicks cause loss. When the time between standing-wave pulses is $T = \alpha T_T/2$ (with T_T being the Talbot time and $\alpha \in \mathbb{N}$), the survival probability can display resonant enhancement. These survival resonances appear because the Talbot-Lau effect causes the atoms to form a density pattern that peaks at the standing-wave nodes (the position where the loss is low) when the majority of pulses are applied. This is shown in Fig. 1(a) for a sequence of five pulses and $\alpha = 2$. The black line shows the atomic density distribution arising from kicking an atomic cloud with an initial temperature of $5\ \mu\text{K}$ at time $t = 5T_T$ after the first pulse. The red dashed line represents the intensity profile of the standing-wave light and we see that at this time (when the sixth pulse will be applied), the atoms are at the low-intensity positions of the standing wave, giving them a high chance of survival. It takes at least two standing-wave pulses before the interference pattern forms downstream the diffraction gratings when using an initial thermal ensemble of atoms [29]. It therefore takes more than two such pulses to observe survival resonances.

The black solid line in Fig. 1(b) shows the momentum space probability density of the same atoms as in Fig. 1(a).

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FIG. 1. Probability density distributions at $t = 5T_T$ in (a) position and (b) momentum spaces for atoms surviving a $N = 5$, $T = T_T$ pulse sequence, where the amplitude is not to scale.

We notice two features: (i). Only momenta that have quasimomentum close to 0 or $\hbar k$ have nonzero probabilities. Here, k is the wave vector of the light used to form the standing wave. (ii) The envelope of the distribution is also broader than the initial thermal momentum distribution (see the red dotted line). This is caused by the standing wave diffracting initial waves into coherent superpositions of diffraction orders that differ in momentum by $2\hbar k$.

Atoms with the particular quasimomenta of Fig. 1(b) survive longer pulse sequences than atoms with other quasimomenta. The reason for this is that their spatial density distribution revives at the time of the next standing-wave pulse, thereby ensuring that the atoms are close to the standing-wave nodes when it is applied. We deem such atomic states “long-surviving modes.” To determine a general formula for the long-surviving quasimomenta, we write the state $|\psi\rangle$ with given quasimomentum β in terms of momentum eigenstates $|p\rangle$, where $\beta \in [0, 2\hbar k)$. This gives $|\psi\rangle = \sum_m c_m |\beta + 2m\hbar k\rangle$, where c_m is the expansion coefficient and $m \in \mathbb{Z}$. Applying the time evolution operator $U(T) = \exp(-\frac{i}{\hbar} \frac{p^2}{2M} T)$ (M is the atom mass and p is the momentum operator), we see that after a free evolution of duration $T = \alpha T_T/2$ it becomes $U(\alpha T_T/2)|\psi\rangle = \sum_m c_m \exp[-i\pi m \alpha (m + \frac{\beta}{\hbar k})] |\beta + 2m\hbar k\rangle$, where we have omitted a global phase without physical significance. The wave function undergoes revival when $m\alpha(m + \frac{\beta}{\hbar k})$ is an even integer for all m , which gives the criteria for the long-surviving quasimomenta:

$$\beta = 2\alpha^{-1}\ell\hbar k + \begin{cases} \alpha^{-1}\hbar k & \alpha \text{ is odd} \\ 0 & \alpha \text{ is even} \end{cases} \quad (1)$$

with ℓ an integer.

Note that the standing-wave pulse sequence conserves quasimomentum. The atoms that do not happen to have an initial quasimomentum close to one of those in Eq. (1) thereby cannot contribute to the survival resonances. On the other hand, the standing wave diffracts a proportion of the atoms with a suitable initial quasimomentum into the long-surviving modes, where they effectively go dark to the standing-wave light and give rise to the resonant survival [16].

III. RECYCLING

The standing wave optically pumps atoms that do not end in the long-surviving modes into a different electronic state, where they form an inert reservoir. Our idea is then to reset these atoms' momentum distribution and recycle them back

FIG. 2. (a) The experimental time sequence (not to scale). The red narrow rectangles represent the standing-wave light pulses while the border blue rectangles are the recycle light pulses. (b) Simplified energy level diagram of the D_2 line of ^{85}Rb atoms (not to scale).

to their initial state where they get another chance to end up with a suitable quasimomentum. We implement this simply by applying laser cooling to the atoms in the reservoir state. The cooling light, which we in the following deem the “recycle light”, also optically pumps the atoms back to the initial state.

The combined effect of the recycle light and pulsed standing wave leads the atomic population to build up in the long-surviving modes. This gives a nonthermal distribution that includes large “dark” superpositions of momentum states. The scheme bears similarity to the velocity-selective coherent population trapping [30,31], where the cooled atoms are dissipatively driven into a coherent superposition of momentum states that are decoupled from the laser field.

To realize the scheme, we consider the pulse sequence shown in Fig. 2(a). It consists of a recycling stage of N_1 standing-wave pulses, each being followed by a recycle light pulse. It is this stage that enhances the population of the long-surviving modes. A probe sequence formed by N_2 standing-wave pulses follows the recycling stage. We choose $N_2 = 5$ throughout this work as this gives the highest survival resonances without a recycling stage. The probe sequence is used to characterize the enhancement of the atomic population in the long-surviving modes. If the recycling stage enhances the population in the long-surviving modes, it will appear as an increased height of the survival resonances that the probe sequence detects.

We make the following considerations. During the recycling stage, the atoms in the initial and reservoir states experience two different dissipative processes. The laser cooling and optical pumping erase any memory of the prior dynamics of the reservoir atoms and reset their momentum distribution to the red dotted curve in Fig. 1(b). However, the atoms surviving previous pulses in their initial state have a memory of the prior dynamics, giving a higher chance of surviving subsequent pulses. The dissipative processes do not destroy the quantum properties of atoms in the long-surviving modes, since these are effectively decoupled from them.

In order to write an expression for the probability S that an atom is in its initial state after the sequence shown in Fig. 2(a), we define the following quantities. We denote the probability that atoms, with an initial momentum distribution given by the red dotted curve in Fig. 1(b), survive N consecutive standing-wave pulses s_N . References [16,17] provide the method for calculating s_N . The probability that atoms, in the reservoir state right after a standing-wave pulse, are recycled before the next is γ , where γ is a function of the recycle light pulse duration τ_R . We denote the probability that atoms are in the reservoir state just before the χ th pulse as P_χ , with $\chi \leq N_1$, and the proportion of atoms that get transferred to the reservoir state by the χ th standing-wave pulse d_χ . Finally, we assume that atoms in the initial state are not affected by the recycle light. The following recursion relations then determine P_χ and d_χ :

$$\begin{aligned} P_{(\chi+1)} &= (1 - \gamma)(P_\chi + d_\chi), \\ d_{(\chi+1)} &= (s_\chi - s_{(\chi+1)}) + \sum_{i=1}^{\chi} \gamma(d_{(\chi+1-i)} + P_{(\chi+1-i)}) \\ &\quad \times (s_{(i-1)} - s_i). \end{aligned} \quad (2)$$

After computing the appropriate s_N , P_χ , and d_χ , it is straightforward to calculate the probability S for being in the initial state after the sequence of Fig. 2(a). One sums the probability that the atoms never left the initial state ($s_{(N_1+N_2)}$) with the probabilities that the atoms are recycled from the reservoir state to the initial state between the χ th and $(\chi + 1)$ th pulse [$\gamma(d_\chi + P_\chi)$] multiplied with the probability that the atoms survive the remaining $N_1 + N_2 - \chi$ pulses:

$$S = s_{(N_1+N_2)} + \sum_{\chi=1}^{N_1} \gamma(d_\chi + P_\chi)s_{(N_1+N_2-\chi)}. \quad (3)$$

We note that changing an experimental parameter such as the pulse period T affects s_N and through this the P_χ s and d_χ s.

IV. EXPERIMENT

In the experiment, we use ^{85}Rb atoms and their $F = 2$ and $F = 3$ hyperfine ground states as the initial state and the reservoir state [see the simplified D_2 line diagram in Fig. 2(b)]. The standing wave (red solid-line arrow) is formed by retroreflecting a horizontally propagating and linearly polarized laser beam with an intensity of 5 mW/cm^2 . The frequency of the laser beam is tuned $\Delta/2\pi = 5 \text{ MHz}$ above the open atomic transition from $F = 2$ to the $F' = 3$ excited state. Three pairs of counterpropagating laser beams constitute the recycle light (blue double-line arrow), and cools atoms via gray molasses (GM) [32,33]. Its frequency is $\delta/2\pi = 25 \text{ MHz}$ above the transition from $F = 3$ to $F' = F = 3$, and it rapidly transfers atoms from the $F = 3$ to $F = 2$ ground state and thereby enable large values for γ .

We start the experiment by laser cooling a cloud of ^{85}Rb atoms to a temperature of $5 \text{ } \mu\text{K}$ and preparing them in the $F = 2$ hyperfine ground state. We then expose them to the sequence of light pulses illustrated in Fig. 2(a) that has a pulse period T . During the recycling stage, each standing-wave pulse of variable duration τ_1 is followed by a GM recycle light pulse with duration τ_R . τ_R determines γ as $\gamma(\tau_R) = 1 -$

FIG. 3. (a) Measured survival resonances at $T = T_T$ with (blue triangles) and without (red circles) the recycling stage. Each point is the average of 20 experimental runs and the error bars show the standard deviation of the mean. The lines are the two-piece normal distributions fitted to guide the eye. (b) Calculated survival resonances with a manually added offset that accounts for the atoms spontaneously decay back to their original $F = 2$ hyperfine ground state.

$\exp(-\lambda\tau_R)$ with $\lambda = 3.2 \times 10^4 \text{ s}^{-1}$ (determined empirically) for our parameters of the GM cooling light. During the probe sequence, the standing-wave pulse duration is $\tau_2 = 400 \text{ ns}$. Finally, we measure the probability S that atoms are in the $F = 2$ state through a normalized internal state detection.

V. RESULTS

To demonstrate the effect of the recycling stage, we measure S with $N_1 = 10$, $\tau_1 = 400 \text{ ns}$, and $\gamma = 0.65$ while scanning T across the resonance expected at $T = T_T$ ($\alpha = 2$). The blue triangles in Fig. 3(a) display the measured survival probability with the recycling sequence present while the red circles are the result in the absence of a prior recycling stage (red circles with $N_1 = 0$ and $N_2 = 5$). The peak heights are in the following deduced from the fits of two-piece normal distributions which Fig. 3(a) also shows as black dashed and red solid lines. We see that the recycling stage results in a significant enhancement (a factor of more than 2). This demonstrates that the dissipative recycling sequence causes atoms to populate the long-surviving modes.

Figure 3(b) shows a plot of Eq. (3) without any fitted parameter. The model captures the increase in peak height well. Recall that Refs. [16,17] outline how to calculate the survival probabilities in the absence of recycling s_N needed for evaluation of Eq. (3). The calculation of s_N includes the imbalance of the standing wave due to the power loss from view ports and retromirror. A perfectly balanced standing wave has completely dark nodes that potentially allows the atoms to live longer in the long-surviving modes. However, our calculation shows that an ideally balanced standing wave only leads to $\approx 10\%$ further improvement of the peak height.

To gain a deeper understanding of the dynamics during the recycling stage, we proceed to explore how the survival peak height depends on different experimental parameters. Figure 4(a) shows the dependence of the peak height on the standing-wave pulse duration τ_1 during the recycling stage, with $N_1 = 5$. The measurement (red circles) exhibits a good agreement with the calculation based on Eq. (3) (blue squares

FIG. 4. (a) Measured (red circles) and calculated (blue squares connected with a solid line) peak height as a function of the pulse duration τ_1 , where $N_1 = 5$ and τ_R is set to be equal to T to maximize the recycling effect yielding a value of γ about 0.87. (b) The measured (markers with error bars) and calculated (lines) peak heights as functions of the pulse number N_1 with the recycling efficiencies $\gamma = 0.65$ (red circles and dot-dashed line), 0.35 (green squares and dashed line), and 0 (blue triangles and dotted line). The black solid line is a calculation with $\gamma = 1$. Error bars in panels (a) and (b) denote statistical 68% confidence intervals. (c) The calculated MSSS of the survival peaks when varying N_1 for $\gamma = 1$.

connected by a solid line) and shows a maximum enhancement factor for $\tau_1 \in [200, 400]$ ns of about 2.4.

The trends in Fig. 4(a) are not surprising since the enhancement of the survival peak comes as a tradeoff between two competing effects. One is preserving atoms in the long-surviving modes; the other is to remove atoms that are not in these modes to the reservoir state, such that they get a second chance to populate a long-surviving mode. When τ_1 is so short that atoms remain in the initial state throughout the recycling stage, it has little effect. The peak height therefore increases with τ_1 when it is small. For sufficiently long τ_1 , atoms only survive in the vicinity of the standing-wave nodes. When τ_1 increases in this regime, the region around the nodes where the atoms can survive becomes narrower. Eventually, each standing-wave pulse effectively pumps all atoms to the reservoir state, and the recycling sequence has no effect again. This is the reason that the peak height declines to the one in the absence of a recycling stage for large τ_1 . In the following, we use $\tau_1 = \tau_2 = 400$ ns since this gives a good enhancement.

Next we study how the peak enhancement varies with the pulse number N_1 and recycle efficiency γ . The red circles in Fig. 4(b) show the measured peak height of the survival resonance as a function of N_1 for $\gamma = 0.65$. The measured data agrees well with the calculation (the red dot-dashed line). The peak increases for $N_1 \leq 10$ but the height saturates for $N_1 > 10$. The saturation occurs because atoms in the long-surviving modes do not decouple perfectly from the standing-wave light. The growth of the peak height therefore ceases when the system reaches a steady state between the

long-surviving modes being populated through the recycling process and depleted due to the incomplete decoupling from the standing-wave light.

When γ is very small [blue triangles and dotted line in Fig. 4(b) have $\gamma = 0$] the recycling stage deteriorates the peak height rather than enhancing it. This is because it will leave the atomic population predominantly in the reservoir state ahead of the probe sequence, without sufficient enhancement of the population in the long-surviving modes to counteract this. For the recycling stage to have a positive impact on the peak height, γ therefore needs to be above a critical value, which in our experiment is $\gamma_c \simeq 0.35$. The green squares show that when $\gamma \simeq \gamma_c$ the recycle sequence has a vanishing effect on the peak height for all N_1 .

Presently, we cannot achieve the ideal recycling efficiency of $\gamma = 1$ in the experiment. However, the solid line in Fig. 4(b) shows the prediction of Eq. (3) with $\gamma = 1$. In this case, the recycling stage can lead to enhancement of the peak by a factor of 3.

To further estimate the sensitivity gain factor, we study the maximum slope at the steep side (MSSS) of the survival peak shown in Fig. 3. Figure 4(c) shows the calculated MSSS when varying N_1 for $\gamma = 1$. It indicates enhancement by more than a factor of 6.

VI. DISCUSSION AND CONCLUSIONS

In the future, it would be interesting to investigate more advanced recycle sequences. For example, dynamically varying τ_1 and pulse period T might allow the atoms to stay longer in a long-surviving mode and thereby lead to a higher survival peak. Additionally, the ability for generating periodic atomic density distributions may find applications as state preparation for quantum ratchet [34], and quantum random walk experiments [35–37], since it can replace the need for a Bose-Einstein condensate.

In conclusion, we have demonstrated a dissipative process that causes laser-cooled atoms to dissipate into coherent superpositions of momentum states. We have experimentally studied how to use this process as a preparation stage, which leads to a substantial enhancement of survival resonance peaks in the δ -killed rotor. This can improve the sensitivity of measurements based on survival resonances [17].

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