

Reservoir-Mediated Quantum Correlations in Non-Hermitian Optical System

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Recent advances in non-Hermitian physical systems have led to numerous novel optical phenomena and applications. Such systems typically involve gain and loss associated with dissipative coupling to the environment, hence interesting quantum phenomena are often washed out, rendering most realizations classical. Here, in contrast, we propose to employ dissipative coupling to enable quantum correlations. In particular, two distant optical channels are judiciously designed to couple to and exchange information with a common reservoir environment, under an anti-parity-time-symmetric setting of hot but coherent atoms. We realize a non-Hermitian nonlinear phase sensitive parametric process, where atomic motion leads to quantum correlations between two distant light beams in the symmetry-unbroken phase. This Letter starts a new route to exploring the non-Hermitian quantum phenomena by bridging the fields of atomic physics, non-Hermitian optics, quantum information, and reservoir engineering. Potential applications include novel quantum light sources, quantum information processing and sensing, and generalization to correlated many-body systems.

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Standard quantum mechanics requires Hermiticity to ensure real eigenvalues of the energy spectra and conservation of the total probability of a quantum system. Surprisingly, it was found that a non-Hermitian Hamiltonian satisfying parity-time symmetry (\mathcal{PT}) can still exhibit real spectra [1]. With roots of symmetry in quantum field and topological theory, \mathcal{PT} and anti- \mathcal{PT} symmetry have attracted great interests in photonics [2–9] and many other systems [10–15], opening opportunities to explore exotic scattering features for applications in artificial materials and functional devices [16–24]. With the rapid development of quantum technology, especially in quantum information processing, quantum photonic devices are highly in demand. The ultimate goal of non-Hermitian optics is to be applied to quantum photonics [16–19]. Furthermore, potential sensing applications involving exceptional points (EP) [25–27] raised the open question of whether the quantum noise limit can be reached or surpassed. Investigating the information retrieval and criticality in \mathcal{PT} systems [28] is necessary for deeper understanding of \mathcal{PT} symmetric systems as open quantum systems. However, most \mathcal{PT} symmetry realizations up to date rely on optical gain-loss systems, where thermal noise stemming from dissipative baths washes out interesting quantum effects and impedes the observation of quantum dynamics. As a result, quantum phenomena in these systems remain unexplored experimentally.

Here, we propose a unique approach, reservoir engineering, to accessing and investigating the quantum regime of non-Hermitian systems. It allows to address the main

challenge that conventional optical gain-loss non-Hermitian systems face in pursuit of reaching quantum regime. Unlike typical gain-loss systems where each optical channel couples to its own bath, in our scheme they couple to a common bath. To illustrate the idea, in the anti- \mathcal{PT} system we consider, two optical modes indirectly couple to each other through their dissipative coupling to the moving atoms, which carry and spread out the information of light and act as a common reservoir. By engineering the coupling of the light to the atomic spin waves, nonlinear parametric process is realized, leading to the observation of phase sensitive gain in each optical channel. Moreover, the optical system is driven to a stationary quantum correlated state, akin to recent demonstrations of dissipation induced quantum states preparation [29–31]. Strikingly, although each channel by itself only enables linear optics, the flying atoms serve as effective feedback and turn the two-channel system into a nonlinear one. This demonstration provides a fundamentally new route to the development of key building blocks in quantum technology, such as the preparation of novel quantum states of light [32], quantum frequency translation [19], as well as to the enhancement of photon-photon interactions.

The optical system considered here builds on the anti- \mathcal{PT} symmetry platform [12] we developed previously, but the key change is to use different light polarization configurations than before in order to enable the non-linearity and quantum correlations. As shown in Fig. 1, two spatially separated laser beams interact with Rb atoms

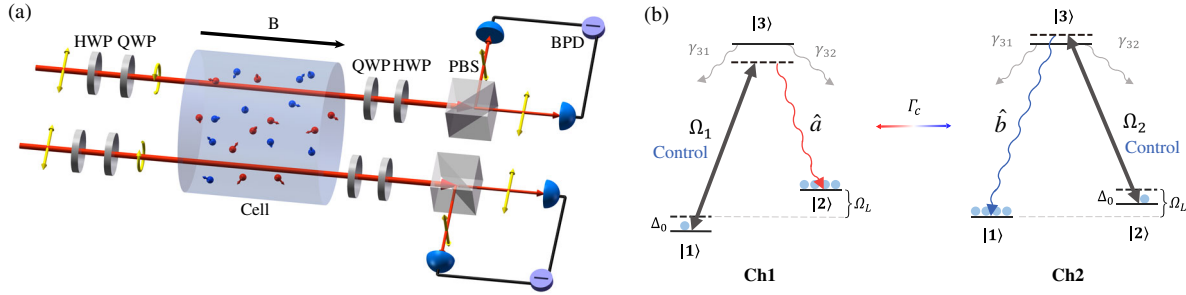


FIG. 1. Schematics for observation of quantum correlation in an anti- \mathcal{PT} -symmetry platform. (a) The experiment schematics. Two spatially separated optical channels (Ch1 and Ch2) with orthogonal circular polarizations propagate in the warm paraffin-coated ^{87}Rb vapor cell under EIT interaction. The coupling between them is mediated by coherent mixing (through atomic diffusion) of the atomic population and coherence of ground states created in each channel. The cell is mounted inside a four-layer magnetic shielding. Inside the shield a solenoid gives precise control over the internal longitudinal magnetic field. After the cell, the output beams are recollimated and directed to the polarization homodyne detection setup. The noise power of the amplified subtracted photocurrents is recorded with a spectrum analyzer. PBS, polarization beam splitter; BPD, balanced photodetector; -, subtractor; HWP, half-wave plate; QWP, quarter-wave plate. (b) The Λ three-level scheme in the two channels. The ground states are Zeeman sublevels of $|F = 2\rangle$, and the excited state is $|F = 1\rangle$ of the ^{87}Rb D1 line. The left- and right-circularly polarized control fields in Ch1 and Ch2 drive the dipole transitions $|1\rangle \rightarrow |3\rangle$ and $|2\rangle \rightarrow |3\rangle$, with Rabi frequency Ω_1 and Ω_2 , respectively. The Zeeman splitting Ω_L is induced by a common longitudinal magnetic field, serving as either the Larmor frequency in the noise spectra measurement or the two-photon detuning in the EIT measurement [denoted as δ_B as in Fig. 2(a)]. Fictitious magnetic fields of opposite sign in Ch1 and Ch2 are, respectively, applied to shift the spin waves frequency by $|\Delta_0|$, via additional off-resonant laser beams (not shown). Phase coherence between the two control fields are not required.

inside an antirelaxation coated vapor cell, so-called optical channels. Each undergoes a Λ -type control-probe electromagnetically induced transparency (EIT) to create a collective spin wave ρ_{12} (ground state coherence), which is then dissipatively coupled to each other through atomic diffusion. Since EIT creates a linear mapping between the probe light and the spin excitation, the coupling between the two probe fields in EIT can be described by the effective Hamiltonian for the two spin waves [12]:

$$H = \begin{pmatrix} |\Delta_0| - i\gamma_{12} & i\Gamma_c \\ i\Gamma_c & -|\Delta_0| - i\gamma_{12} \end{pmatrix}, \quad (1)$$

where $|\Delta_0|$ is half the frequency difference between the two spin waves, and Γ_c is the ground-state-coherence coupling rate between the two channels. The off-diagonal coupling term is imaginary due to the random nature of the coherence transfer between the two channels via ballistic motion and wall bouncing of atoms. γ_{12} is the common decay rate of the spin waves. Anti- \mathcal{PT} symmetry breaking occurs at EP where $|\Delta_0| = \Gamma_c$ and the two eigen EIT modes perfectly overlap. In the symmetry-unbroken regime ($|\Delta_0| < \Gamma_c$), the two eigen-EIT resonance centers coincide (but linewidths bifurcate), enabling spin wave synchronization (analogous to synchronization phenomena demonstrated in Refs. [33,34]) and quantum correlation in our experiment. To account for the microscopic nature of this system, we have developed a theoretical model describing spin dynamics inside and outside the optical channels, with Langevin noises [35].

By judiciously designing reversed control-probe EIT configurations in the two channels [Fig. 1(b)], we realize non-Hermitian phase sensitive parametric process, leading to the buildup of quantum correlation from dissipation. In particular, one atomic spin excitation \hat{S}^\dagger is accompanied by a lower sideband photon creation locally in one channel, e.g., Ch1 [see Fig. 1(b)], represented as $\hat{H}_1 \propto \hat{a}_l^\dagger \hat{S}^\dagger + \text{H.c.}$ This excitation then diffuses out to the dark region outside the beam, i.e., the reservoir. When it diffuses to the other channel, e.g., Ch2, with reversed Λ -type EIT polarization configurations, the photon in the upper sideband is scattered along with the annihilation of the same spin excitation, captured by $\hat{H}_2 \propto \hat{b}_u^\dagger \hat{S} + \text{H.c.}$ Thanks to the collective buildup effect along the propagation direction of light [43,44], this two-step interaction results in a two-mode squeezing-type (TMS) optical parametric process $\propto \hat{a}_l^\dagger \hat{b}_u^\dagger + \text{H.c.}$ in stark contrast to previous setups [12,45] where identical polarization configurations in the two channels lead to the dissipative beam-splitter-type (BS) coupling between the two optical probes, and hence no quantum correlation occurs there.

Now we report experimental observation of the non-Hermitian phase-sensitive parametric amplification. We emphasize that the nonlinear optical phenomena here is realized with linear atom-light interaction but with moving atoms serving as effective feedback. First, the EIT spectra were measured with only one channel on. Their centers are offset from each other [Fig. 2(a)] due to the opposite ac Stark shift induced by the orthogonally polarized control beams, which interact off-resonantly with the other upper

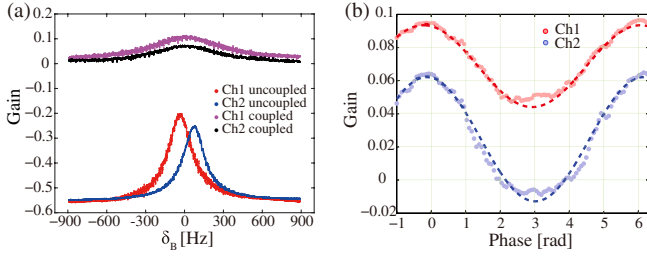


FIG. 2. Non-Hermitian parametric interaction between two weak-probe fields aided by anti- \mathcal{PT} -symmetric coupling of spin waves. (a) Probe gain as a function of two-photon detuning δ_B , proportional to the common magnetic field applied, under coupled (both channels on) and uncoupled (only one channel on) conditions. Here, “Gain” is defined by the ratio of the probes output power and input power (calibrated at output with a far-off-resonance probe of the same input power) minus one. Positive (negative) value of “Gain” stands for gain (absorption). (b) Gain for the two probes changes as the probe’s phase (in radian) in one of the channels is swept. In (a) and (b), the cell temperature is at 40 °C. The lines in (b) are to guide the eye.

excited state [not shown in Fig. 1(b)]. In stark contrast, with both channels on, the dissipative coupling leads to parametric amplification and the overlapping of two EIT spectra. Remarkably, such a behaviour illustrates the synchronization of two spin waves due to atomic motion. Here, the two distant optical (probe) modes play the role of the two different spins in Ref. [33] or different mechanical resonators in Ref. [34], and the collective atomic spin excitation coupling to both modes plays the role of the common cavity mode in Refs. [33,34]. The one-to-one mapping between the optical field and the local spin waves [43] then allows the spin synchronization. Although each channel by itself is linear where the gain of the probe should not appear, here, their opposite control-probe configuration, as well as coupling to a common bath, makes the gain appear. Mathematically, we confirm that the nonlinear parametric process with gain indeed arises from the dissipative coupling in the symmetry unbroken phase [35]. In Fig. 2(b), we verify the phase sensitivity of the gain by only varying the relative phase between the control and probe in one of the channels.

For measurements of quantum noise and correlations, we remove the input probes and let them be the vacuum. Joint polarization homodyne detection [46] is operated to extract the information of the quantum fluctuations in the output probe, as well as the quantum correlations between the two channels [35]. A common bias magnetic field is applied to shift the homodyne measurement from dc to the Larmor frequency, bypassing low frequency technical noises. To characterize the dynamics of quantum correlation between the two channels, Gaussian discord is evaluated via the reconstruction of a bipartite covariance matrix (CM) [47,48] in continuous variables, more resilient to dissipative environments than quantum entanglement. Here,

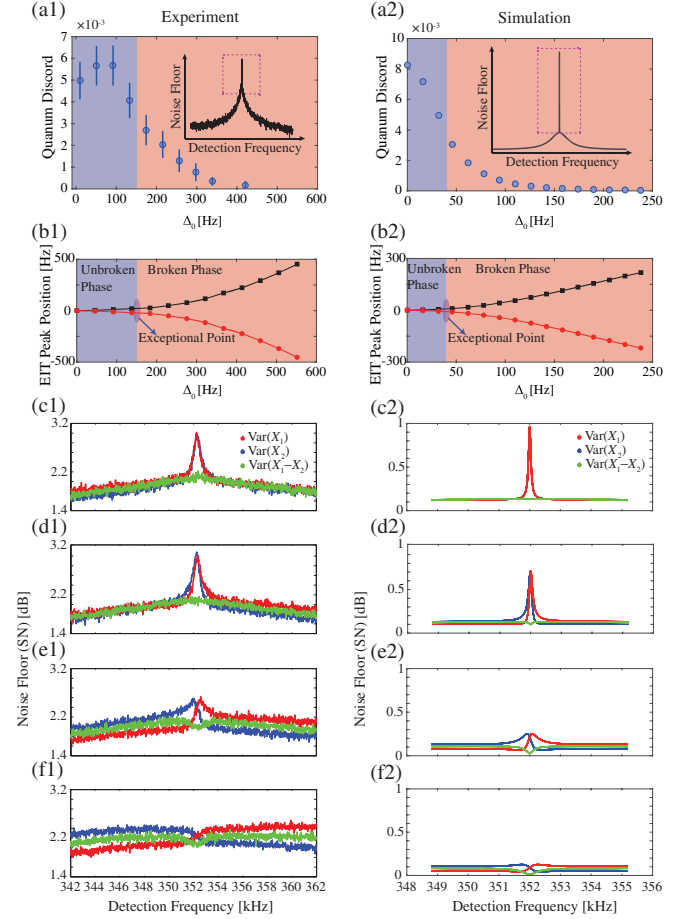


FIG. 3. Discord, EIT separation, and noise spectra at varying $|\Delta_0|$, the frequency offset of both spin waves but towards opposite directions as shown in Fig. 1(b). The left column is experiment and the right is theory result. (a) The discord shown at various $|\Delta_0|$ values. (b) The separately measured EIT peak positions at various $|\Delta_0|$ values. The narrow structure (in dashed box) of the noise spectrum shown in the inset of (a) is displayed in (c)–(f) for sampled $|\Delta_0|$, where the red and blue traces are $\text{Var}(\hat{X}_1)$ and $\text{Var}(\hat{X}_2)$ respectively, and the green is $\text{Var}(\hat{X}_1 - \hat{X}_2)$. They are identical to $\text{Var}(\hat{P}_1)$, $\text{Var}(\hat{P}_2)$, and $\text{Var}(\hat{P}_1 + \hat{P}_2)$, respectively, which are not shown. The experiment noise spectra (c1)–(f1) correspond to the 1st, 3rd, 7th, and 10th point on the discord curve in (a1). The theory noise spectra (c2)–(f2) correspond to the 1st, 3rd, 7th, and 11th point on the discord curve in (a2). The shot noise level is set at 0 dB in both columns, observed when only one channel is on. As expected, when $|\Delta_0|$ increases, the two spin waves are not synchronized, responsible for decreased contrast of the narrow structure. The discord drop is more dramatic near EP, where the EIT separation curve bends. The slight (abnormal) drop in discord for the left two points in (a1) is due to the unwanted optical pumping of the off-resonant beams which changes $|\Delta_0|$ through ac-stark shift. This optical pumping destroys some coherence and slightly decreases the contrast of the noise spectrum, as can be seen from (c1) compared to (d1). The input power of the control in each channel is 700 μW in the experiment. The cell temperature is at 63 °C.

canonical position and momentum operators of the quantum light field can be defined through Stokes operators as $\hat{X} = \hat{S}_x / \sqrt{|S_z|}$ and $\hat{P} = \hat{S}_y / \sqrt{|S_z|}$.

To study the change of quantum discord near EP, we vary the frequency difference of the two spin waves $2|\Delta_0|$ by applying two local fictional magnetic fields of opposite sign [35]. The noise spectra of the vacuum probes and the Gaussian discord at different $|\Delta_0|$ are shown in Fig. 3. A typical noise spectrum [Fig. 3(a) inset] includes a broad feature originating from single pass atom-light interaction, and a sharp peak from multiple returns of atoms back to the beam. This narrow structure is the outcome of the engineered $\hat{a}_i^\dagger \hat{b}_u^\dagger$ parametric process that will contribute to quantum correlation. Measured noise spectra of each channel $\text{Var}(\hat{X}_{1,2})$ and the joint variance $\text{Var}(\hat{X}_1 - \hat{X}_2)$ [identical to $\text{Var}(\hat{P}_{1,2})$ and $\text{Var}(\hat{P}_1 + \hat{P}_2)$, respectively] for four representing $|\Delta_0|$ values are displayed in Figs. 3(c1)–3(f1), accompanied by the theoretically calculated spectra in Figs. 3(c2)–3(f2). Discord is calculated at the Larmor frequency in the noise spectra [35]. Gaussian quantum correlations beyond entanglement can be captured by the measure of Gaussian discord, hence a discord value well above zero indicates the quantum nature of the correlation between the two channels.

Around EP, we observe apparent changes of the Gaussian discord with respect to $|\Delta_0|$. For $|\Delta_0|$ large enough, the phases of the two spin waves are not synchronized, reducing the efficiency of mutual coherence stimulation between the two channels. Consequently, the two noise spectra are offset away from the Larmor frequency, and also become dispersivelike, accompanied by contrast drop and broadening of the narrow peak. These together reduce the discord. When $|\Delta_0|$ is smaller than Γ_c , the system is in the symmetry unbroken regime, and the two spin waves frequencies are pulled together, giving rise to relatively larger discord generated by TMS operation. To verify that the relatively sharp change in discord happens near EP, we independently measured the peak separation between the two channels' EIT with the weak probes on, and found that the separation versus $|\Delta_0|$ curve bends around the region where discord drops fast, which corresponds to $|\Delta_0| \sim \Gamma_c$. The corresponding theoretical curves qualitatively agree with the experiment, although the linewidth of the noise spectra is smaller than those in the experiments, mainly due to the neglect of multi-level effects in the model.

We report the first implementation of non-Hermitian quantum nonlinear optics or photonics in the form of stationary quantum correlations between two distant optical modes, thus making a first step towards experimental quantum studies of non-Hermitian systems with (anti-) \mathcal{PT} symmetry without resorting to single-spin systems [14,49]. By engineering the dissipative coupling of light channels to the common reservoir formed by flying atoms, non-Hermitian phase-sensitive parametric gain and

spin-wave synchronization are achieved. This Letter opens up a new avenue for exploring quantum properties in non-Hermitian photonic systems, with potential applications in quantum information processing and sensing. Due to the tight connection to the ion trap [30] and atomic ensembles [31], this approach could be extended to strongly correlated many-body \mathcal{PT} systems, where a recent study suggested that there exists a novel quantum phase transition without a correspondence in a Hermitian quantum many-body system [50]. Experimental advances towards such directions will facilitate new progress in \mathcal{PT} symmetric quantum science.

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