

Mirror symmetry breaking of superradiance in a dipolar Bose-Einstein condensate

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Dicke superradiance occurs when two or more emitters cooperatively interact via the electromagnetic field. This collective light-scattering process has been extensively studied across various platforms, from atoms to quantum dots and organic molecules. Despite extensive research, the precise role of direct interactions between emitters in superradiance remains elusive, particularly in many-body systems where the complexity of interactions poses significant challenges. In this study, we investigate the effect of dipole-dipole interaction between 18 000 atoms in dipolar Bose-Einstein condensates (BECs) on the superradiance process. In dipolar BECs, we simplify the complex effect of anisotropic magnetic dipole-dipole interaction with Bogoliubov transformation. We observe that anisotropic Bogoliubov excitation breaks the mirror symmetry in decay modes of superradiance.

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Introduction. Collective light scattering [1], a cooperative emission process inducing directional scattered atoms, has been observed in various atomic systems ranging from thermal atoms [2,3], degenerate Bose gases [4–12], and free fermions [13] to atoms coupled to the cavity mode [14–16]. Among them, a Bose-Einstein condensate (BEC) has served as a promising platform for exploring a superradiant light-scattering process owing to its unique coherence property with [4–12,17] and without external light fields [18–21]. When the external light shines on atoms in the condensate, collective scattering of light creates a quasiparticle in the form of recoiling atoms that interfere with condensate atoms at rest, leading to the generation of matter-wave grating that is further enhanced by subsequent light scattering [22]. So far, however, prior studies have primarily focused on a noninteracting regime, leaving the effect of interactions largely unexplored [2,23–25]. This makes it challenging to explore exotic states of matter using light scattering even though fundamental excitations in exotic states are expected to manifest themselves in the light-matter interaction process [26].

In this work, we investigate a superradiance light-scattering process from a dipolar BEC in an elongated trap, in which the mirror symmetry in superradiance is broken due to the dipolar interaction. Here, magnetic dipolar interactions result in anisotropic dispersion of dipolar superfluid [24,25], which allows us to control the asymmetry of superradiant

peaks by changing the direction of the external magnetic field. Such dipolar effects in quantum gases [27] have recently opened up a regime where anisotropic dipole-dipole interactions play a crucial role in realizing new phases of matter, such as quantum droplets and supersolids [27]. Our work demonstrates how fundamental excitations begin to contribute and manifest themselves in light-matter interaction processes.

Experiment. We initiate experiments with a quasi-one-dimensional dipolar BEC of approximately 1.8×10^4 erbium (^{168}Er) atoms in the $|M_J = -6\rangle$ state [28–30]. By aligning the dipole orientation along a specified direction (parallel to an external magnetic field), we excited the ground-state BEC at $|q = 0\rangle$ to an excited state $|e\rangle$ using a largely detuned pump beam. This excited state then decays back to the ground state, acquiring nonzero momentum in the process due to momentum conservation. In a typical condensate without dipolar interactions, this scattering process is amplified along the long axis of the condensate [4–6]. It leads to decay in two opposite directions symmetrically and emits photons with momentum $\hbar k_{583}$, where k_{583} represents the wave vector of the pump beam. As a result of this symmetric light-scattering process, the quasiparticles are created with the momentum of $\sqrt{2}\hbar k_{583}$ along the 45° relative to the long axis of the condensate [see Fig. 1(a)]. We can simplify our model by eliminating the intermediate excited state and considering a two-level system comprising the initial state at $|q = 0\rangle$ and a final state at $|q = \sqrt{2}\hbar k_{583}\rangle$, owing to the relatively large detuning (Δ) of the pump beam compared to the Rabi frequency (Ω) of the driving field and the spontaneous emission rate from $|e\rangle$ to $|q = \sqrt{2}\hbar k_{583}\rangle$.

A distinct feature of a dipolar BEC, as opposed to one with only isotropic contact interactions, is its anisotropic dispersion relation due to dipole-dipole interactions. The elementary anisotropic dipolar Bogoliubov excitation spectrum, $\hbar\omega(q)$,

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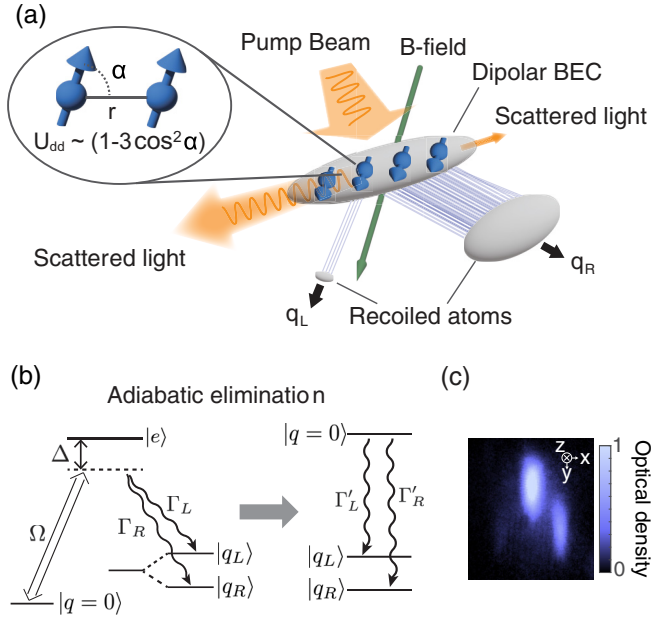


FIG. 1. Mirror symmetry breaking of the superradiance in a dipolar BEC. (a) A quasi-one-dimensional dipolar condensate is exposed to the pump beam propagating along the $+y$ axis. Due to the anisotropic dipolar interaction presented in the dipolar BEC (circular inset), the Bogoliubov excitation spectrum becomes anisotropic, leading to the mirror symmetry breaking for two excitations along the elongated direction of the condensate. As a result, we observe the asymmetric outcoupled atoms after the expansion of the cloud. (b) The superradiance process can be simplified by adiabatically eliminating the intermediate state $|e\rangle$ for a sufficiently large detuning $\delta = 6.6$ MHz, compared to the optical linewidth. Given the anisotropic dispersion spectrum, the two final ground states, $|q_R\rangle$ or $|q_L\rangle$, are shifted in energy with different transition rates. (c) Time-of-flight image of asymmetric superradiant dipolar BEC.

for a uniform density n is expressed as

$$\hbar\omega(q) = \sqrt{E(q)\{E(q) + 2gn[1 + \epsilon_{dd}(3\cos^2\phi - 1)]\}}, \quad (1)$$

where $E(q) = \frac{\hbar^2 q^2}{2m}$ and ϕ is the angle between the external magnetic field and the atomic excitation direction. Here, $g = 4\pi\hbar^2 a_s/m$ with atomic mass m and $\epsilon_{dd} = a_{dd}/a_s$ for the characteristic dipolar length of $a_{dd} = 66.3a_0$. This leads to a broken symmetry in the two end-fire modes, as evident from the asymmetry in their decay rates, $\Gamma'_L \neq \Gamma'_R$ [see Fig. 1(b)]. In consequence, one decay channel becomes dominant in the scattering process, leading to an observed increase in atoms in one of the two collective excitation [see Fig. 1(c)]. To confirm that the observed asymmetric scattering is a collective phenomenon and not typical spontaneous Raman scattering, we measure the dynamic change in the scattering rate of atom decay. In Fig. 2(a), we observe the burst in scattering, which is consistent with quantum Monte Carlo simulations, confirming the distinct collective nature of this interaction. To simulate this behavior, we solve the Lindblad master equation,

$$\dot{\rho}(t) = -\frac{i}{\hbar}[H, \rho(t)] + \sum_i \frac{\Gamma_i}{2} L(\rho), \quad (2)$$

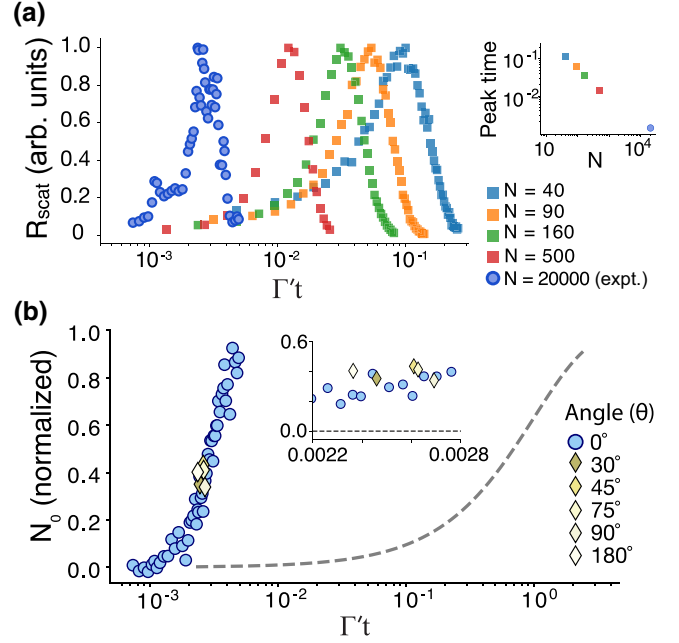


FIG. 2. Collective enhancement of the atom-light scattering in dipolar BEC. (a) Bursts in the Dicke superradiance with the measurement and the simulation. Data is normalized such that the peak R_{scat} are set to 1. Inset shows the time of peak scattering for different numbers of atoms. (b) Change of the ground-state population (N_0) against the change of $\Gamma't$. The dashed line shows the calculated single-atom Raman scattering. N_0 is normalized such that maximum N_0 is 1.

that describes the superradiant decay rate of N atoms with multiple decay modes Γ_i . The decay rate can be estimated by taking the time derivative of the population of the ground state. Assuming two decay modes, Γ_L and Γ_R , the Lindblad equation can be simplified to $\dot{\rho}(t) = \frac{\Gamma_L}{2} L(\rho) + \frac{\Gamma_R}{2} L(\rho)$. We use a quantum Monte Carlo solver in the Quantum Toolbox in PYTHON (QUTIP) [31] to solve this equation.

As more atoms participate in the collective emission process, the peak scattering time advances, as shown in Fig. 2(a) and its inset. In Fig. 2(b), we also confirm enhanced decay to the ground state in asymmetric cases ($\theta = \pi/6, \pi/4$, and $5\pi/12$), indicating superradiance even when mirror symmetry is broken. The ground-state population resulted from the typical spontaneous Raman scattering without collective scattering is provided as a comparison (dashed line).

Mirror-symmetry breaking in superradiance. Next, we examine the mirror-symmetry-breaking mechanism with the statistical analysis of our measurements. In Fig. 3, we characterize a superradiant sample by recording an asymmetry of superradiant peaks. For each condition, we obtain around 170–300 data and plotted a histogram for an asymmetry ratio ($R_{\text{asym}} = \frac{N_R - N_L}{N_R + N_L}$), where N_R (N_L) represents the atom number of the right (left) superradiant peak. When the left (right) atom cloud is dominant, the mean value of the histogram has a negative (positive) value.

Scattering events create two quasi-particle excitations, k_L and k_R , with different angles (ϕ) relative to the external magnetic field, leading to asymmetric decay rates [see Figs. 3(a)

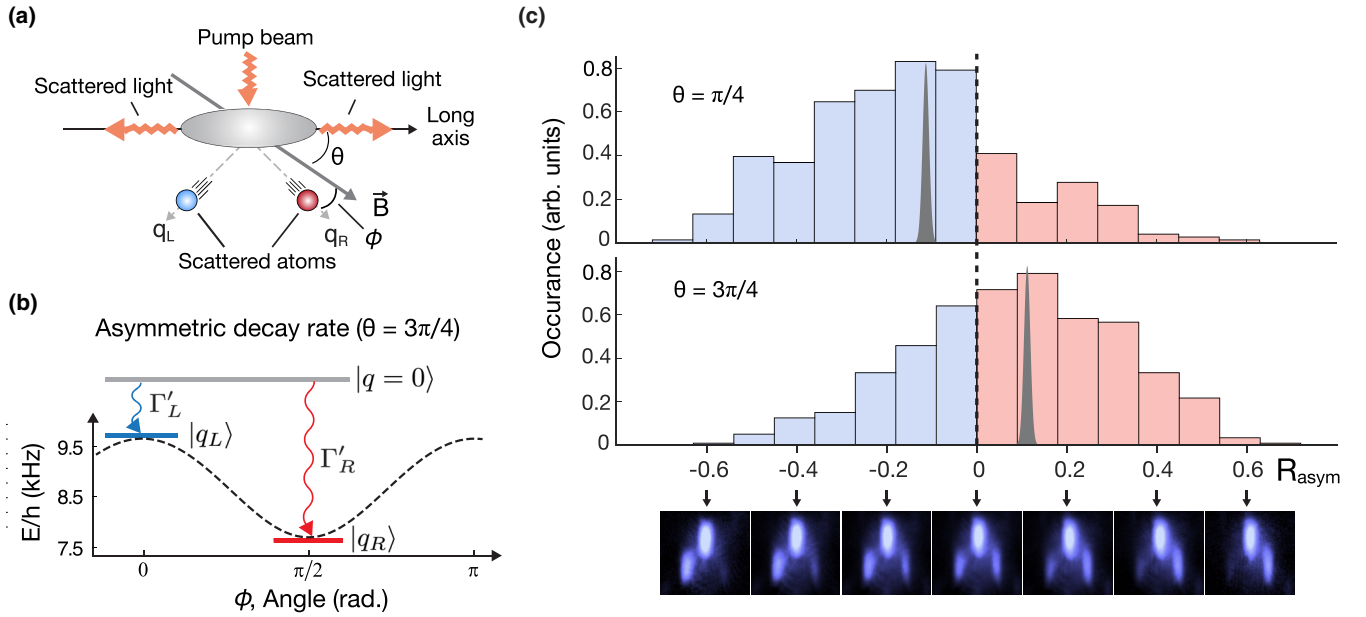


FIG. 3. Experimental demonstration of asymmetric superradiance in a dipolar BEC. (a) Geometry of asymmetric excitation spectrum in experimental setup. Orange arrows represent the pump beam (top) and scattered lights (side). Gray ellipse represents the original dipolar condensate. Blue (red) circle represents the atoms transferred to $|q_L\rangle$ ($|q_R\rangle$) state. (b) This is exemplified by an asymmetric dipolar Bogoliubov excitation spectrum in Eq. (1). At $\theta = \pi/4$, where the decay rates for leftward (Γ'_L) and rightward (Γ'_R) excitations vary because the leftward excitation's energy level $|q_L\rangle$ is higher than that of the rightward excitation $|q_R\rangle$. (c) By counting the number of atoms in $|q_L\rangle$ ($|q_R\rangle$) states for each experimental sequence, the distributions of R_{asym} are obtained for $\theta = \pi/4$ and $3\pi/4$. Blue (red) regime corresponds to q_L (q_R) dominant data. Gray distributions theoretically result from assuming independent light scatterings. (low) Averaged adsorption images after 16-ms time-of-flight for corresponding R_{asym} values are provided.

and 3(b)]. For instance, at $\theta = 3\pi/4$, the decay rate to $|q_R\rangle$ (Γ'_R) is stronger than the decay rate to $|q_L\rangle$ (Γ'_L) since the detuning for the transition from $|q=0\rangle$ to $|q_R\rangle$ is smaller than $|q_L\rangle$. As a result, the population in the q_R mode is predominantly observed [see Fig. 3(c)]. Histograms of the asymmetry ratio R_{asym} from the data in Fig. 3(c) show this dominance. It is important to note that a non-negligible portion of the data exhibits dominant excitation to q_L (q_R) even when $\Gamma'_R > \Gamma'_L$ ($\Gamma'_L > \Gamma'_R$) at $\theta = 3\pi/4$ ($\theta = \pi/4$). This result is due to the stochastic nature of the initial scattering events, which trigger an avalanche-like scattering of the remaining atoms. This outcome aligns with the collective behavior observed in Fig. 2. Similar broken-mirror symmetry in superradiance has recently been studied theoretically in the chiral-waveguide system [32], where a similar wide distribution of R_{asym} is predicted. We note that the theoretical estimation for the chiral-waveguide system expected that peak of the histogram is closer to $R_{\text{asym}} = -1$ or 1. We attribute the difference in our experimental data to several experimental imperfections, such as decoherence or nonuniform distribution of atoms in the dipolar BEC.

Angle dependence of asymmetric superradiance. Lastly, we further examine the angle dependence of symmetry breaking in superradiant scattering by varying the angle of the dipole orientation θ from 0 to $7\pi/4$. Figure 4 depicts the measured periodic oscillation of asymmetry against the change of dipole orientation. To elucidate the effect of magnetic field direction

on superradiance, we keep the Rayleigh scattering rate constant and therefore effectively the gain term of superradiance the same. In our experiment, the end-fire mode always occurs along the x direction regardless of the magnetic field direction. In this case, the spontaneous emission strength along the x direction is sensitive to the quantization direction (i.e., external magnetic field) following the radiation pattern (see the Supplemental Material [33]). Therefore, we calibrate the intensity of the pump beam such that spontaneous emission along the longitudinal direction of the atom cloud remains constant for the different quantization directions. Furthermore, to avoid the shape change of condensate induced by the field direction, we switch on a pump beam immediately after rapidly rotating the magnetic field in less than 0.5 ms.

When the magnetic field is oriented at $\theta = 0^\circ$ or 90° , atomic excitations that involve opposite matter-wave gratings occur with the same strength as ϕ is $\pi/4$ for both cases resulting in $\Gamma_R = \Gamma_L$. The effect of anisotropic dispersion becomes prominent when the magnetic field is aligned to one of the excitation directions (e.g., $\theta = 45^\circ$ or 135°). At $\theta = 45^\circ$, for example, the atomic excitation involving the right superradiant peak (N_R) undergoes stiffer dispersion with a larger excitation resonance frequency (for $\phi = 0$) compared to the left peak (N_L). According to the f -sum rule [34], the excitation involving the increased resonance frequency (i.e., right peak) is relatively more suppressed than the left peak with a smaller resonance frequency with $\Gamma_R \neq \Gamma_L$ (see Fig. 4).

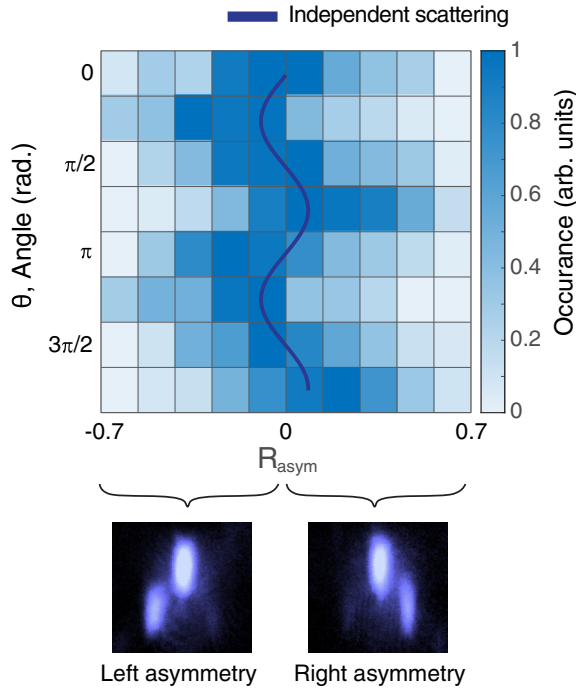


FIG. 4. Observation of asymmetric superradiant peaks. Heat map of distribution of R_{asym} against the change of the orientation of the magnetic dipoles in the dipolar BEC. Solid blue line is obtained from the independent light scattering model for $\Gamma'_L \neq \Gamma'_R$. Distribution of each angle is normalized such that the peak occurrence is set to 1. Momentum distribution of BECs after 16-ms time-of-flight are shown below. Left (right) asymmetric recoiling atoms correspond to the negative (positive) mean value of R_{asym} .

Our work opens an interesting avenue for future experiments. First, when a dipolar condensate is exposed to the pump beam across the BEC to the quantum droplet [35–37], it would be worthwhile to explore how unusual states of matter appear in the process of interaction between light and matter [38]. The coherence property of quantum droplets can be further manifested by the superradiant light scattering. Another intriguing idea is to study how the emission direction can be spontaneously broken with shot-to-shot fluctuation associated with avalanche-like behavior of superradiance [32]. Full characterization of fluctuation may allow us to explore memory effects in the presence of dipolar and/or s -wave interactions [32].

In conclusion, we have explored a superradiant process in a dipolar BEC and explained how magnetic dipolar interactions influence atom-light scattering. The anisotropic dispersion allows us to manage asymmetric superradiant peaks by adjusting the external magnetic field's direction. Future research could explore a superradiant process in an oblate dipolar condensate [39]. This could potentially control the direction of recoiling atoms based on the external magnetic field direction. Another interesting area to explore is collective light scattering in dipolar fermions [40,41] or dipolar molecules [42].

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