

Cavity-mediated collective emission from steady-state subradiance

Corresponding Author: Professor Je-Hyung Kim

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Summary:

In this work, two incoherently pumped quantum dots in an optical cavity are prepared in a steady state which populates a single excitation subradiant state. To certify the steady state subradiance the second order correlation function of the emitted light is measured. When the system is in a state with reduced single particle decay (subradiance) but can decay through a state with enhanced decay (superradiance), then the zero-time second-order light correlation function shows large bunching with $g^{(2)}(0) \gg 2$ as predicted theoretically. Measuring such a super-thermal (i.e. $g^{(2)}(0) > 2$) bunching thus serves as an indirect measure of steady state subradiant behavior. This represents the main result of the work. In the remaining part of the paper, the authors compare the results with a theoretical model, and use this latter to investigate a larger parameter regime inaccessible by their experimental set-up. They conclude with a discussion of the effects of dephasing that leads to a reduction of the super-bunching behaviour and experimentally analyze ways to mitigate it.

Assessment:

This work shows for the first time (to my knowledge) evidence of the preparation of a steady state subradiant state in a system of two incoherently pumped quantum dots. This observation was made possible by the emitters cooperativity established by working close (as compared to previous experiment) to a balanced regime $\kappa \sim g$ thanks to the directed optical cavity used in the experiment.

In my opinion, however, the importance of these results does not go beyond this experimental demonstration. In particular, the physics of two incoherently driven emitters in a cavity can be efficiently simulated (and in certain regime, such as the one of the experiment analytical solution are also available [see Ref. 29]. Hence, the experiment does not demonstrate novel physical effects.

Additionally, there is not enough support to the claim that this represent a first step towards using subradiance for applications in quantum science such as metrology, quantum storage, etc.

First, steady state subradiance is only indirectly demonstrated through the large bunching behaviour. The authors mention that subradiance would allow, after switching off the pump, to store the excitation for long time. Could this be demonstrated directly in their experiment?

Second, according to the author's simulations (Supplemental Information) the population in the subradiant state is significant only in the weak pump regime (Fig.S3a). In that case, however, the population is less than half of the total system population in the steady state, and hence the subradiant state preparation fidelity is small. This limits the efficiency of several protocol relying on subradiance.

Third, for quantum storage it is necessary to map a specific quantum state into a long-lived excitation and to later retrieve it. This requires a careful control that has been recently demonstrated for superconducting qubits in Nat. Phys. 18, 538 (2022) (probably should be cited). I do not clearly see how steady state subradiance via incoherent driving can be complemented with such control to store and retrieve a quantum state with high fidelity. Do the authors have an particular application in

mind?

Suggested improvements:

In the last part of the work, a method to suppress dephasing is presented. Dephasing is known to be detrimental for subradiance for several applications, hence any method to mitigate is potentially useful. To suppress its effects, the authors vary the driving wavelength to produce above band, below band, and resonant excitations. They show an enhanced bunching for below band excitation, and conclude that this occurs because of reduced dephasing. I do not understand why dephasing is suppressed in this case. Is there a physical intuition behind this? Maybe, it is known but I ignore this effect. In any case, it would be useful to give the reader a better understanding of this phenomenon especially given its importance both for the super-thermal bunching reported in the paper, and for potential application of subradiance states.

Methodology:

- I think the methodology is sound and the experimental procedure are clearly explained.

References:

I believe some references are currently missing and should be included:

The authors mention “previous studies” (line 54) but do not refer to any in particular. What previous studies? The most relevant/recent ones should be cited to give context. For instance, Jahnke et al Nat Comm. 7 11540 (2016) is closely related as they also measure g^2 in different regime (antibunched, thermal, and super-thermal) with a pulsed scheme.

On applications of subradiance, PRX 7 031024 (2017) should probably be mentioned, as well as the paper Nat. Phys. 18, 538 (2022).

Decision:

I think the experiment shows a substantial improvement in the experimental control of two quantum dots in a cavity. In particular, it is able to clearly show the large bunching behaviour attributed to steady state subradiance of two emitters. However, as interesting as these technical advantages are, I do not find the result having a strong resonance beyond the demonstration of such effects. For the reasons I listed above, I also do not see how the steady state subradiance could be used for applications in quantum metrology and quantum memory. Based on these arguments, I do not recommend publication of this work in Nature Communication.

Reviewer #2

(Remarks to the Author)

In the manuscript by Kim et al., the authors present an experimental investigation of CBG cavity-mediated subradiance between multiple InAs quantum dots (QDs) through the photon statistics of emitted light field. The work validates the previous theoretical prediction (e.g., [Phys. Rev. Research 6, 023207 (2024)]) that the establish of subradiance between correlated quantum emitters will give rise to bunched photons emission, thus is important and timely in the field of quantum optics. The results are also valuable to understand the fundamental physics process of quantum light-matter interaction as well as build the on-chip quantum devices such as quantum light sources. While this study is of great significance, there are several major concerns that should be addressed.

1. Figure 3h shows the theoretical $g^{(2)}(0)$ of different numbers of QDs, however, the experimental details confirming the number of QDs are unclear. I did not find any image profile around the center of the CBG cavity for characterizing the spatial distribution and emission features of the ensemble of QDs, as those shown in, e.g., [Nat. Photon. 18, 318 (2024)] and [Nat. Commun. 15, 9509 (2024)]. This is the crucial evidence for an experimental study to elucidate the physical origin of $g^{(2)}(0)$.
 2. On page 5, the authors said that “At $\delta=320\text{GHz}$, the photon correlation curve exhibits an antibunching curve with $g^{(2)}(0)\sim 0.5$, indicative of two independent QDs in a spectrally detuned cavity.” If it is the case of two independent QDs, I expect that $g^{(2)}(0)\sim 0.5$ for $\delta>320\text{GHz}$, as the author claimed. Can the authors show the experimental evidence of $g^{(2)}(0)\sim 0.5$ for any $\delta>320\text{GHz}$?
 3. On page 9, the authors claimed that the order-of-magnitude reduction of experimental $g^{(2)}(0)$ (3.27 compared to 54 of the theoretical value) is because of the dephasing, by varying the excitation wavelength. It is not the direct evidence that the $g^{(2)}(0)$ is reduced by dephasing, as the single-photon blockade can also lead to the variation of $g^{(2)}(0)$. The dephasing and spontaneous emission rates of QDs should be directly characterized and compared the corresponding $g^{(2)}(0)$ with experimental reported values.
 4. On the page 8, the authors defined a cooperativity parameter, however, it is very confusing since it is dubbed “cooperativity” but defined through the quantum correlations between QDs.
 5. In the bad-cavity regime and the case of two QDs, the expressions of steady-state density matrix and $g^{(2)}(\tau)$ can be analytically obtained. It might be helpful to analyze the experimental results through the analytical expressions.
 6. The reference list does not comprehensively reflect the recent advancements of correlated emissions between QDs. Including additional relevant references could make the bibliography more comprehensive and useful for readers. Moreover, citing these works would situate this manuscript within a broader context of related studies.
- With the above concerns to be addressed, I believe the work is suitable for the publication of Nature Communications, as it presents the unambiguous experimental evidence of quantum correlations between two quantum emitters.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I am content with the revised manuscript submitted by the authors and to their reply to my concerns.

I see more clearly now the fundamental importance of these experimental results in the context of accessing collective subradiance; especially in relation to previous experimental work.

I remain skeptical about the practical application of this method and set-up for quantum technologies. While I see the possibility to use this method to generate non-classical light, successful applications in metrology would require to consider other figures of merit (e.g. repetition rate, quality of the state that is produced etc) and a comparison with existing methods. Similarly, for other applications mentioned by the authors. However, I concur with the authors that such a discussion is beyond the scope of the article. Furthermore, in the new version of the manuscript this part is tuned down in favor of better contextualization of the results and focus on fundamental physics. I think this make the message of the paper clearer and more compelling. I thus think the current version of the manuscript could be published in Nature Communication.

I just have a few minor concerns for the authors to consider:

- It would be good if the author gave a definition of “cooperative parameter” in the abstract. This is important as “cooperative parameter” is a technical term that can be confused with the much more broadly known “cavity cooperativity”, also labelled by “C”. The similarity of these two terms could lead to confusion as also pointed out by referee two. I thus suggest to explicitly mention what “cooperativity parameter” stands for in the abstract and, in the main text, highlight that this should not be confused with the cavity cooperativity.
- In line 267, I would write $P=0.1g$ instead of just 0.1g, for greater clarity.
- There are some odd phrasing in a few passages in the paper, but I think this could be corrected during publication.

Reviewer #2

(Remarks to the Author)

In the revised manuscript by Kim et al., the authors have carefully addressed my concerns. I support the publication with only two suggestions for the authors:

- 1) The newly added results and discussions of Supplementary Sections 11 should be given in the main text;
- 2) While the physical mechanism presented in this work is clear and solid, the potential quantum applications should be discussed even the authors have not experimentally demonstrated in the current study.

made.

In cases where reviewers are anonymous, credit should be given to 'Anonymous Referee' and the source.

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Dear editors and reviewers,

We would like to thank the editors for the consideration of our manuscript, now titled “**Cavity-mediated collective emission from steady-state subradiance.**” Also, we would like to thank the reviewers for helpful comments and suggestions. We have revised our manuscript to address the comments with responses to each comment as below. In the revised manuscript and supplementary material, we have marked the correction in red.

Reviewer #1

This work shows for the first time (to my knowledge) evidence of the preparation of a steady state subradiant state in a system of two incoherently pumped quantum dots. This observation was made possible by the emitters cooperativity established by working close (as compared to previous experiment) to a balanced regime $\kappa \sim g$ thanks to the directed optical cavity used in the experiment.

In my opinion, however, the importance of these results does not go beyond this experimental demonstration. In particular, the physics of two incoherently driven emitters in a cavity can be efficiently simulated (and in certain regime, such as the one of the experiment analytical solution are also available [see Ref. 29]. Hence, the experiment does not demonstrate novel physical effects. Additionally, there is not enough support to the claim that this represent a first step towards using subradiance for applications in quantum science such as metrology, quantum storage, etc.

We thank the reviewer for the insightful comment. While superradiance has been extensively studied both theoretically and experimentally across various quantum emitters, such as atoms and quantum dots, our work presents the first experimental access to steady-state subradiance through cavity-mediated interactions with incoherent pumping. Until now, this regime has remained purely theoretical, with no prior experimental realization. **Implementing theoretical predictions into real-world, controlled experiments is a critical step in advancing scientific understanding.** It not only validates theory but also provides a realistic platform for exploring various regimes. Furthermore, previous studies on subradiance have primarily reported partially slowed decay in pulsed regimes, which do not clearly show the boundary of collective effects and make it difficult to quantify cooperativity. In contrast, our work investigates subradiance through photon statistics for the first time to probe such a system. Our approach offers a more fundamental and quantitative perspective on the nature of the subradiant state. In this context, we respectfully argue that our work is not just a demonstration of existing theory and numerical simulation but represents a significant milestone that establishes an experimental approach for exploring subradiance and its rich physics, paving the way for intriguing phenomena and future applications.

Regarding the second concern raised by the reviewer, we agree that the realization of practical applications is an important long-term goal. Potential applications in metrology and quantum storage can be motivated by the suppressed decay rate and enhanced photon correlations (i.e., large bunching signals) that are important characteristics of steady-state subradiance. While such possible applications have been theoretically proposed and experimentally demonstrated in coherent regimes, e.g., atomic ensembles under coherent control, they remain largely unexplored experimentally in the context of incoherent control. In our study, we experimentally observe, for the first time under incoherent control, a significantly elongated single-photon decay time along with strong photon bunching signals. At this early stage, **our primary focus**

is to demonstrate the physical feasibility of accessing and controlling steady-state subradiance using our new approach, rather than directly linking our results to specific applications. We believe that establishing such a platform is a critical prerequisite for future applications.

We have now clarified this perspective in the revised manuscript with a range of additional experimental and simulation data with further analysis and discussion. In addition, we have changed the title of the manuscript to “Cavity-mediated collective emission from steady-state subradiance” which more clearly reflects the main achievement of our work.

1. First, steady state subradiance is only indirectly demonstrated through the large bunching behaviour. The authors mention that subradiance would allow, after switching off the pump, to store the excitation for long time. Could this be demonstrated directly in their experiment?

We thank the reviewer for the helpful suggestion. The strong bunching signal is theoretically expected as an important signature of steady-state subradiance. To investigate how this feature changes under different experimental conditions, we **systematically conducted a range of experiments, such as varying the cavity detuning to modify the coupling strength g and changing the excitation wavelength to alter emitter dephasing or the number of emitters coupled to the cavity.** Additionally, we have now included results **showing the temperature dependence and cases involving two quantum dots with larger detuning** in Supplementary Sections 4, 5, and 9. **This diverse set of measurements effectively reveals the underlying nature of steady-state subradiance,** and they are also well-supported by simulations, offering a comprehensive understanding of the rich phenomena enabled by subradiant interactions.

Regarding excitation storage, the storage and retrieval of quantum states have indeed been experimentally demonstrated in atomic systems (Phys. Rev X 11.021031 (2021)). In our study, together with a strong bunching signal, **we observed a significantly suppressed single-photon decay time** in a subradiant state by a factor of 400 compared to that of a cavity-coupled single QD. **This long-lived, non-decaying state is a prerequisite for storing the excitation.** However, extending the first experimental demonstration of steady-state subradiance to the actual implementation of such storage and retrieval requires additional capabilities in system design, state preparation, and control protocols, which are beyond the scope of the present demonstration. We, therefore, consider this as a promising direction for future work and plan to explore it as a follow-up to the present study.

2. Second, according to the author’s simulations (Supplemental Information) the population in the subradiant state is significant only in the weak pump regime (Fig.S3a). In that case, however, the population is less than half of the total system population in the steady state, and hence the subradiant state preparation fidelity is small. This limits the efficiency of several protocol relying on subradiance.

We thank the reviewer for the insightful comments.

One of the most important aspects of **cavity-mediated subradiance is an effective extension of the accessible excitation power regime,** and the effect of the subradiance becomes maximal when the cavity dissipation rate is balanced with the coupling strength. In the absence of a cavity, the subradiant regime only exists under extremely weak pumping conditions, while with

the balanced cavity, the weak pumping region extends to pumping power on the order of $0.1g$ (g is the cavity-emitter coupling strength), corresponding to 60% saturation power of the quantum dots used in our experiment. **This mechanism enables us to successfully address steady-state subradiance, which was previously inaccessible** under conventional conditions. We have clarified and emphasized this point more explicitly in the revised manuscript. (Page 9).

As the reviewer points out, the population of the subradiant state is limited to at most half under current conditions. We agree that this limitation may restrict the direct use of subradiance prepared via incoherent pumping for certain practical applications. However, steady-state subradiance under incoherent pumping exhibits a uniquely strong bunching effect, which does not occur in the coherent pumping scheme. This collective emission could envision alternative applications such as a source of strong nonclassical light for quantum metrology (A. Karsa et al., Quantum Sci. Technol. **9**, 035042 (2024)) and spectroscopy (Q. Bin et al., Phys. Rev. A **97**, 043802 (2018)). **We believe the significance of our work extends beyond specific use cases and will inspire further research in this field. We have added a discussion on broader applications in the manuscript (Page 12).**

3. Third, for quantum storage it is necessary to map a specific quantum state into a long-lived excitation and to later retrieve it. This requires a careful control that has been recently demonstrated for superconducting qubits in Nat. Phys. **18**, 538 (2022) (probably should be cited). I do not clearly see how steady state subradiance via incoherent driving can be complemented with such control to store and retrieve a quantum state with high fidelity. Do the authors have an particular application in mind?

We thank the reviewer for the constructive comment. As noted above, the long-lived state and strong bunching emission observed in our study present promising quantum resources for applications such as quantum illumination and quantum metrology. The fact **we can address subradiance using simple incoherent pumping, instead of previous precise coherent control, would be a strong advantage of this approach. This accessibility significantly lowers the experimental complexity** for realizing collective quantum effects.

While the continuous generation of strong collective emission remains valuable for quantum metrological tasks, the direct use of incoherently prepared subradiance for quantum storage could be challenging due to limited fidelity and lack of coherence. This suggests that alternative approaches, possibly involving hybrid or coherently driven schemes, would be required to realize quantum storage functionalities. In this context, **we consequently suggest that coherently prepared subradiance may be more suitable for storing excitations, while incoherently pumped subradiance is beneficial for generating highly correlated photon emissions.**

In the revised manuscript, **we have added references to previous demonstrations of subradiance in coherently driven schemes such as superconducting qubits and atomic ensembles** (M. Zanner et al., Nat. Phys. **18**, 538-543 (2022) and G. Ferioli et al., Phys. Rev. X **11**, 021031 (2021)) and discussed the key different advantages between incoherent and coherent excitation schemes in Conclusion part.

Suggested improvements:

In the last part of the work, a method to suppress dephasing is presented. Dephasing is known to be detrimental for subradiance for several applications, hence any method to mitigate is potentially useful. To suppress its effects, the authors vary the driving wavelength to produce above band, below band, and resonant excitations. They show an enhanced bunching for below band excitation, and conclude that this occurs because of reduced dephasing. I do not understand why dephasing is suppressed in this case. Is there a physical intuition behind this? Maybe, it is known but I ignore this effect. In any case, it would be useful to give the reader a better understanding of this phenomenon especially given its importance both for the super-thermal bunching reported in the paper, and for potential application of subradiance states.

We thank the reviewer for questioning this important aspect. In contrast to atoms or ions trapped in a vacuum, solid-state quantum emitters can be effectively excited with non-resonant pumping since various interactions and scattering with phonons and other carriers exist in solid-state systems (R. Ferreira and G. Bastard, Appl. Phys. Lett. **74**, 2818 (1999), G. A. Narvaez et al., Phys. Rev. B **74**, 075403 (2006), and K.-Y. Kim et al., APL Photonics **6**, 080801 (2021)). Therefore, **non-resonantly excited excitons undergo complex recombination dynamics, which causes significant dephasing**. This dephasing becomes particularly enhanced when we use above-band excitation. The source of dephasing can be minimized by getting the laser wavelength shifts to the emitters' wavelength. This is a standard approach for increasing the coherence properties of QD emission (T. Huber et al., New J. Phys. **17**, 123025 (2015) and N. Tömm et al., Nat. Nanotechnol. **16**, 399 (2021)).

To verify this, **we have added an enhanced coherence time from two-photon interference data with different excitation wavelengths** in Supplementary Section 10 and have also added the temperature dependence of the subradiant bunching signal in Supplementary Section 9.

Methodology:

I think the methodology is sound and the experimental procedure are clearly explained.

We thank the reviewer for the positive feedback regarding our methodology.

References:

I believe some references are currently missing and should be included:

The authors mention “previous studies” (line 54) but do not refer to any in particular. What previous studies? The most relevant/recent ones should be cited to give context. For instance, Jahnke et al Nat Comm. **7** 11540 (2016) is closely related as they also measure g^2 in different regime (antibunched, thermal, and super-thermal) with a pulsed scheme.

On applications of subradiance, PRX **7** 031024 (2017) should probably be mentioned, as well as the paper Nat. Phys. **18**, 538 (2022).

Regarding the references, we appreciate the suggestions. To provide better context for our study and to situate it within the broader field, **we have added relevant discussion with references**, including the above ones, to the revised manuscript (Page 2 and Page 12).

Decision:

I think the experiment shows a substantial improvement in the experimental control of two quantum dots in a cavity. In particular, it is able to clearly show the large bunching behaviour attributed to steady state subradiance of two emitters. However, as interesting as these technical advantages are, I do not find the result having a strong resonance beyond the demonstration of such effects. For the reasons I listed above, I also do not see how the steady state subradiance could be used for applications in quantum metrology and quantum memory. Based on these arguments, I do not recommend publication of this work in Nature Communication.

We appreciate the reviewer's positive evaluation of our work that a substantial improvement has been made in the experiment controlling two incoherently driven emitters in a cavity. However, the reviewer has raised concerns regarding the immediate applications of our system alongside the observed effects. For their concern, we would like to emphasize that the first experimental realization of such a system represents a significant milestone in itself. Importantly, **the value of our work goes beyond simply confirming existing theories or simulations—it establishes a novel and versatile experimental platform for exploring subradiant behaviors under well-designed and engineered conditions**, potentially opening the door to experimental investigation of new phenomena that may not be fully accessible through theory alone. Moreover, we expect that our approach will also **inspire further research across a range of quantum systems, such as color centers and atoms with engineered cavity interactions**. In this context, **our work is not just a demonstration of known effects but rather an essential foundational step that makes future advances possible in an area that, until now, lacked experimental realization**.

Reviewer #2

In the manuscript by Kim et al., the authors present an experimental investigation of CBG cavity-mediated subradiance between multiple InAs quantum dots (QDs) through the photon statistics of emitted light field. The work validates the previous theoretical prediction (e.g., [Phys. Rev. Research 6, 023207 (2024)]) that the establish of subradiance between correlated quantum emitters will give rise to bunched photons emission, thus is important and timely in the field of quantum optics. The results are also valuable to understand the fundamental physics process of quantum light-matter interaction as well as build the on-chip quantum devices such as quantum light sources. While this study is of great significance, there are several major concerns that should be addressed.

We appreciate the reviewer for their thorough and encouraging evaluation of our work. Below, we address the specific concerns raised, and we have revised the manuscript accordingly to clarify and strengthen the presentation of our results.

1. Figure 3h shows the theoretical $g^{(2)}(0)$ of different numbers of QDs, however, the experimental details confirming the number of QDs are unclear. I did not find any image profile around the center of the CBG cavity for characterizing the spatial distribution and emission features of the ensemble of QDs, as those shown in, e.g., [Nat. Photon. 18, 318 (2024)] and [Nat. Commun. 15, 9509 (2024)]. This is the crucial evidence for an experimental study to elucidate the physical origin of $g^{(2)}(0)$.

We thank the reviewer for pointing out the importance of experimentally confirming the number of QDs within our cavity. To address this, **we have added several experimental evidence** in Supplementary Sections 2–5 as follows.

First, a comparison of spectral linewidths shows that **the two-QD sample exhibits broader emission lines** than that of a single QD, further supporting the presence of multiple QD transitions (Supplementary Section 2).

Second, **we now present confocal mapping of spatially overlapped two QDs**. In comparison, an isolated single-QD sample, characterized by ($g^{(2)}(0) \approx 0$), exhibits a circularly symmetric spatial profile. In contrast, the sample exhibiting collective effects displays a distorted elliptical profile, indicative of partial spatial overlap between multiple QDs. By suppressing the collective effects through cavity detuning, we observe $g^{(2)}(0) \approx 0.5$, indicating that the system consists of two QDs (Supplementary Section 3).

Third, a reduction of collective behavior has been presented from **two QDs with different amounts of spectral detunings** (Supplementary Sections 4 and 5).

Taken together, **these comprehensive experimental characterizations conclusively confirm that two QDs are coupled to the cavity in our experiment.**

2. On page 5, the authors said that “At $\Delta=320\text{GHz}$, the photon correlation curve exhibits an antibunching curve with $g^{(2)}(0)\sim 0.5$, indicative of two independent QDs in a spectrally detuned cavity.” If it is the case of two independent QDs, I expect that $g^{(2)}(0)\sim 0.5$ for $\Delta>320\text{GHz}$, as the author claimed. Can the authors show the experimental evidence of $g^{(2)}(0)\sim 0.5$ for any $\Delta>320\text{GHz}$?

We thank the reviewer for the constructive comment. Instead of further increasing the cavity

detuning, due to the limitation of gas tuning, **we conducted a separate photon correlation measurement using two spectrally detuned QDs, which more clearly represent two independent QDs.** As expected for independent emitters, the result showed a similar value of $g^{(2)}(0) \approx 0.5$. We have added the discussion and the experimental result in Supplementary Section 5.

3. On page 9, the authors claimed that the order-of-magnitude reduction of experimental $g^{(2)}(0)$ (3.27 compared to 54 of the theoretical value) is because of the dephasing, by varying the excitation wavelength. It is not the direct evidence that the $g^{(2)}(0)$ is reduced by dephasing, as the single-photon blockade can also lead to the variation of $g^{(2)}(0)$. The dephasing and spontaneous emission rates of QDs should be directly characterized and compared the corresponding $g^{(2)}(0)$ with experimental reported values.

We appreciate the reviewer's thoughtful suggestion. In our experiment, the use of incoherent pumping eliminates the influence of single-photon blockade, which typically arises under coherent excitation. **To support this, we have now provided additional evidence in Supplementary Section 10 by demonstrating the variations in measured coherence times with the excitation wavelength through two-photon interference experiments.** Additionally, we conducted **temperature-dependent experiments and observed that the bunching feature rapidly disappears** with increasing temperature due to enhanced dephasing, presented in Supplementary Section 9.

To further investigate the role of dissipative processes, we parametrized relevant system, including dephasing and spontaneous emission rates. The spontaneous emission rate is measured via time-resolved photoluminescence measurement under above-band pumping, and the coherence times are measured by implementing Hong-Ou-Mandel experiments under above-band pumping condition. Incorporating these experimentally determined parameters into numerical simulation, **we have achieved good quantitative agreement between experimental and theoretical $g^{(2)}(0)$ values,** as detailed in Supplementary Section 11.

4. On the page 8, the authors defined a cooperativity parameter, however, it is very confusing since it is dubbed "cooperativity" but defined through the quantum correlations between QDs.

We thank the reviewer for pointing out the potentially confusing expressions. In the references (A. Auffèves et al., New J. Phys. 13, 093020 (2011) and E. Mascarenhas et al., Phys. Rev. A 88, 063825 (2013)), the term "the cooperativity parameter" is used to quantify the collective behavior of the system. **To avoid ambiguity with the more common definition of "cooperativity" used in cavity-QED, we have corrected "cooperativity" into "cooperativity parameter" in the manuscript.**

5. In the bad-cavity regime and the case of two QDs, the expressions of steady-state density matrix and $g^{(2)}(\tau)$ can be analytically obtained. It might be helpful to analyze the experimental results through the analytical expressions.

We thank the reviewer for the helpful comment. For further study, **we have added a discussion about the analytical solutions of the steady-state density matrix and the second-order coherence function $g^{(2)}(\tau)$ at certain regimes in Supplementary Section 11.**

6. The reference list does not comprehensively reflect the recent advancements of correlated emissions between QDs. Including additional relevant references could make the bibliography more comprehensive and useful for readers. Moreover, citing these works would situate this manuscript within a broader context of related studies.

We thank the reviewer for the suggestion. **We have added recent references on correlated emissions between QDs to offer a more comprehensive view** for readers and appropriately recognize previous studies.

Dear editors and reviewers,

We are grateful to the editor and reviewers for their support of the publication. We have revised our manuscript based on the final recommendations as below.

Reviewer #1

I am content with the revised manuscript submitted by the authors and to their reply to my concerns.

I see more clearly now the fundamental importance of these experimental results in the context of accessing collective subradiance; especially in relation to previous experimental work.

I remain skeptical about the practical application of this method and set-up for quantum technologies. While I see the possibility to use this method to generate non-classical light, successful applications in metrology would require to consider other figures of merit (e.g. repetition rate, quality of the state that is produced etc) and a comparison with existing methods. Similarly, for other applications mentioned by the authors. However, I concur with the authors that such a discussion is beyond the scope of the article. Furthermore, in the new version of the manuscript this part is tuned down in favor of better contextualization of the results and focus on fundamental physics. I think this make the message of the paper clearer and more compelling. I thus think the current version of the manuscript could be published in Nature Communication.

We appreciate the positive comments and support regarding our revised manuscript.

I just have a few minor concerns for the authors to consider:

- It would be good if the author gave a definition of “cooperative parameter” in the abstract. This is important as “cooperative parameter” is a technical term that can be confused with the much more broadly known “cavity cooperativity”, also labelled by “C”. The similarity of these two terms could lead to confusion as also pointed out by referee two. I thus suggest to explicitly mention what “cooperativity parameter” stands for in the abstract and, in the main text, highlight that this should not be confused with the cavity cooperativity.

We have clarified the term of “cooperativity parameter” in both abstract and main text.

- In line 267, I would write $P=0.1g$ instead of just $0.1g$, for greater clarity.

We have clarified it (Page 9).

- There are some odd phrasing in a few passages in the paper, but I think this could be corrected during publication.

We have carefully reviewed the manuscript and corrected any awkward phrasing in the manuscript.

Reviewer #2:

In the revised manuscript by Kim et al., the authors have carefully addressed my concerns. I support the publication with only two suggestions for the authors:

We appreciate the reviewer's support for the publication of our manuscript and for the additional constructive comments provided.

1) The newly added results and discussions of Supplementary Sections 11 should be given in the main text;

Now we have properly referred to Supplementary Sections 11 in the main text.

2) While the physical mechanism presented in this work is clear and solid, the potential quantum applications should be discussed even the authors have not experimentally demonstrated in the current study.

Potential quantum applications of steady-state subradiance, including photon-statistics dependent spectroscopy, nonlinear interaction at the few-photon level, and quantum-enhanced energy harvesting, are introduced and discussed in the discussion session.