

Strong coupling of a microwave photon to an electron on helium

Corresponding Author: Professor Johannes Pollanen

This manuscript has been previously reviewed at another journal. This document only contains information relating to versions considered at Nature Physics.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors present a study of electron charge qubits trapped on the surface of superfluid helium using a quantum dot nanostructure and coupled to a microwave resonator. By using a novel high-impedance resonator design recently developed by some of the same authors, they obtain strong coupling between the motional states of the electron charge qubit and the microwave photons. They verify the presence of strong coupling using both spectroscopy of the resonator as well as two-tone electron charge state spectroscopy. Lastly, they use the strong coupling to study the decoherence properties of the electron charge qubit and find pure dephasing as the limiting decoherence mechanism, whereas population decay occurs at an approximately two orders of magnitude lower rate.

While the electron on helium qubit platform and the coupling to microwave resonators have already been demonstrated in recent years, this work marks the first demonstration of strong coupling in this qubit platform – a crucial milestone for practical applications in quantum computing. The precise control of the electron charge state and the authors' deep understanding of the device physics via finite-element modelling (Fig 1e,f) is remarkable and demonstrates the systems capabilities as a viable platform for quantum computing. These demonstrated features uniquely distinguish this platform from similar approaches such as semiconductor quantum dots, making this work relevant to a wide range of research in both applied quantum technologies, but also for more fundamental studies in cavity QED based on complex engineered quantum systems. The investigation of decoherence mechanisms in this relatively new qubit platform will be crucial to realizing its full potential and this work presents a significant advance towards this direction. The manuscript is well written, appropriately referenced and of excellent technical quality, including its extensive Supplementary Information. For the above reasons I recommend publication of this work in Nature Physics.

However, I have several comments and suggestions for improvements of the manuscript:

- The authors should discuss whether there are ways in future studies to distinguish the decoherence induced by the ripplon field from the stray charges.
- In addition, are there any numerical estimates for the amount of stray charges present in the device and simulations for their impact on electron decoherence?
- On the same note, it seems that more negative voltage offsets ΔV would be highly beneficial as they significantly reduce the decoherence rate, however, ΔV is currently limited by electron loss at strongly negative ΔV . Do the authors expect further improvements of the decoherence rate by enabling more negative ΔV through optimized designs of the quantum dot geometry or is there any more fundamental limitation?
- In Figure S1 in the Supplementary Information, it would help to add a visual legend labelling which color in the figure corresponds to which material.
- In the Supplementary Information Section 7, the authors find that when the charge qubit and microwave resonator are off-resonant, the qubit lifetime T_1 is still significantly shorter than the Purcell-limited lifetime. Through a combination of an analytical model and FEM, the authors attribute this discrepancy to electron decay through other electrodes, which seems reasonable. Are there any practical implications of this observation in terms of future device design considerations to increase the qubit lifetimes?

In addition to these comments, there are a few minor typos in the manuscript:

- In the main text, in the beginning of the section "Single electron strong coupling": In the sentence '[...] we observe large

frequency shifts exceeding several resonator linewidths that appear when the electron motion approaches that of the [...] would better be [...] we observe large frequency shifts exceeding several resonator linewidths that appear when the frequency of the electron motion approaches that of the [...].

- In the Supplementary Information, beginning of caption of Figure S5: "elative" should be "relative".

Reviewer #2

(Remarks to the Author)

In the manuscript "Strong coupling of a microwave photon to an electron on helium", the strong coupling regime between a microwave photon and the motional state of a single electron on helium is demonstrated. Also single-electron control. This is an important step in the advancement of electron on He-based quantum and hybrid processors, and this work contains the first demonstration. Therefore, the work is novel and relevant.

The presentation and quality of the data, text and figures is very high. And every claim is backed up with explanations, nicely presented theory and extra data in the Supplemental Material and Methods. Here a list of questions/comments that came up while reading, so possibly points for improvement:

- Figure 1: In panel d), the potential minima (or less negative) seems to lie at positive x values, where the yellow circle is represented. However, in panel e), in the inset, the minima are at negative x values. What is the chosen V_r - V_u set in panel d) that makes this so different? And wouldn't it be better to choose a set like the ones in panel e)?

- Figure 2: I am not understanding why in panel e) from Fig. 1 the values of V_r and V_u change together, while in Fig. 2 a) the values of these two voltages are very different (more than a factor of 2). I am not able to navigate the density plot in Fig. 2 a) at the same time as I follow the info about the number of electrons shown in Fig. 1 e).

- In Fig. 3, and the text in section "Electron charge state spectroscopy", I don't see exactly what the definition of ΔS_{21} is. Difference with respect to what? I say this because the text mentions a "decrease of readout signal when ω_d is resonant with the electron motional state transition", but such decrease would be blue color in Fig. 3 b), however the 2 resonance points correspond to white of the colormap. I may be understanding it wrong, but that must mean that it is not clear enough.

In conclusion, as I said, the text is clearly written and I think that the figures are the appropriated ones, also the references, but I feel that the figures explanation needs some work.

After such a revision, I am happy to recommend the manuscript for publication in Nature Physics.

Reviewer #3

(Remarks to the Author)

A. The paper describes successful experimental demonstration of coupling single electrons on liquid helium with microstrip line based photon cavity. In particular, a single electron strong coupling regime is achieved. The parameters of the coupling are obtained and compared with a FEM based analysis to get good agreement. In other systems like Ne, this level of agreement is difficult because there are many uncontrollable ingredients in the system. Particular advantage of electrons on helium is of its cleanliness, which enables a good control of their states. The future use of this system as quantum computing is emphasized, which sounds promising. Therefore, I believe that it is a masterpiece in the field, well deserved for publication.

B. This article has a high originality and significance.

C. Data & methodology are good.

D. Data treatment sounds scientific.

E. Conclusion of this paper is reliable.

F. Suggested improvement, if I may point out, is about the condition for single electron trapping. In Fig 1, this condition is described around V_u , $V_r = -0.6V$ although the single electron strong coupling is demonstrated at around $V_r = -2.035V$ and $V_u = -4.291V$. These values are very different from the previous values. There may be a single electron valley in $V_r - V_u$ plane. Such a description may help understanding of readers.

G. References are appropriate.

H. The text is clearly written and comprehensive.

Reviewed by Kimitoshi Kono

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I appreciate the authors thorough considerations of and answers to my remarks. All my questions were addressed appropriately. I do not have any further questions and fully recommend publication of this manuscript in Nature Physics.

Reviewer #2

(Remarks to the Author)

My questions and, I believe, all comments and questions raised by the other 2 Referees, have been answered satisfactorily. Therefore I recommend the paper for publication.

Reviewer #3

(Remarks to the Author)

I very much appreciate authors reply to all referees' comments, including mine. All the answers sounds reasonable to me. Therefore, I believe that the manuscript is ready for publication.

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Response to Reviewers

We thank the Reviewers for their thoughtful comments and for their interest in our manuscript. We have addressed all of the Reviewers' remarks in the responses below and in the revised version of the manuscript. A detailed, point-by-point response is provided for each comment, along with a description of the corresponding changes made to the manuscript. For clarity, we have included the Reviewers' comments below (in red), followed by our responses (in black). In addition to the revised manuscript, we have also uploaded a marked-up PDF version in which all changes are explicitly indicated. We hope that the revised manuscript meets the requirements for acceptance.

Sincerely,
Johannes Pollanen (on behalf of all authors)

Reviewer comments

Reviewer #1 (Remarks to the Author):

The authors present a study of electron charge qubits trapped on the surface of superfluid helium using a quantum dot nanostructure and coupled to a microwave resonator. By using a novel high-impedance resonator design recently developed by some of the same authors, they obtain strong coupling between the motional states of the electron charge qubit and the microwave photons. They verify the presence of strong coupling using both spectroscopy of the resonator as well as two-tone electron charge state spectroscopy. Lastly, they use the strong coupling to study the decoherence properties of the electron charge qubit and find pure dephasing as the limiting decoherence mechanism, whereas population decay occurs at an approximately two orders of magnitude lower rate.

While the electron on helium qubit platform and the coupling to microwave resonators have already been demonstrated in recent years, this work marks the first demonstration of strong coupling in this qubit platform – a crucial milestone for practical applications in quantum computing. The precise control of the electron charge state and the authors' deep understanding of the device physics via finite-element modelling (Fig 1e,f) is remarkable and demonstrates the systems capabilities as a viable platform for quantum computing. These demonstrated features uniquely distinguish this platform from similar approaches such as semiconductor quantum dots, making this work relevant to a wide range of research in both applied quantum technologies, but also for more fundamental studies in cavity QED based on complex engineered quantum systems. The investigation of decoherence mechanisms in this relatively new qubit platform will be crucial to realizing its full potential and this work presents a significant advance towards this direction. The manuscript is well written, appropriately referenced and of excellent technical quality, including its extensive Supplementary Information. For the above reasons I recommend publication of this work in Nature Physics.

We appreciate the Reviewer's succinct and very accurate summary of the manuscript. We agree that progress in the field of electrons-on-helium will have broader implications in other platforms such as semiconductor quantum dots, and that this work opens up the ability to further investigate the dominant noise mechanisms in the system.

However, I have several comments and suggestions for improvements of the manuscript:

- The authors should discuss whether there are ways in future studies to distinguish the decoherence induced by the ripplon field from the stray charges.

We agree with the Reviewer that it would be valuable to mention in the main text how future experiments may help differentiate the effects of ripplons from the effects of stray charges on the decoherence of the motional state. We have clarified this point by adding the following text to the end of the section "Electron state decay and dephasing":

"To distinguish between these two effects, future devices and packaging can be designed so that electron emission occurs in an area far removed from the dot to mitigate the effects of stray charges."

In fact, we have begun experiments to test these kinds of devices which we hope to report on soon in a future publication.

- In addition, are there any numerical estimates for the amount of stray charges present in the device and simulations for their impact on electron decoherence?

The Reviewer raises an important question regarding the charge noise. Addressing this question requires an analysis of various noise models and an understanding of the different regimes and approximations applicable to our system.

While we do not know the density of stray charges, the nature of the charging process in our electron-on-helium devices means the entire chip is exposed to electrons emitted from the filament. We believe that some electrons can potentially be localized on the thin film of liquid helium at trapping centers originating from surface roughness of the metal electrodes. Thermal fluctuations of these localized charges (which could be localized vibrational modes within the trap or two-level fluctuators) can jitter the electrostatic potential seen by the electron (qubit) in a quantum dot, thus causing decoherence. As we note in the manuscript, our experimental results suggest that dephasing is the dominant source of decoherence, implying that the qubit primarily couples longitudinally to this type of bath. Under the assumption of a quasistatic regime, where decoherence is driven by long-lived low frequency excitations of the stray charges, the coherence function is expected to follow a Gaussian decay [Petersson, K. D., et al. "Quantum coherence in a one-electron semiconductor charge qubit." *Physical Review Letters* 105.24 (2010): 246804]. In this regime, the dephasing rate is proportional to the root-mean-square amplitude of the noise. If the noise originates from a thermally activated bath of fluctuating charges, this leads to a temperature dependence of the form $\Gamma_{\phi} \propto \sqrt{T}$, which is consistent with

our experimental observations. While this consistency is promising, there are many assumptions that go into this type of modeling, which we are currently working to understand by comparing to new experiments in which we can control the electron emission process more carefully.

- On the same note, it seems that more negative voltage offsets ΔV would be highly beneficial as they significantly reduce the decoherence rate, however, ΔV is currently limited by electron loss at strongly negative ΔV . Do the authors expect further improvements of the decoherence rate by enabling more negative ΔV through optimized designs of the quantum dot geometry or is there any more fundamental limitation?

The Reviewer is correct. We do expect further improvement in devices that can reach more negative voltage offsets, either through the repulsion of stray charges from the dot area, or the reduction of the pressing field holding the electron to the surface of the liquid helium. In particular, we are developing devices with optimized lateral confinement of the electron, which would allow us to apply a lower pressing electric field and, in principle, improve the coherence. In particular, we have been developing new devices with improved lateral confinement in the dot to be able to achieve more negative voltage offsets. We have added a statement to this effect in the caption of Fig. 4c:

“However, the voltage offsets can potentially be made more negative in future devices optimized for improved lateral confinement.”

- In Figure S1 in the Supplementary Information, it would help to add a visual legend labelling which color in the figure corresponds to which material.

We thank the Reviewer for the suggestion and have added a legend to Figure S1.

- In the Supplementary Information Section 7, the authors find that when the charge qubit and microwave resonator are off-resonant, the qubit lifetime T_1 is still significantly shorter than the Purcell-limited lifetime. Through a combination of an analytical model and FEM, the authors attribute this discrepancy to electron decay through other electrodes, which seems reasonable. Are there any practical implications of this observation in terms of future device design considerations to increase the qubit lifetimes?

Decay through bias electrodes is governed by two main factors: the coupling strength and the density of states of the microwave field in the electrode at the qubit frequency. In the first case, a more intentional design of the quantum dot is required, where the electric field originating from the control electrodes is minimized (parameter $\partial\alpha/\partial y$ in Section 7 in SI), while preserving all essential functionalities of the quantum dot (these include the ability to shape the electrostatic potential to define a specific charge qubit quantization axis, the capability to tune the curvature of the potential, which determines the appropriate frequency range for the motional states of the qubit, and other operational parameters). The second factor involves the need for improved design of on-chip low-pass filters made from high-kinetic-inductance materials, through which a DC bias can be applied. These filters are engineered to function as microwave mirrors

(controlled by filter cut-off frequency $\frac{1}{\sqrt{C_f L_f}}$ in Section 7 in SI), effectively suppressing the number of photons at frequencies close to the qubit's transition frequency. Both of these design factors have to be considered in future device designs.

We have added statements on these key improvements necessary for the future devices in the Section 7 SI:

“The coupling parameter $\partial\alpha/\partial y$ and on-chip filters with lower cut-off frequencies $\frac{1}{\sqrt{C_f L_f}}$ should be optimized in future device designs to reduce the microwave leakage through dc bias electrodes.”

In addition to these comments, there are a few minor typos in the manuscript:

- In the main text, in the beginning of the section “Single electron strong coupling”: In the sentence ‘[...] we observe large frequency shifts exceeding several resonator linewidths that appear when the electron motion approaches that of the [...]’ would better be ‘[...] we observe large frequency shifts exceeding several resonator linewidths that appear when the frequency of the electron motion approaches that of the [...]’.

We thank the Reviewer for this suggestion and have implemented this change in the text.

- In the Supplementary Information, beginning of caption of Figure S5: “elative” should be “relative”.

We thank the Reviewer for noticing this typo and have fixed it to say “relative.”

Reviewer #2 (Remarks to the Author):

In the manuscript "Strong coupling of a microwave photon to an electron on helium", the strong coupling regime between a microwave photon and the motional state of a single electron on helium is demonstrated. Also single-electron control. This is an important step in the advancement of electron on He-based quantum and hybrid processors, and this work contains the first demonstration. Therefore, the work is novel and relevant. The presentation and quality of the data, text and figures is very high. And every claim is backed up with explanations, nicely presented theory and extra data in the Supplemental Material and Methods. Here a list of questions/comments that came up while reading, so possibly points for improvement:

We thank the Reviewer for their positive comments regarding our work.

- Figure 1: In panel d), the potential minima (or less negative) seems to lie at positive x values, where the yellow circle is represented. However, in panel e), in the inset, the minima are at negative x values. What is the chosen V_r - V_u set in panel d) that makes this so different? And wouldn't it be better to chose a set like the ones in panel e)?

The Reviewer is correct to point this out. The difference in the Unload and Resonator voltages used for Fig 1d and Fig 1e reflects two different processes in the electron characterization process. The inset in Fig 1e reflects the electrostatic potential needed to expel electrons from the dot, where the Unload and Resonator voltages are both set negative and to the same value. In this scenario, the potential is shaped such that there is no resonance between the electron and resonator. On the other hand, Fig 1d reflects voltages where the potential is oblong and aligns the quantization axis of the electron motion along the y direction such that coupling between the electron and resonator is maximized. In other words, Figure 1d reflects the potential needed to measure features such as those shown in Figure 2a.

We agree that the difference in voltage configurations is unclear, and have added the following text in the caption of Figure 1d:

“Typical map of $\varphi(x, y)$ in the dot, calculated using FEM, needed to achieve resonance with the motional state and measure features such as those in Fig 2a. The voltages are similar to those presented in Table S2 and are tuned to promote the quantization axis to be aligned with the y-axis, maximizing the electron coupling to microwave photons.”

We have also added the following text in the caption of Figure 1e:

“Steps in the resonator frequency shifts $\Delta\omega_r$ measure the number of electrons the dot (black lines are modeled values from FEM). Inset shows modeled electrostatic potential energy U along the channel for $V_r = V_u = -0.7$ V (blue, $N = 0$), -0.6 V (orange, $N = 1$) and -0.5 V (green, $N = 2$), **as required for unloading electrons.**”

- Figure 2: I am not understanding why in panel e) from Fig. 1 the values of V_r and V_u change together, while in Fig. 2 a) the values of these two voltages are very different (more than a factor of 2). I am not able to navigate the density plot in Fig. 2 a) at the same time as I follow the info about the number of electrons shown in Fig. 1 e).

As noted in our response to the Reviewer’s previous comment, the plots in Fig 1e and Fig 2a are associated with two separate processes. Fig 1e represents an electron unloading process. Here, the Resonator and Unload electrodes are biased together to uniformly raise one side of the dot confining potential, making it easy to push electrons over the barrier and out of the dot. During this unloading process, no resonance is achieved between the electron(s) and resonator. This is why the measured frequency shifts in Fig 1e are much smaller than those in Fig 2a.

Once the dot has been unloaded to a single electron, the Unload and Resonator voltages are independently tuned, as shown in Figure 2a, to achieve a resonance condition. The voltages needed to achieve this resonance condition are different from the voltages needed to unload electrons from the dot, and are similar to the voltages used to generate the potential in Fig 1d. The difference in the coupling constants of the Resonator and Unload electrodes explains the factor of 2 difference between the voltages in Fig 2a. Because the Unload electrode coupling constant is much smaller than the Resonator electrode coupling constant, larger biases are

needed to tune the electron motional frequency using the Unload electrode compared to the Resonator electrode. Additionally, the data in Fig. 2a is taken at a global offset voltage configuration, as described in Table S2, where the motional state decoherence rate is suppressed and the measured resonator shifts are the clearest. This adds further discrepancy between the axes voltage values in Fig 1e and Fig 2a.

We agree with the Reviewer that these points are nuanced and non-obvious, and therefore have edited the section “Single electron strong coupling” in the main text to clarify:

“To characterize the properties of the single electron cQED system, we load one electron into the dot and measure the resonator frequency shift $\Delta\omega_r/2\pi$ as we **change ω_e by independently sweeping the Resonator and Unload voltages (Fig. 2 a), to generate a trapping potential similar to that shown in Fig. 1d.**”

- In Fig. 3, and the text in section "Electron charge state spectroscopy", I don't see exactly what the definition of ΔS_{21} is. Difference with respect to what? I say this because the text mentions a "decrease of readout signal when ω_d is resonant with the electron motional state transition", but such decrease would be blue color in Fig. 3 b), however the 2 resonance points correspond to white of the colormap. I may be understanding it wrong, but that must mean that it is not clear enough.

This experiment is a version of so-called “two-tone spectroscopy” in which we tune the electron drive frequency through the resonance of the electron motional state. Further elaboration on this technique can be found in Reference 22 in the main text: Schuster, et al. *Phys. Rev. Lett.* 94, 123602 (2005). During this measurement we monitor the transmission through the resonator at a fixed readout frequency (ω_r) near the bare resonator frequency. We then send in a second drive tone, which is swept across the electron motional state frequency. When the drive is far detuned from the electron state frequency it does not excite the electron motion and we use this as a baseline reference for the transmission, i.e. $\Delta|S_{21}| = 0$ for this far detuned case. However once the drive is resonant with the electron motional state transition it drives Rabi oscillations of the electron, which results in a reduction in the transmission through the resonator at the readout frequency, $\Delta|S_{21}| < 0$.

We agree with the Reviewer that we did not define $\Delta|S_{21}|$ in the main text. We define $\Delta|S_{21}|$ to be the measured magnitude of the transmitted signal for a particular drive frequency minus a baseline reference magnitude measured far off resonance. We have included the following change in the main text to more clearly state the definition of $\Delta|S_{21}|$:

“ $\Delta|S_{21}|(\omega_d) = |S_{21}|(\omega_d) - |S_{21}|(\omega_{\text{off}})$ where ω_{off} is a drive frequency far off resonance $|\omega_e - \omega_{\text{off}}| > 1$ GHz.”

In conclusion, as I said, the text is clearly written and I think that the figures are the appropriated ones, also the references, but I feel that the figures explanation needs some work.

After such a revision, I am happy to recommend the manuscript for publication in Nature Physics.

We thank the Reviewer for their recommendation for publication of the manuscript in Nature Physics. We agree that the figure explanation needed further clarification and hope that our responses and suggested edits to the main text and captions are sufficient.

Reviewer #3 (Remarks to the Author):

A. The paper describes successful experimental demonstration of coupling single electrons on liquid helium with microstrip line based photon cavity. In particular, a single electron strong coupling regime is achieved. The parameters of the coupling are obtained and compared with a FEM based analysis to get good agreement. In other systems like Ne, this level of agreement is difficult because there are many uncontrollable ingredients in the system. Particular advantage of electrons on helium is of its cleanliness, which enables a good control of their states. The future use of this system as quantum computing is emphasized, which sounds promising. Therefore, I believe that it is a masterpiece in the field, well deserved for publication.

B. This article has a high originality and significance.

C. Data & methodology are good.

D. Data treatment sounds scientific.

E. Conclusion of this paper is reliable.

F. Suggested improvement, if I may point out, is about the condition for single electron trapping. In Fig 1, this condition is described around $V_u, V_r = -0.6V$ although the single electron strong coupling is demonstrated at around $V_r = -2.035V$ and $V_u = -4.291V$. These values are very different from the previous values. There may be a single electron valley in $V_r - V_u$ plane. Such a description may help understanding of readers.

G. References are appropriate.

H. The text is clearly written and comprehensive.

Reviewed by Kimitoshi Kono

We thank the Reviewer for their extremely generous comments regarding the manuscript. With regards to comment F, we received a similar comment from Reviewer #2, and we agree that this distinction is non-obvious. We would like to address comment F below:

The plots in Fig 1e and Fig 2a are intended to convey two separate processes.

Fig 1e represents an unloading process. Here, the Resonator and Unload electrodes are biased together to uniformly raise one side of the confining potential, making it easy to push electrons out of the dot. In this unloading process, no resonance is achieved between the electron(s) and resonator. This is why the resonator frequency shifts in Fig 1e are much smaller than those in Fig 2a.

Once the dot has been unloaded to a single electron, the Unload and Resonator voltages are independently fine-tuned, as shown in Fig 2a, to achieve a resonance condition by shaping the trapping potential to look similar to the one shown in Fig 1d. The difference in the coupling constants of the Resonator and Unload electrodes explains the factor of two difference between the voltages in Fig 2a. Because the Unload electrode coupling constant is much smaller than the Resonator electrode coupling constant, larger biases are needed to tune the electron motional frequency using the Unload electrode versus the Resonator electrode. Additionally, the data in Fig. 2a is taken at a global offset voltage configuration, as described in Table S2, where the motional state decoherence rate is suppressed and the measured resonator shifts are the clearest. This is another reason why there is a difference in the voltage configurations in Fig 1e and Fig 2a.

We agree with the Reviewer that this point should be clarified and have added the following sentences in the main text:

“To characterize the properties of the single electron cQED system, we load one electron into the dot and measure the resonator frequency shift $\Delta\omega_r/2\pi$ as we **change ω_c by independently sweeping the Resonator and Unload voltages (Fig. 2 a), to generate a trapping potential similar to that shown in Fig. 1d.**”

Additional changes to manuscript:

During our revision we also corrected a typo present in the original manuscript. Specifically, in the caption to Fig.3(a) ‘50 μ s’ should have read ‘5 μ s’ and the readout pulse duration should have been ‘1.5 μ s’ instead of ‘1 μ s.’ We have corrected this in the updated manuscript.

We thank the Reviewers again for their thoughtful comments and for their interest in our manuscript. Below we provide a brief response to the final Reviewers' comments (copied in red), followed by our responses (in black).

Sincerely,
Johannes Pollanen (on behalf of all authors)

Final Reviewers comments:

Reviewer #1:

Remarks to the Author:

I appreciate the authors thorough considerations of and answers to my remarks. All my questions were addressed appropriately. I do not have any further questions and fully recommend publication of this manuscript in Nature Physics.

We thank the reviewer for their time and contributions. Our final manuscript to Nature Physics is better as a result of their efforts.

Reviewer #2:

Remarks to the Author:

My questions and, I believe, all comments and questions raised by the other 2 Referees, have been answered satisfactorily. Therefore I recommend the paper for publication.

We thank the reviewer for their time and contributions. Our final manuscript to Nature Physics is better as a result of their efforts.

Reviewer #3:

Remarks to the Author:

I very much appreciate authors reply to all referees' comments, including mine. All the answers sounds reasonable to me. Therefore, I believe that the manuscript is ready for publication.

We thank the reviewer for their time and contributions. Our final manuscript to Nature Physics is better as a result of their efforts.