Reviewer #1 (Remarks to the Author)

The authors report the first experimental observation of "exotic" or non-trivial trajectories in a 3-slit experiment. They unequivocally show that, very surprisingly there are trajectories that involve the photon returning back on itself and performing a loop trajectory. In the experiments, these trajectories are enhanced by using resorting to metallic slits and the excitation of plasmons. This in turn allows to link these trajectories to the near field dynamics of the field. FDTD simulations further confirm that the "loop" interpretation is indeed correct.

I truly enjoyed reading this manuscript (I have definitely spent worse Sunday afternoons). It is precise, clear and very well articulated. Most importantly, the physics is very exciting and far from trivial.

I honestly could not find anything wrong with the manuscript nor do I feel compelled to do so at all costs.
There are only a few typos that I am sure will be corrected at the proof-reading stage.

My recommendation is that the manuscript is accepted for publication in its current form without any need for revision.

Reviewer #2 (Remarks to the Author)

It is more or less universally accepted that multi-slit interference can be understood by adding the amplitudes for traversing each slit, and then taking the square. Very recently, it was recognized that although it is correct to add the amplitudes for every pathway, in Feynman's sense, it is incorrect to suppose that the set of pathways available with multiple slits open is simply the union of the sets of pathways available with each slit open; this is because a pathway may traverse more than a single open slit. This is as true in classical electomagnetism as in quantum mechanics, and while it is therefore implicit in rigorous diffraction theory, I do not believe it had been recognized in the past. Since the recognition of this surprising fact (which in principle should lead to a non-zero measurement in a famous "null result" experiment which purported to test nothing less fundamental than Born's rule), it has remained an exciting challenge to test it in the laboratory.

The present paper uses a very clever application of plasmonics to enhance the effect, and to do so in a polarization-dependent way, so that it can in some sense be switched on and off. As a first demonstration, the authors show that even with light focused onto a given slit, the presence of two other slits leads to interference fringes, but only for the polarization with the enhanced effect. This is very dramatic. For a more quantitative demonstration, they measure the "Sorkin parameter" for both polarizations, using a variety of slit combinations, as in earlier Born's-rule experiments.

This is a result that most if not all of the physics community would have thought impossible a few years ago, and which provides experimental proof of an important addendum to the conventional understanding of interference. It should be published in a broad-interest, high-impact journal, and I recommend it strongly for publication.

While I am inclined to believe the data analysis, I do have to say that the second measurement relies on precise data treatment to identify this "deviation" paramter, and therefore doesn't provide much of a visual "smoking gun" for the reader. In this sense, it was an excellent idea to carry out part 1 as well. I think that section could be strengthened if they authors have data for situations where slit A was illuminated, but only slits B and C were open, or only slits A and B, as a confirmation that the interfering trajectories are indeed the ones they identify in the paper. It would be nice to see, for a given polarisation, that those fringes really do require the presence of all three slits, even though only a single slit is illuminated (unlike the case in the second part of the paper).

On a smaller point, figures 1b and 1c appear violate the Rochester rule that light travels from left to right. In all seriousness, although 1a is in perspective (so the light could be interpreted as coming "towards the reader" or else "to the right"), I found it difficult to situate myself when making the transition from 1a to b and c. I suspect that if the latter two were rotated by 90 degrees, their meaning would be more immediately apparent to most readers. This is obviously merely a suggestion, for the authors to do with as they please.

The concluding sentence, "We believe that looped paths can have important implications in the study of decoherence mechanisms in interferometry and to increase the complexity of protocols for quantum random walks, quantum simulators and other algorithms used in quantum computation," sounds very dramatic, and I have trouble seeing how any of it is justified. I strongly support the publication of this work for its fundamental interest, but would prefer the authors to remove unsubstantiated claims which sound more like salesmanship, and unnecessary salesmanship in this case, than like serious scientific proposals. Alternatively, if there are serious paths to such applications, I would ask the authors to at least provide a few words about the rough idea of what they have in mind.

In sum, however, this is an excellent and creative experimental work which provides an important addition to the body of literature on quantum (and electromagnetic) interference, and should be published, after the authors consider my suggestions.

Reviewer #3 (Remarks to the Author)

To authors and editor:

The work presented in this manuscript has used surface plasmons to demonstrate the so-called 'looped trajectories'. The contribution of 'looped trajectories' to the interference could be tuned by exciting surface plasmons with different polarized light. This is purely classical optical phenomenon, which has been calculated by Maxwell equation and realized by using classical laser light. Although the authors have used heralded single photons as input, there is no difference between classical laser light and single photons in this work. The relevance of their work to the foundations of quantum physics is highly questionable. Therefore, I do not recommend it for publication.

November 15, 2016

Dr. Federico Levi
Senior Editor
Nature Communications

Dear Dr. Levi,

On behalf of my coauthors, we would like to thank you for considering our manuscript and for your careful handling of our submission. As requested, we have addressed the comments and questions of the reviewers in a point-by-point fashion below. In addition, we have highlighted all the associated changes made to the manuscript.

We are very thankful to the reviewers for the comprehensive report and the many helpful comments. Based on the report we have improved the quality of our manuscript. We believe that our manuscript is now suitable for publication in Nature Communications.

Best Regards,

Omar S. Magaña-Loaiza and Robert W. Boyd
The Institute of Optics
University of Rochester
275 Hutchison Rd Rochester, NY 14627

November 15, 2016

Response to the Reviewer
Manuscript NCOMMS-16-22116-T

Summary response statement,

Our detailed response is given below. For the aid of the editor, we first provide the reviewers' comments and then a brief statement of what changes we have made to address these comments.

Report of Reviewer #1 (in blue) followed by a detailed response to each point (in black)

Comment 1: The authors report the first experimental observation of "exotic" or non-trivial trajectories in a 3-slit experiment. They unequivocally show that, very surprisingly there are trajectories that involve the photon returning back on itself and performing a loop trajectory. In the experiments, these trajectories are enhanced by using resorting to metallic slits and the excitation of plasmons. This in turn allows to link these trajectories to the near field dynamics of the field. FDTD simulations further confirm that the "loop" interpretation is indeed correct.

Reply to Comment 1: We would like to thank the reviewer for providing an accurate summary of our work and for his/her comprehensive report.

Comment 2: I truly enjoyed reading this manuscript (I have definitely spent worse Sunday afternoons). It is precise, clear and very well articulated. Most importantly, the physics is very exciting and far from trivial.

Reply to Comment 2: We thank the reviewer for his/her positive opinion of our work. We agree with the reviewer that the family of effects that we have unveiled in our work is very interesting.

Comment 3: I honestly could not find anything wrong with the manuscript nor do I feel compelled to do so at all costs. There are only a few typos that I am sure will be corrected at the proof-reading stage.

Reply to Comment 3: We thank the reviewer for pointing out typos in our paper, we have carefully edited our manuscript and we feel it is suitable for publication.

Comment 4: My recommendation is that the manuscript is accepted for publication in its current form without any need for revision.

Reply to Comment 4: We thank the reviewer for his/her exhaustive revision of our manuscript.

Report of Reviewer #2 (in blue) followed by a detailed response to each point (in black)

Comment 1: It is more or less universally accepted that multi-slit interference can be understood by adding the amplitudes for traversing each slit, and then taking the square. Very recently, it was recognized that although it is correct to add the amplitudes for every pathway, in Feynmans sense, it is incorrect to suppose that the set of pathways available with multiple slits open is simply the union of the sets of pathways available with each slit open; this is because a pathway may traverse more than a single open slit. This is as true in classical electomagnetism as in quantum mechanics, and while it is therefore implicit in rigorous diffraction theory, I do not believe it had been recognized in the past. Since the recognition of this surprising fact (which in principle should lead to a non-zero measurement in a famous null result experiment which purported to test nothing less fundamental than Borns rule), it has remained an exciting challenge to test it in the laboratory.

Reply to Remark 1: We thank the referee for his/her accurate review of the antecedents in the field. We devoted the introductory part of our manuscript to a discussion of these ideas.

Comment 2: The present paper uses a very clever application of plasmonics to enhance the effect, and to do so in a polarization-dependent way, so that it can in some sense be switched on and off. As a first demonstration, the authors show that even with light focused onto a given slit, the presence of two other slits leads to interference fringes, but only for the polarization with the enhanced effect. This is very dramatic. For a more quantitative demonstration, they measure the Sorkin parameter for both polarizations, using a variety of slit combinations, as in earlier Borns-rule experiments.

Reply to Comment 2: We agree with the reviewer, we utilize plasmons to unveil the physics behind exotic looped trajectories of light. We present theoretical and experimental evidence that demonstrate that these peculiar behaviors of photons are physically due to the near-field component of the wavefunction.

Comment 3: This is a result that most if not all of the physics community would have thought impossible a few years ago, and which provides experimental proof of an important addendum to the conventional understanding of interference. It should be published in a broad-interest, high-impact journal, and I recommend it strongly for publication.

Reply to Comment 3: We would like to thank the reviewer for his/her positive assessment of our work.

Comment 4: While I am inclined to believe the data analysis, I do have to say that the second measurement relies on precise data treatment to identify this deviation paramter, and therefore doesnt provide much of a visual smoking gun for the reader. In this sense, it was an excellent idea to carry out part 1 as well. I think that section could be strengthened if they authors have data for situations where slit A was illuminated, but only slits B and C were open, or only slits A and B, as a confirmation that the interfering trajectories are indeed the ones they identify in the paper. It would be nice to see, for a given polarisation, that those fringes really do require the presence of all three slits, even though only a single slit is illuminated (unlike the case in the second part of the paper).

Reply to Comment 4: We agree with reviewer that the experimental realization of the situation described in Figure 1 **d** and **e**, where slit A is illuminated while slits B and C are open would be of interest for readers. In Figure 1 **f** and **g**, we present new and cleaner data obtained when heralded single photons illuminate slit A.

Comment 5: On a smaller point, figures 1b and 1c appear violate the Rochester rule that light travels from left to right. In all seriousness, although 1a is in perspective (so the light could be interpreted as coming towards the reader or else to the right), I found it difficult to situate myself when making the transition from 1a to b and c. I suspect that if the latter two were rotated by 90 degrees, their meaning would be more immediately apparent to most readers. This is obviously merely a suggestion, for the authors to do with as they please.

Reply to Comment 5: We thank the reviewer for his/her suggestions. However, due to the fact that Fig. 1d is aligned along the horizontal axis we have decided to keep the same orientation for Fig. 1 **b** and **c**.

Comment 6: The concluding sentence, "We believe that looped paths can have important implications in the study of decoherence mechanisms in interferometry and to increase the complexity of protocols for quantum random walks, quantum simulators and other algorithms used in quantum computation," sounds very dramatic, and I have trouble seeing how any of it is justified. I strongly support the publication of this work for its fundamental interest, but would prefer the authors to remove unsubstantiated claims which sound more like salesmanship, and unnecessary salesmanship in this case, than like serious scientific proposals. Alternatively, if there are serious paths to such applications, I would ask the authors to at least provide a few words about the rough idea of what they have in mind.

Reply to Comment 6: We thank the reviewer for providing this positive criticism, we have modified this sentence. Now it reads as follow:

"Our work elucidates new properties of light that could be used to enrich protocols that rely on interference effects such as quantum random walks and quantum simulators [3, 24]."

Comment 7: In sum, however, this is an excellent and creative experimental work which provides an important addition to the body of literature on quantum (and electromagnetic) interference, and should be published, after the authors consider my suggestions.

Reply to Comment 7: We thank the reviewer for his/her rigorous review, we concur that our paper should be published.

Report of Reviewer 3 (in blue) followed by a detailed response to each point (in black)

Comment 1: The work presented in this manuscript has used surface plasmons to demonstrate the so-called looped trajectories. The contribution of looped trajectories to the interference could be tuned by exciting surface plasmons with different polarized light. This is purely classical optical phenomenon, which has been calculated by Maxwell equation and realized by using classical laser light. Although the authors have used heralded single photons as input, there is no difference between classical laser light and single photons in this work. The relevance of their work to the foundations of quantum physics is highly questionable. Therefore, I do not recommend it for publication.

Reply to Comment 1: We thank the reviewer for taking the time to read our manuscript. However, we disagree with his/her assessment of our work. We believe that his/her report does not describe our manuscript in an accurate fashion. Consequently, it is difficult for us to refute his/her arguments. Specifically, we find that he/she raises objection to ideas that we never claimed in our manuscript.

Sincerely,

Omar S. Magaña-Loaiza and Robert W. Boyd
The Institute of Optics
University of Rochester
275 Hutchison Rd Rochester, NY 14627