From:	Charles M. Marcus <marcus@nbi.ku.dk>
Sent:	20-11-2021 18:41:33 (UTC +01)
To:	Anders Bau Truelsen <anbat@adm.ku.dk>
Cc:	FA-REKSEK-Rektorsekretariatet <rektorsekretariatet@adm.ku.dk>
Subject:	Comments regarding claims for case 504-0057/21-7000(Aspose.Email Evaluation)

Dear Anders Bau Truelsen and Practice Committee,
Please find attached comments responding to claims filed by Jake S. Yeston, case 504-0057/21-7000, regarding our paper "Flux-induced topological superconductivity in full-shell nanowires" (Science vol. 367 no. 6485). If the Practice Committee would like further information, either as documents or via in-person discussion, I would be pleased to provide it.
Regards,
Charles Marcus

____
Charles Marcus
Villum Kann Rasmussen Professor
Center for Quantum Devices
Niels Bohr Institute
University of Copenhagen
(+45) 20 34 11 81

Response to Complaint by Jake S. Yeston on behalf of Sergey Frolov and Vincent Mourik

A complaint to the Practice Committee of the University of Copenhagen was submitted by Jake S. Yeston, editor at Science, on behalf of Sergey Frolov and Vincent Mourik (F&M), focusing on the question of whether the data presented in our paper, "Flux-induced topological superconductivity in full-shell nanowires" by S. Vaitiekėnas *et al*. (Science, 2020) accurately represented the outcome of the experiments undertaken, and if data that did not support the conclusions were withheld.

The complaint is based on the document *Post-publication analysis of 'Flux-tuned topological superconductivity in full-shell nanowires' Vaitiekenas et al. Science 2020,* dated June 1, 2021, prepared by F&M, which presents an assortment of criticisms of our paper. F&M state that based on their analysis "the core conclusions of the paper are invalidated" [F&M, p2].

It is useful to state at the outset the main conclusions of our paper, quoted from paragraph 2 of the main text: "Here, we show both experimental and theoretical results *suggesting* that a hybrid nanowire consisting of a full superconducting (aluminum) shell surrounding a semiconducting (indium arsenide) core *can* be driven into a topological phase that supports MZMs at the wire ends by a flux-induced winding of the superconducting phase." [emphasis added]

All authors of the Science 2020 paper stand behind all aspects of the paper, data, analysis, interpretation, and conclusions, and find no merit in the complaints of F&M.

Background

The realization in 2015 of epitaxial growth of semiconductor-superconductor hybrid nanowires (Krogstrup, *et al.* Nat. Mat. 2015) yielded new types of materials and devices to be investigated. One interesting system was an InAs nanowire fully surrounded by an epitaxial Al shell. Hollow superconducting shells had been widely investigated previously, dating to the seminal work of Little and Parks (1962). Two previous experiments on small-diameter superconducting shells on insulating cores (Liu, *et al.* Science 2001; Sternfeld, *et al.* PRL 2011) had observed the so-called destructive Little-Parks effect, with reentrant lobes of superconductivity down to the lowest measured temperature, characteristic of a quantum phase transition (similar to Figs. 1C and 1D of our paper). The theory of this effect has been worked out, yielding good agreement with experiment. How destructive superconductivity affected the proximity effect in the semiconductor core had not been previously considered, experimentally or theoretically, as far as we know.

It was demonstrated previously by the Copenhagen group and others that related hybrid semiconductor-superconductor nanowires with partial coverage by epitaxial Al (covering two or three facets of the hexagonal nanowire) showed a well-developed proximity effect in InAs with a "hard" induced gap, that is, with an induced Bardeen-Cooper-Schrieffer (BCS)-like gapped spectrum with very low subgap tunneling conductance.

Tunneling spectroscopy into the end of the semiconductor core could be achieved by removing the shell via wet etching and depleting the semiconductor in the tunneling regime via electrostatic gates, with a normal-metal electrode deposited on the wire end, on the other side of the etched barrier region. The geometry of these devices was similar to previously investigated devices, allowing spectroscopy into the end of the wire. In the case of full-shell wires, the core was protected from the substrate and processing by the shell and not influenced by gating, except in regions that were etched to make the barrier and normal-metal contact.

Four-terminal measurements contacting the Al shell revealed the lobe structure of destructive superconductivity (Figs. 1C and 1D). The data was perhaps cleaner than previous studies, though consistent with Liu and Sternfeld, and in good agreement with theory.

We next turned our attention to tunneling spectroscopy of the semiconductor core. In the zeroth superconducting lobe, a simple proximity effect was observed. When the exposed barrier region was gate-tuned into the tunneling regime, avoiding obvious resonances barrier, tunneling spectroscopy in the zeroth lobe showed a familiar BCS-like spectrum, similar to what we had observed in previous studies of nanowires with two or three facets covered with Al. In those studies, we also needed to avoided junction resonances unless, of course, those resonances were the subject of the study, as in Deng *et al.*, Science 2016.

When an axial magnetic field was applied (using a vector magnet), the tunneling spectrum followed the reentrant lobe structure seen in the measurements of critical current and critical temperature of the shell: a gap decreased to zero around half-quanta of applied flux and re-opening around integer flux quanta. In those nanowires that showed reentrant lobe structure (not all did, for instance wires with thinner shell from other growth batches, as in Fig. S7) tunneling spectra in the first lobes (around +1 and -1 quantum of applied flux) a rich subgap structure was observed, including, in the majority of working devices (working = electrically connected, gates working, no obvious fabrication or measurement issues), a prominent peak at zero bias in the first lobes. Because one flux quantum causes the phase of the superconductor to wind by 2π around the circumference of the shell, perhaps the analogy to an extended vortex should have occurred to us, but it didn't, and we were quite surprised by the result. In most, though not all, of the wires, by the third lobe superconductivity was destroyed.

As with the two or three facet wires, one could always find resonances in the barrier, but one could just as easily avoid them. We have not figured out a way to eliminate disorder from the etched barrier.

We emphasize that nanowires from the same growth batch are not identical and did not behave the same when fabricated into devices. In the context of Fig. 2, this variation was emphasized in the paper by including data from wires from the same growth batch that showed differences in tunnel spectroscopy (see Fig. S5 and S6).

Upon learning of our experimental observations, our theory colleagues Karsten Flensberg and Roman Lutchyn were able to show theoretically, and later, with other colleagues, demonstrate in detailed numerical modeling, that quantized phase winding in the shell could yield a topological phase roughly in the range of material and device parameters relevant to the experiment. These theoretical results motivated a tentative identification of the zero-bias conductance peaks seen experimentally in the first lobe with the topological phase seen theoretically. Theory also revealed a rather restricted region of superconducting gap, electron density in the wire, spin-orbit coupling, and wire diameter, where the topological phase would occur. However, just because theory indicated that a topological phase can be present in the first lobe but not the zero lobe, we were not convinced that the observed zero-bias conductance peak could be taken as sufficient evidence of topological superconductivity. We sought more evidence specifically to distinguish Majorana zero modes from localized Andreev bound states that happen to stick to zero energy.

The goal of finding evidence distinguishing Majorana zero modes from Andreev bound states motivated the second half of our study, and the second half of the paper, a detailed study of the length dependence of even-odd Coulomb blockade peak spacing, following a technique developed in our lab a few years earlier (Albrecht, *et al.* Nature 2016). An investigation of even-odd peak spacing in the first lobe for several Coulomb islands yielded an exponential dependence of length. Careful analysis of peak spacing was required to produce quantitative statistical measurement of peak spacing that could distinguish between algebraic and exponential length dependence.

After observing the tunneling spectroscopy and length dependence in several devices, we wrote an experiment-only manuscript, coordinating with our theory colleagues who wrote their own theory manuscript. We sent both manuscripts to Science on September 6, 2018.

After the first round of reviewing, Jelena Stajic, the editor, felt that combining the manuscripts would improve the presentation. We expressed our reluctance to mix experiment and theory too heavily, but Dr. Stajic prevailed, and we agreed to rewrite a single combined manuscript. The separated versions are currently available on arXiv (Vaitiekenas, *et al.* arXiv:2003.13177 and Lutchyn, *et al.* arXiv:1809.05512).

Discussion

When reporting the spectroscopy data, we were careful to state in the text and demonstrate with data that the subgap structure was repeatable, but not seen in every device. We showed that when the junction is tuned into the tunneling regime, away from resonances, we observed a BCS-like spectrum in the zeroth lobe and, at the same gate voltage, a distinct conductance peak at zero bias in the first lobes. These were our typical observations, and we showed this behavior in Figs. 2, S5, and S6. We also showed in the paper the gate-voltage dependence of conductance in the lobes to illustrate how we tuned devices into the tunneling regime, where tunneling spectra reflected the density of states of the wire absent the complicating effects of resonant states or an open barrier, where transport does not reflect the density of states. We showed this, for example, in Figs. 2C and 2E. An even broader range of gate voltages, outside the tunneling regime, where resonant states predominate as the junction is fully depleted, or the junction is opened, are presented in the Zenodo file. Sweeping gates over a large voltage range can induce jumps and drift due to charge motion induced by the gate sweep. We showed such jumps in the paper, pointed them out in the text and provided our interpretation. We also felt it was important to show in the paper that not all the devices show a zero-bias peak in the first lobe. This was illustrated in Fig. S7 and described in the text.

Much of the rest of the paper was concerned with the length dependence study, investigating devices of six lengths with similar results for corresponding segments in three wires.

We feel that the main text of the paper, with its four multi-panel experimental figures, and the 41-page supplementary section of the paper, with 18 additional experimental data figures, was sufficient to make the case for our interpretation, the discovery that a full-shell hybrid nanowire can, under experimentally accessible conditions, repeatably show features consistent with topological superconductivity. We had observed the zero-bias peaks in seven devices, convincing us that the effect was real. The effect was also consistent with theory, which produced strikingly similar numerical results. Finally, the length dependence study, with 2e-periodic Coulomb blockade in the zeroth lobes, 1e periodic Coulomb blockade in the destructive regimes between lobes, and even-odd Coulomb blockade in first lobes, showing an exponential dependence of even-odd spacing difference on wire-segment length, supported this interpretation. Three years after the initial submission, we still do not know of another explanation of the whole body of data presented in the paper besides the one we provided, namely topological superconductivity.

To aid readers in examining our results, we prepared an additional set of files giving access to the data in numerical form along with a program for plotting the files. That was submitted to Zenodo when we submitted the original manuscript.

Not long after publication, as we were moving on to other experiments, including experimental measurements involving further tests of full-shell wires, such as placing the full shell wires in a SQUID geometry, we began receiving requests—it is fairer to call them demands—for "all data" including lab notebooks, from the first sample to the last, from F&M, also cc'd to the Science editor, our department chair, and several others. These letters stated that we were obliged by Danish law and journal regulations to comply with their demands.

When Jelena Stajic subsequently contacted us in response to F&M's requests to her, suggesting that we post additional data, we did so promptly. Every experiment in nanoelectronics has devices that do not work, are shorted or blown up, or are lithographic failures. Each knob in the experiment has untuned regimes where one cannot take good data. It is the job of the experimentalist to tune a device, in this case to create a tunnel barrier to measure density of states, representative among devices and gate voltages, and to recognize when it is not tuned on a resonance or to the open regime. Despite our misgivings, we posted data that included untuned regimes, preliminary sweeps, and characterization runs in response to Jelena Stajic's request as a second set of files, along with plotting programs and a 136-page guide to the additional data.

Summary of responses to Frolov and Mourik

In April 2021, we received a long document from F&M claiming that they had gone through the second Zenodo submission and found that there were devices that did not show zero-bias peaks, and ranges of gate voltages where the data was more complicated, like there were resonances in the barriers. F&M also stated that they felt there was more data and that we were holding back. We responded to F&M in May 2021, in much the same way that we have responded to their subsequent correspondence below. In fact, the document that forms the basis of the complaint contains the same concerns as before but does not acknowledge that we responded to the issues previously. Those responses are presented in the appended document as comments added to the document of F&M. Our comments only address the key points of the F&M complaint, not each point with which we disagree. The main points of our response to the F&M document can be summarized as follows:

1. In their complaint, F&M use the terms "representative" without definition or explanation. It seems natural to us that when reporting a new discovery, the emphasis should be on the new phenomenon, along with some indication of whether the new phenomenon is typical or rare. A paper about an earthquake will focus on seismograph data taken during the earthquake. Those data are not "invalidated" by data taken during quiet periods before or after the earthquake. In our paper, we show data from several devices with features closely resembling those in Fig. 2, with a clean subgap region in the zero lobe and a zero-bias conductance peak and surrounding subgap features in the first lobe, such as Figs. S5 and S6. We also point out that some devices do not show the zero-bias feature, consistent with expectations and detailed modeling. Figure S7 is titled "Tunneling spectroscopy without zero-bias peaks in device with thinner Al shell (device 5)."

2. F&M claim that our data is not "reproducible," which is simply false. All relevant features in the data were reproduced in multiple devices, as reported in the original manuscript. Theory presented in the paper shows that a topological phase is only present under certain experimental conditions. The wires are not identical, not every wire shows a topological phase, nor is it expected to. Even within a single device, gate sweeps over a multi-volt range induce drifts and jumps, so the barrier changes within a single run when the gate is swept over several volts.

3. Regarding Fig. 2, a focus of the complaint, F&M suggest that Figs. 2C and 2E are cropped subsets of larger ranges of gate voltage. This is not true. The extended sweeps that F&M analyze [F&M, p9-11] were from characterization runs of several devices on the chip taken one week before the data in Fig. 2 was taken, with numerous scans over large voltage ranges of a global back gate taken in between. The large voltage excursions used for numerous runs over the course of a week evidently altered the disorder potentials. All data in Fig. 2, along with Fig. S3b, were taken back-to-back within a few hours. Gate sweeps are complete and uncropped. Time stamps are in the Zenodo repository.

4. Regarding comparisons to subsequent work by Valentini *et al*. (Science, 2021), we note that those devices were fabricated in a different lab using different fabrication techniques and materials, at least a year later, and were measured in different operating regimes. It is known that there is considerable variation in size and shape among nanowires within a growth batch and that nanowires age and oxidize with time, depending on how they were stored and processed. It is not surprising that different labs using different fabrication methods find different behavior.

5. We have demonstrated experimentally and theoretically that zero-modes consistent with a Majorana interpretation *can* exist in full-shell proximitized nanowires,

identifying a new route to topological superconductivity. There are devices where the topological phase was not seen, and these are described and presented in the original paper. This does not invalidate data from the several devices where it was seen, or that this route exists. Our paper also reports that when a topological phase is present, it does not have to persist throughout the first lobe. Theory and experiment are consistent in these aspects.

6. We are quite aware that resonances can form in the etched junctions. As is routine, we looked for regions of gate voltage where simple tunneling was observed, away from resonances and away from high conductance. We then fixed the gate voltage to a value for a given field sweep. By doing so, tunneling data reflected (was proportional to) the local density of states in the wire, rather than a complicated mix of wire states and resonant states in the junction. The use of tunneling spectroscopy as a tool to look at local density of states involves avoiding these resonances. We previously intentionally investigated the interaction of localized resonances and zero modes in the wires (Deng, *et al.*, Science, 2016). The phenomenology and theory of this hybridization is well understood, but not our interest in this paper.

7. Beyond the NIS tunneling data in Fig. 2, which is the focus of the analysis by F&M, the second half of the paper addressed length-dependent even-odd Coulomb peak spacing in Coulomb blockaded full-shell islands. Those results are consistent with an interpretation in terms of Majorana zero modes with finite separation, and are not consistent with trivial Andreev bound states or other interpretations as far as we know.

8. Throughout, we have adhered to established scientific practices in all aspects of our work. Firstly, we appropriately describe all data processing that went into the publication. Secondly, when, in response to requests by F&M, Jelena Stajic urged that we make an additional Zenodo posting, we did so in a timely fashion (see Attachment 1 for timeline), posting an extensive amount of tabulated data, well beyond community standards.

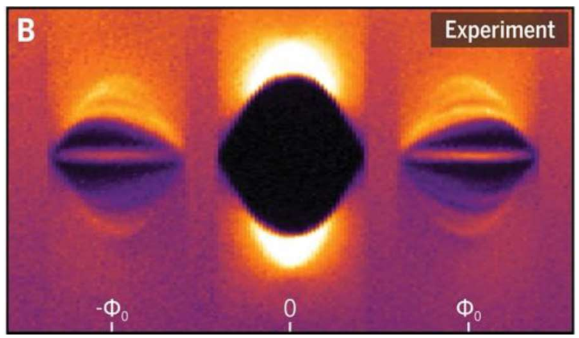
Post-publication analysis of ‘Flux-tuned topological superconductivity in full-shell nanowires’ Vaitiekenas et al. Science 2020

Sergey Frolov, University of Pittsburgh
Vincent Mourik, University of New South Wales

June 01 2021

1. Summary of our findings

In March 2020 a paper was published in *Science* titled “Flux-induced topological superconductivity in full-shell nanowires” https://science.sciencemag.org/content/367/6485/eaav3392 (in what follows Science-2020)
Having carefully studied the paper, as well as additional data that were only made available after the paper was published, we conclude the following.



Key data of the paper, showing a pattern that is irreproducible in the larger dataset. From the Research Article Summary of the Science-2020 paper.

Data in the key Figure 2 are not representative of the full experimental data obtained. The additional data contain datasets that contradict Figure 2 in significant ways. Contradictions are found in data over larger parameter ranges from the same device, as well as in analogous data from other devices.

With respect to data as shown in Figure 2, multiple statements throughout the paper are irreproducible or misleading. These statements concern both the description of the data, as well as the interpretation of the data as relevant to ‘flux-induced topological superconductivity’ - the topic of the paper. Thus the core conclusions of the paper are invalidated. We do not see how this paper can remain in the present form, nor how the problem can be addressed by publishing any form of clarification such as a correction.

Selection of data for publication or for another form of presentation is an inevitable part of the research process. Hundreds or thousands of datasets are obtained for each study in our field. Yet only 5-10 become figures in a given paper. Here we identify a situation in which the selection of data for this paper is not representative of the total data obtained. This could be a consequence of one or several factors. We do not attempt to assign a particular explanation as to why data were chosen in a non-representative way.

1.
This statement about irreproducibility is false. Statistics of devices that do and do not show the features like the ones in Fig. 2 are provided: Of the 23 NIS devices we made, seven showed zero bias peaks in the first lobe with no peaks in the zeroth lobe, similar to the data in Fig. 2. Of the others, eight suffered fabrication failures, six were not tunable, for instance due to incomplete etching, and two were tunable but did not show zero bias peaks. From the nine NIS (tunneling spectroscopy) devices presented in the paper and Zenodo repository, devices 1, 3, 4, 8, 9, 10, and 11 showed zero-bias peaks; devices 5 and 12 did not. In fact, data from several devices showing zero bias peaks like those in Fig. 2 are presented below in F&M’s own document, indicating that they know perfectly well that numerous devices showed similar phenomena. As presented in detail in the paper, theory does not expect all devices to show a topological phase.

2.
Not every device is topological, as expected theoretically. Our claim is that devices *can* show a topological phase, and that a significant fraction do, but not that every device must. Are all the wires exactly the same? No. Do we expect all to show topological phase? No. But many do. To be specific, Fig. S5 shows tunneling spectroscopy from device 3, which qualitatively reproduces the data shown in Fig. 2 from device 1.

3.
Not a single false statement or mistake is pointed out by F&M. It is patently false that the data is irreproducible; it was reproduced in multiple devices. It is also incorrect to say that statements in the paper are misleading. At best, we see disagreements of interpretation. However, no alternative interpretation to ours is put forward that can accommodate all the evidence presented in the paper. One can look at a selected subset of data and stretch to explain it in ways other than the one we put forward, but no model that we know of, or that F&M propose, can explain the full body of observations in the paper.

4.
The main findings of this paper are the experimental observation of signatures of the topological superconductivity in a full-shell nanowire devices and a theoretical analysis of this phase of matter in a full shell nanowire. We observe the phenomenon in several devices but a detailed study of the yield statistics is beyond the scope of this paper. We focused on a regime in parameter space where it is reasonable to expect to observe topological phase. Several devices show data consistent with a topological phase. Some do not, in agreement with expectations, not to mention those that simply did not work, which have also been reported.

To be specific, Figs. 2 and S5 illustrate qualitatively similar behavior from different devices. Given that we are reporting a new route to a topological phase, supported by excellent agreement with theory, it is not surprising that we have emphasized devices that show the signatures of a topological phase. However, we also show devices which did not show signs of a topological phase, like the device in Fig. S7. Theory predicts the existence of both types of devices, and we have faithfully represented data from both types.

1.2 Who we are

Sergey Frolov (SF) is an associate professor at the University of Pittsburgh specializing in experimental condensed matter physics, in particular on transport experiments on low dimensional systems at cryogenic temperatures. Vincent Mourik (VM) is a postdoctoral scholar at UNSW focusing on spin physics in silicon defects. Majorana research has been the topic of the PhD work of VM. SF has been focusing on Majorana in his research for the past 10 years. Both VM and SF have written articles for *Science* and are familiar with editorial policies and standards. Neither SF nor VM are driven by personal or other disqualifying motives to misrepresent our findings in any way to the magazine.

1.3 What this analysis is based upon

Our analysis is based on publicly available materials and can be verified and reproduced by third parties. The available data that are relevant to Figure 2 of Science-2020 paper is 52 datasets from tunneling measurements. We perform our analysis under the assumption that these data are the best available in support of the claims of the paper. This is because the authors shared the additional data in response to a request from us that clearly stated our goal was to re-analyze their results.

Data can be found at: http://doi.org/10.5281/zenodo.4263106 and can be split in three groups:

•**The *Science-2020* paper main figures**: In March 2020, *Science* published a paper 'Flux-induced topological superconductivity in full-shell nanowires'.

•**SOM:** Supplementary Online Materials published with the *Science-2020* paper.

•**Additional data**: On August 18 2020 we asked the corresponding authors of the *Science-2020* paper to share more data. They uploaded more data on November 8 2020. These data can be found in additional_data.zip on Zenodo.

The data made available to us are likely incomplete. Typically many more samples are studied that inform a given paper than those presented in the paper. The Zenodo repository gives the number of samples that exhibited ZBP as 9. All those studied samples and data obtained are part of the full volume of data. The conclusions of the paper are based upon those even if the data are not presented within the paper. Data obtained at a later moment in time, after the publication, or by different researchers, are not part of the full volume of data for the published study.

5.
When the editor asked us on Oct. 22, 2020 to post additional data (noting that our original submission satisfied pre-publication transparency) we promptly provided the requested data, comprising over 300 MB of data in 130 files, which further supported the conclusions of our paper. We satisfied the request in just over two weeks, posting on Nov. 9, 2020. We received a response from the editor indicating their appreciation (see Attachment 1).

6.
We have provided data needed to support the conclusions in the paper, demonstrate reproducibility, and show that the data featured in the figures is representative.

7.
This statement is false.

The Zenodo repository gives 9 as tunable NIS junctions. 7 of these devices showed ZBPs, with the following practical definition:

Number of NIS junctions that showed a zero bias peak visible (by eye) well outside experimental noise, and not necessarily persisting throughout the 1st lobe.

A dataset is a single graph, usually derived from executing a measurement script on a measurement computer that controls the measurement equipment. In the original form, a dataset is a spreadsheet of numbers that can be plotted as a curve or a two-dimensional colormap. ‘Original’ refers to the datafile, a settings file and a script as recorded at the moment of the measurement, without any further alteration. Sometimes ‘raw data’ is used which some people use to describe original data and others to describe any spreadsheet data including those already processed, e.g. for publication. To us, ‘raw data’, or ‘full data’ imply what we describe here as the original data.

2. Background information on the physics of Majorana states

It is not required to be an expert on Majorana research to understand our findings. In fact, little to none of the Majorana physics is involved in our arguments because the issue we identify is the lack of reproducibility of the regimes shown in the figures. However, it is helpful to know several well-established and non-controversial facts about Majorana states and their relationship to the specific subject of the Science-2020 paper.

Names used for this phenomenon are: Majorana fermions, Majorana bound states (MBS), Majorana zero modes (MZM). A regime in which Majorana modes are present is commonly referred to as ‘topological regime’ or ‘topological superconductor’. The title of the Science-2020 paper contains the words ‘topological superconductivity’, and the authors describe their observation of Majorana modes in the paper.

8. What we describe is experimental data on two types of measurements (NIS spectroscopy and even-odd Coulomb blockade peak spacing), realized in dozens of devices, as well as theoretical analysis and numerical modeling, which together form a consistent picture describing a new route to topological superconductivity. We know of no other explanation for our data besides the one we present, with full consistency between experiment, theory, and detailed model.

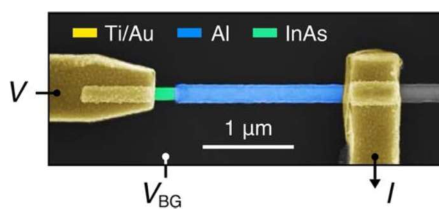
Majorana states have been predicted to produce conductance peaks in electronic transport measurements. These peaks are expected at zero source-drain bias voltage, hence Majorana Zero Modes. The peaks are referred to as zero-bias peaks (ZBP) or zero-bias conductance peaks (ZBCP). They are expected to not be transient, but rather remain at zero voltage while electric and magnetic fields are varied by experimentalists over some range.

It is also important to know that Majorana is not the only phenomenon that results in non-transient zero bias peaks. Another well-studied effect is called Andreev bound states and such states are expected to form much more easily than Majorana states, meaning they can exist over much wider ranges of experimental parameters. It is known, at least since 2014, that under certain conditions Andreev bound states can generate non-transient ZBCPs that can mimic Majorana states. Andreev states are sometimes called ‘trivial’, which is understood as ‘not a Majorana state’ and/or ‘not topological’.

Having provided this background, we emphasize that the conclusions of the present analysis and its findings do not depend on the currently ongoing scientific debates about whether evidence supporting the existence of Majorana modes in any device or materials platform has been already obtained. We do not rely on the present scientific understanding of this question, and we do not rely on any research that has taken place after 2018, the date of the initial posting of results on arXiv. Instead, our analysis is confined to checking for consistency between written statements and the figures presented by the authors in their Science-2020 paper, and the larger dataset now available.

2.2 Measurement techniques used

The technique used to obtain data in Figure 2 is electrical measurements where a small bias voltage is applied across a sample and current, or conductance (the change in current as bias voltage varies), is measured. This is the technique used to search for a ZBP in nanowire devices. Devices studied this way are referred to by the authors as 'NIS' (normal-insulator-superconductor). This is because a separate voltage on a nearby gate electrode is used to deplete a segment of the bare semiconductor nanowire in a field effect transistor-like manner. This creates an insulating segment located between superconductor and non-superconductor (normal) metal contacts. Electrons have to quantum-mechanically tunnel across the insulating segment, so a zero-bias peak is obtained in a tunneling or a tunneling spectroscopy measurement.



A segment of Figure 2A. Source-drain voltage bias V is applied to normal contact (Ti/Au) on the left. Current I is measured after passing through Al superconductor (blue shell on top of nanowire). InAs (green) is the bare nanowire that becomes an insulator when gate voltage V_{BG} is applied to the doped silicon layer underneath (dark background).

Once a device is fabricated and set up for measurements in a cryostat, the primary control knobs available to the authors are source-drain bias voltage between normal and superconducting contacts, gate voltage(s), external magnetic field (or magnetic flux) and temperature.

The two additional measurement techniques used in the Science-2020 paper are supercurrent through the shell (Figure 1) and Coulomb blockade (Figures 6 and 7). Figure 1 does not show Majorana measurements and is redundant with respect to Figure 2 for the purposes of our analysis. Figures 6 and 7 (Coulomb blockade measurements) are secondary to data in Figure 2, meaning that irreproducibility of Figure 2 cannot be rectified by data or analysis in Figures 6 and 7. We will make further comments on the Coulomb blockade technique below after presenting our analysis. Figures 3, 4 and 5 are devoted to theory, which is not relevant to how representative the tunneling data are. We comment on the theory later.

3. Analysis of tunneling data (Figure 2)

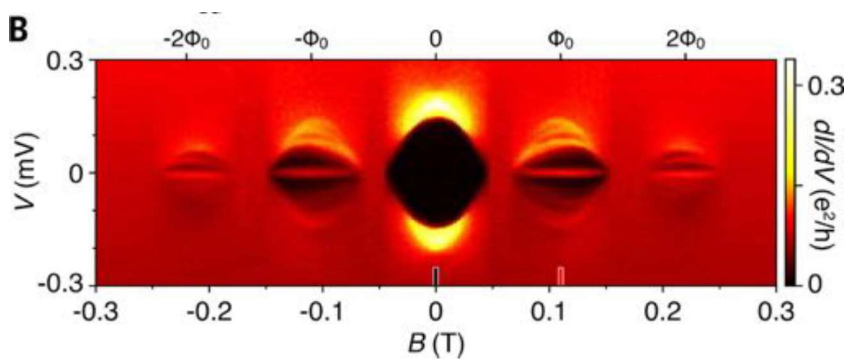


Figure 2 is composed based on three separate datasets, panels B, C and E, all presented as colormaps of conductance dI/dV, given in the units of e^2/h. Panel B is the most illustrative and the most discussed in the paper, it is a magnetic field B(T) evolution of conductance as function of source-drain bias voltage V(mV).

Panel 2B presents two key phenomena. The first of them is the zero-bias peaks that we mark with gray dashed lines below. They are visible at V = 0 mV and around B = 0.1 T and B = -0.1 T as two narrow and long red horizontal streaks surrounded by a dark background. The second is the oscillations of the dark, low conductance region around zero voltage bias that we marked by the green trace. They have been known since 1962 as Little-Parks oscillations in superconducting rings. The lobes of oscillations correspond to the number of flux quanta threading the nanowire which we label with green numbers -2, -1 0, 1, 2. The top horizontal axis labels magnetic flux in units of flux quantum Φ_0. Important for understanding the authors' statements is that each flux quantum corresponds to the winding of the superconducting wavefunction's phase of 2π, a flux of $2\Phi_0$ is 4π winding, etc. This language of 'winding' is used in the paper.

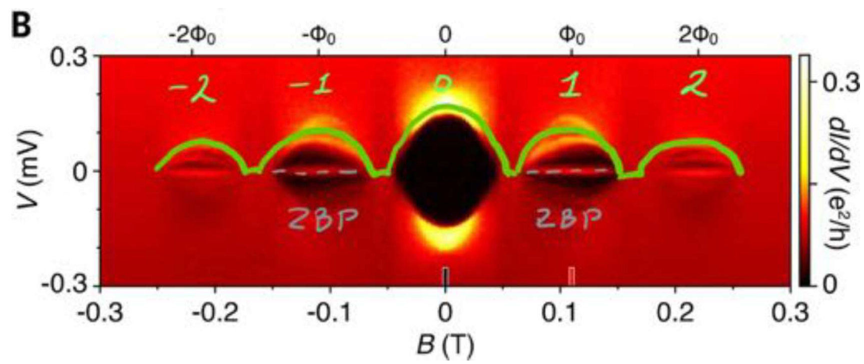
The relationship between the two phenomena, zero-bias peaks (ZBP) and Little-Parks oscillations (LP) is the topic of the Science-2020 paper. The authors use Little-Parks

9.
The data in Figs. 6 and 7 are critical to our interpretation and are in no sense secondary. While zero-bias peaks may have multiple origins, the data in Figs. 6 and 7 are very difficult to explain with alternative models. The totality of the data in the paper is consistent with our interpretation, and no data in the entire data set contradicts our interpretation. While the key signatures of topological superconductivity are reproduced numerous times in the paper, not all devices show a topological phase. That is consistent with expectation, and we show such data to highlight that point. The observation that some devices do not show a topological phase is not contradictory to our interpretation, which is that a topological phase can exist.

10.
The Little-Parks effect that has been known since 1962 is a modulation of the transition temperature of a cylindrical superconductor. The destructive Little-Parks regime is a reentrant complete suppression of superconductivity due to the field threaded through the cylinder. To our knowledge, this phenomenon had been reported only twice before our work, in 2001 (Liu *et al.*, Science) and 2011 (Sternfeld *et al.*, PRL). Tunneling spectroscopy of destructive superconductivity of the sort shown in Fig. 2 has, to our knowledge, never been reported prior to our work.

oscillations as a counter for how many flux quanta are threading the wire. This number of flux quanta they connect to topological superconductivity (MZM):

"We show experimentally and theoretically that the winding of the superconducting phase around the shell induced by the applied flux gives rise to MZMs at the ends of the wire." From the Structured Abstract, also referred to as the Research Article Summary.



Also from the main text:

"The topological phase sets in at relatively low magnetic fields (~0.1 T), is controlled discretely by moving from zero to one phase twist around the superconducting shell" Science-2020, p1.

And here is an example of how the authors describe this relationship in more technical terms, relating zero-bias peaks to the first lobe of Little Parks oscillations (LP-1):

"In the superconducting regions around one quantum of applied flux, corresponding to phase twists of $\pm 2\pi$ in the shell, tunneling spectra into the core show stable zero-bias peaks, indicating a discrete subgap state fixed at zero energy." Science-2020, p1.

In Appendix A we list 30 instances where the relationship between ZBP and LP is stated in Science-2020, including 7 that discuss the reproducible coincidence of ZBP and the first lobe of the LP (LP-1). In what follows we analyze the ZBP/LP-1 coincidence itself and do not contribute any of our own interpretation of its relationship to the topological/Majorana physics. (We also analyze several other statements that the authors make about there being no subgap features in LP-0 or the even/odd pattern. Those statements are important but secondary to the coincidence of ZBP and LP-1.)

11.
We could not find the 30 quoted instances. The few sentences that are quoted do not state that the topological phase must always occur in the entire first Little-Parks lobe, that is, whenever n=1 independent of any other parameters. In fact, our theory indicates that this is not the case, already at the level of the simple toy model studied in the section "Modeling of topological phases". Fig. 3B shows that the extent of the topological phase does not cover the entire flux range with winding number n=1. The same conclusion can be drawn by inspecting the relevant Eqs. 7-12 of the main text.

The more realistic numerical simulations indicate that the winding number n=1 allows the most favorable conditions for a topological phase, in terms of its experimental accessibility, the magnitude of its energy gap, and its magnetic field range. Together with experimental evidence, this explains our focus on the regime with n=1.

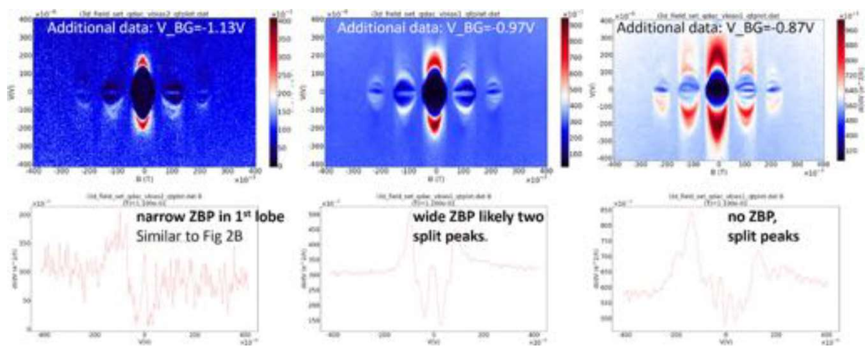
The effect of the winding number is the key ingredient of our proposal, because it allows access to the topological phase at lower magnetic fields than previously thought possible. In our opinion, it was novel and conceptually appealing to connect the Little-Parks effect and topological superconductivity. Thus, it is natural that we have emphasized this connection in the main text and in the article summary.

Figure 2 presents data from Device 1, and shows a clear coincidence of the ZBP with LP-1. To understand how reproducible this is, we first turn to additional data from the same Device 1; these data were not published with the Science-2020 paper. We replot these data from Zenodo files, hence the different colorscale.

We see three additional datasets, the difference between them is the setting of back gate voltage V_BG. Only one of the new datasets, V_BG = -1.13 V, shows a narrow ZBP comparable to panel 2B. At V_BG=-0.87V we see no ZBP in LP-1. Instead, peaks at finite V (also referred two as split peaks) are observed.

12.
From this statrment one might infer that these features are not presented in the paper. This is not the case. In fact, the back-gate range that connects the three magnetic field sweeps is shown in Fig. 2E at B=0.11 T. Thus, Fig. 2E displays the same phenomenology of the three magnetic field sweeps, showing the continuous evolution of the ZBP occurring in between the magnetic field sweeps. We judged it more informative to show the readers this continuous evolution rather than three separate sweeps at discrete values of the back-gate.

Our observation that, at gate voltages corresponding to larger conductance in Fig. 2E, a zero bias peak becomes a dip refers to the curvature around zero bias (peak = local max, dip = local min) and to the fact that the zero-bias conductance increases monotonically, except at the locations of charge jumps, while the curvature changes sign. The bias versus field scans of device 1 that were not included in the main text or supplementary are taken for values of gate voltages characterized by a zero-bias dip and higher conductance levels. In this regime, conductance peaks at finite bias are not a faithful proxy for the local DOS because of the possibility of Andreev enhancement.



At V_BG=-0.97V (center) we see a ZBP which is thicker in voltage bias. Continuing the trend from data at V_BG=-0.87, this thickening of the peak can be a consequence of having not a single ZBP but two closely spaced and overlapping split peaks. This is also confirmed by the additional back gate voltage dependence data shown in the next section.

13.
This feature can be clearly seen in Fig. 2E and our interpretation of it is discussed in the main text.

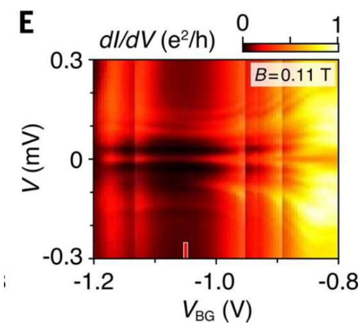
3.2 Gate-dependent zero-bias peaks

Additional data reveal that the presence/absence of ZBP is related to how the back gate voltage is chosen. This is seen in the magnetic field dependences presented above, and in the additional gate voltage dependences plotted below. The fact that gate voltage can control ZBP should be surprising to a reader of the paper. The authors state:

"Although full-shell
do not allow for direct gating of the electron density in thesemiconducting core,
we demonstrated that, using a careful design of the wire

properties—for example, by choosing the appropriate radius— it is possible to obtain wires that harbor MZMs at a predictable magnetic field"

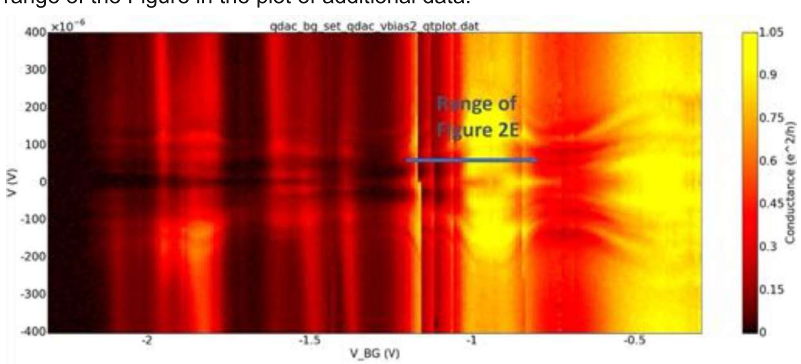
While lack of gating of the inner core of the wire is stated in the paper and is reasonably expected from a device clad in a full metallic shell due to screening, the actual measurements related to gate sensitivity of ZBP are shown in Figure 2E, which is the back gate evolution of conductance, now at a fixed magnetic field. This is how data in panel 2E are described in the text:



"In the first lobe, at B = 110 mT, the sweep of VBG showed a zero-energy state throughout the tunneling regime (Fig. 2E). [...] As the tunnel barrier is opened, the zero-bias peak gradually evolves into a zero-bias dip." Science-2020, p2.

Indeed, in Figure 2E we see a zero-bias peak that spans most of the image. The 'dip' observed around V_BG=-0.8V is also interpreted by the authors in the context of MZM (more on this later). Thus, the entire panel E is associated in the paper with the topological regime.

However, in contrast with Figure 2E, additional data contain a dataset over a larger range of V_BG with a ZBP region similar to that in Figure 2E but which covers about 18% of the full gate voltage range. The additional data in the image below do not show 1:1 correspondence to the data in Figure 2E, presumably due to irreproducible charge jumps. To establish some correspondence with Figure 2E, we mark the gate voltage range of the Figure in the plot of additional data.



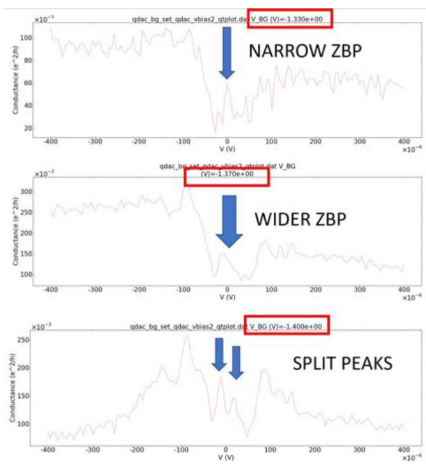
14.
This sentence from the conclusions is taken out of context. On page 2 of the paper we write "The increase in conductance at V_{BG} ~ −1.2 V is likely caused by a resonance in the barrier", pointing out the fact that there are gate-sensitive resonances in the junction.

15.
The charge jumps are reproducible (see Figs. 2C, 2E, S3B, taken at different field values, one after the other). On page 2 of the main text we write "Several discontinuities in spectra occurred as V_{BG} was swept at the same gate voltages in Fig. 2, C and E, presumably because of gate dependent charge motion in the barrier."

We interpret the shift of the data in gate voltage as due to hysteresis in the dielectric, which gets more pronounce when the gate is swept over a larger range.

After replotting and analyzing these data, we find the following regimes:

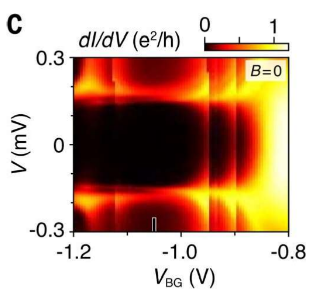
1) Noise without features between V_BG = -2.25 V and -2.19 V
2) Split peaks between V_BG = -2.19 V and -1.38V (does not appear in Figure 2E)
3) ZBP between -1.38V and -1.035V (similar to Figure 2E)
4) Split peaks between -1.03V and -0.90V
   (similar to Figure 2E, and also where the magnetic field dependence shown in the previous section at V_BG=-0.97 falls, though gate voltages may not correspond to each other due to irreproducible charge jumps)
5) ZBP between -0.90 V and -0.70 V (does not appear in Figure 2E)
6) More split peaks between -0.7 V and -0.3 V (does not appear in Figure 2E)



Thus, additional data of gate voltage dependence in LP-1 demonstrate regions of split peaks that exceed in gate voltage range the regions of zero bias peaks, and a second region of zero bias peaks at more positive gate voltages. This contradicts statements in the paper regarding the gate voltage dependence of zero-bias peaks.

We observe that the zero-bias peak never approaches the noise level in this additional dataset. It remains visible until it is replaced by a pair of split peaks. The splitting is gradual, as far as linecuts show.

The description of Figure 2E contains the phrase '*throughout the tunneling regime*'. Science-2020, p2. We understand this phrase as the range of V_BG in Figure 2E (and 2C) being the only relevant range. The 'tunneling regime' is the regime where conductance at finite bias, e.g. V>0.3, is below 2 at zero magnetic field, and below 1 at large magnetic field. Figure 2E is composed in such a way that at the left boundary of the panel the overall conductance is low, 0.1-0.3, and at the right boundary of the Figure conductance is high, approaching 1. The same impression is given by panel 2C which is the same regime as 2E but at zero magnetic field.



16.
The left side of the graph is beyond the tunneling regime, where a resonant dot appears in the junction, complicating the system. This more complicated scenario is not the topic of our paper. These resonances obscure the visibility of the wire density of states, and so, as we mention in the supplementary, "We usually associate such state with a resonant level in the barrier and if possible avoid it in the measurement." We disagree with the statement that the data shows that "the splitting is gradual" as the data for V_{BG} < -1.4V is fully consistent with a scenario of the Majorana ZBP losing visibility while a pair of (split) peaks appear due to barrier states. Note that it has also been shown (by some of the authors) in arXiv:2103.12217, that potential variations that can create barrier states can also reduce the visibility of Majorana modes which supports the above scenario.

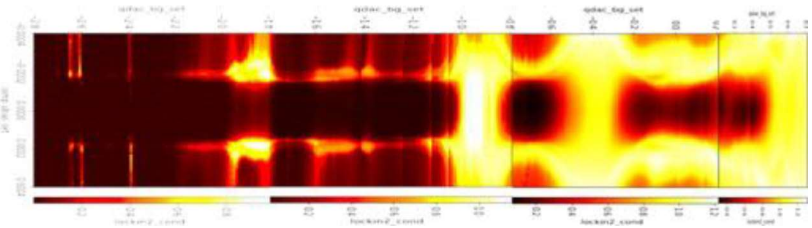
17.
Gate sweeps in Fig. 2 are not cropped version of data from extended gate-voltage ranges, as implied, but show a full gate-voltage range of data taken a week later. The extended-range gate sweeps were part of an initial device screening run, which exposed all devices on the chip to large voltage excursions from a global back gate. A week of time and multiple gate sweeps had changed the impurity configuration in the barrier.

Extended-range data was taken June 4, 2018 starting at 6:09 PM; Figs. 2C, 2E, S3b, and B were taken back-to-back on June 11, 2018 starting at 3:56 PM, 4:16 PM, 4:56 PM, and 6:28 PM. Figs. 2C and 2E show the full gate-voltage ranges of the data sets taken in those runs.

18.
We identify the tunneling regime as the transport regime where the conductance is a good proxy of the local density of states of the end of the wire, on the other side of the junction. This requires the normal state conductance to be well below e^2/h. Typical values would be ~0.1 e^2/h. At higher values, the NS conductance is not be a good proxy anymore of the local density of states, due to the enhancement of Andreev reflection.

Furthermore, to measure a good proxy of the density of states, one should avoid ranges in which the junction hosts localized states in accidental quantum dots. Their presence complicates the interpretation of the conductance traces in terms of density of states because one needs to consider co-tunneling processes and the coupling between states in the wire with the states in the junction. We did not consider these gate ranges to be the tunneling regime.

The statement that the entire tunneling regime has been presented in Figures 2E and 2C can be scrutinized by considering the additional data obtained at zero magnetic field (this is a composite of four separate datasets, the range of Figure 2C is between -1.2 V and -0.8 V):



From these data, not published with the Science-2020 paper, we see that:

1) Conductance is below 1 at high V (e.g. top edge) for back gate voltages as high as V_BG=+0.2V, outside of high current resonances (vertical yellow streaks). At zero magnetic field, tunneling takes place for conductances below 2 in the basic picture.
2) The superconducting gap feature (horizontal peaks at V = +/-0.002) are present for back gate voltages as low as V_BG=-2.7V, indicating that electronic tunneling is still taking place.

From this we conclude that a much larger back gate voltage range -2.7V < V_BG < +0.2, or larger, corresponds to the tunneling regime. The data in Figures 2E and 2C, over the gate voltage range between -1.2 V and -0.8 V occupy only a fraction of the tunneling regime. Consequently, the statements in the paper that zero-bias states are observed throughout the tunneling regime are incorrect, since in other parts of the range split peaks are observed.

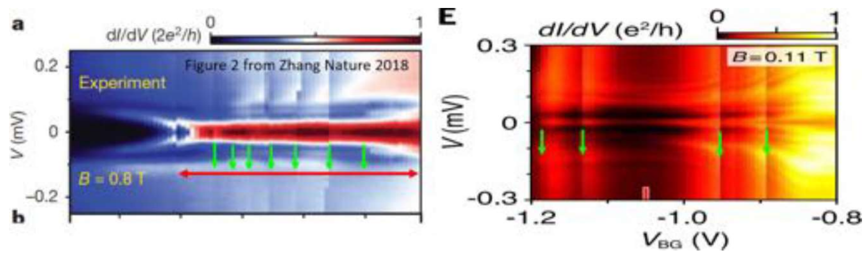
We stress that the argument we make does not boil down to a debate about the appropriate gate voltage extent of the tunneling regime. The need to have presented a larger range of gate voltages within the paper, so as to make it clear that gate voltage does have a significant effect on the apparent zero-bias peak, is only made stronger by the uncertainty in determining which range corresponds to the tunneling regime. The authors did not present these data, but instead put statements in their paper to suggest the absence of gate effect over a relevant gate range. The possibility that this is not the full relevant gate range was not presented.

19.
The regime in which spurious quantum dots form, leading to resonances and hybridization of localized states with nanowire states, is beyond the tunneling regime where one should perform spectroscopy. The quantum-dot regime is not useful for our study, as it brings in new effects associated with hybridization. We deliberately tune to the tunnel regime rather than the quantum-dot regime so that tunneling conductance is proportional to the local density of states.

In the quantum-dot regime, the conductance reflects dot-wire interaction, not the density of states in the end of the wire. One cannot just measure anywhere, one must tune the barrier to use conductance as a proxy for local density of states.

20.
Our paper was written with the intent of describing the published figure to the reader, which we consider to be illustrating the tunneling regime. We did not (and still do not) consider it to be uncertain in which gate regime the junction is in the tunneling regime (~0.1 e^2/h) and in which gate regime we see additional resonances. The hybridization of the zero-bias state with the spurious dots that form at the wire ends are expected, they have been studied and published before, and are not relevant for the first study of a new concept.

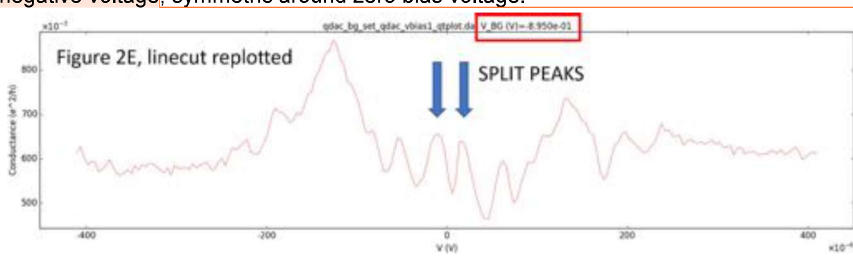
The gate voltage range with ZBP that was shown in Figure 2 is extended by 'charge jumps' which are sharp discontinuities in the colormap. As the back gate voltage increases the signal shifts back to a previous value, in a manner similar to a skipping record, but due to a shift in the position of a small charged particle near the nanowire. Charge jumps were used in a recently retracted 'Quantized Majorana Conductance' Nature paper, originally published in 2018, to extend the gate voltage range of ZBP (green arrows):



We furthermore find that the following sentence from Science-2020 is inaccurate. It is important to point out this inaccuracy because the statement connects a feature of the data to a 'theory supporting MZMs':

"As the tunnel barrier is opened, the zero-bias peak gradually evolves into a zero-bias dip. The increase of finite-bias conductance compared with zero-bias conductance as tunnel barrier decreases is in qualitative agreement with theory supporting MZMs" p2.

The inaccuracy occurs where the authors discuss the evolution from a zero-bias peak to a zero bias dip. In fact, the zero-bias peak splits and becomes two peaks. We replotted Figure 2E ourselves to verify this, and we can also see from additional magnetic field sweep data, as well as from additional gate voltage sweep data, that these are not dips but rather a pair of peaks, split away from zero bias voltage to a finite positive and finite negative voltage, symmetric around zero bias voltage.



21.
Our interpretation is that the ZBP of device 1 reported in Fig. 2E is not related to an accidental, persistent level crossing between local quantum dot states. Qualitatively, we base this interpretation on the observation that the ZBP persists for a finite range of gate voltages without splitting, not even when it approaches the conductance noise level. We are not aware of any quantitative criterion that we could have used to judge the range of stability of a ZBP with respect to tunnel gate against or in favor of our interpretation. The reported observation of charge jumps in this measurement has not influenced our interpretation.

The implied connection to the retracted Nature 2018 paper, by a different lab and different authors – guilt by superficial visual association – is unacceptable.

22.
An inspection of the entire gate range where this feature occurs reveals that:
(1) the zero bias-conductance increases monotonically in the range under consideration, except, understandably, at the position of charge jumps;
(2) the magnitude of the zero-bias conductance follows closely the magnitude of the high-bias (normal state) conductance.

Therefore, we judged these two observations to be at odds with the expected behavior of a peak splitting, which would be likely to determine a decrease in the zero-bias conductance with respect to the high-bias conductance. Thus, in the main text, we have interpreted this behavior as the crossover from a peak to a dip (namely, a change in the conductance curvature vs. magnitude at zero bias).

In a minimal theory of resonant reflection through a Majorana zero mode, the crossover from a conductance peak to a dip should occur when the peak conductance value has reached 2 e^2/h. In our data, this is not the case. This may be due to an overall reduction of the conductance level related to the disorder in the system. While possible, we judged this argument to be too speculative to appear in the main text, where we simply pointed out the presence of a quantitative inconsistency with pre-existing theory by other authors.

As mentioned above, in the gate range of Fig. 2E where the conductance has a zero-bias dip, the junction is not in the tunneling regime anymore, and thus the conductance spectrum cannot be interpreted as a proxy for the local DOS.

At more positive gate voltages an apparent dip can indeed be seen at zero voltage bias. However, where the authors make a link to an MZM theory they do not discuss or explain how split peaks fit into this comparison between experiment and theory. We find this to be significant based on our understanding of the cited and other MZM theories.

To summarize our analysis of available tunneling data for Device 1 (Figure 2 vs. additional data) we conclude that both the magnetic field dependence (panel 2B) suggestive of correlation between ZBP and LP-1, and the gate voltage dependences (panels 2C and 2E) suggestive of zero-energy states present throughout the tunneling region of back gate voltage are not representative of the total data. This leads to statements in the text of the paper, where these data are described and generalized, to be invalid.

23.
Because we interpreted our data as a peak-to-dip crossover and not as a splitting of the zero-bias peak, we did not discuss in detail the latter scenario. We cited the relevant work that discussed the peak-to-dip crossover and pointed out the quantitative inconsistency between that theory and our experimental data. We think that the explicit mention of a quantitative discrepancy is enough to alert the reader that not every detail of the data is claimed to be understood.

24.
The presented data are representative of the tunneling regime, in contrast to the open and quantum-dot regimes.

4. Device-to-device reproducibility

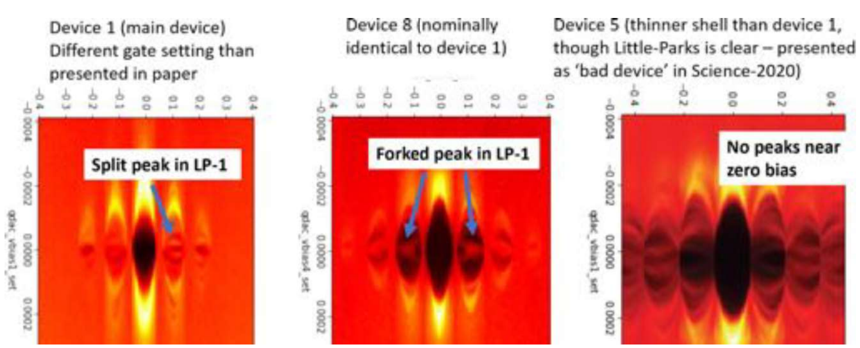
An important part of the argument that the authors make in their Science-2020 paper is reproducibility of these observations from device to device. They write:

"Two device geometries, measured in three devices each, showed similar results." Science-2020, p1.

"Moreover, the full shell naturally protects the semiconductor from impurities and random surface doping, thus enabling a reproducible way of growing many wires with essentially identical electrostatic environments." Science-2020, p6.

25.
"Enabling" is the key word in this sentence. This sentence is taken from the last paragraph of the main text and is meant as a positive outlook for the potential future works. Wires grown in the same batch can still possess different shapes, different diameters, different shell thicknesses, all of which effect the topological regime (for more details, see the comment on page 23 of F&M's analysis). The fact that the measured wires from the same batch are not identical is obvious when comparing, for example, the data from device 3 (Fig. S5) and device 4 (Fig. S6). We did not state that we are able to deterministically select, control or eliminate the intrinsic variability between nanowires.

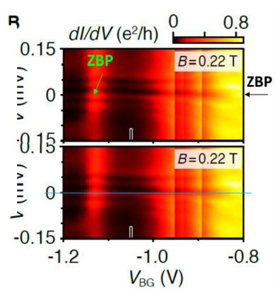
The total number of devices for the tunneling geometry was subsequently disclosed by the authors to be 9. We can compare data from those devices to Figure 2.



On the left we repeat data from Device 1, not shown in Science-2020, where no ZBP is observed in LP-1. In the center, we see data from Device 8, not shown in Science-2020, which authors describe as 'nominally identical' to Device 1. We see that within LP-1 a pair of split peaks merge into a ZBP, a behavior which suggests that there is no connection between the phenomena of LP and ZBP in this case. On the right, we see data from Device 5 which the authors describe as different from Device 1, a statement that does not find strong support in additional data (more on that later). In this device, while LP oscillations are clear, we see no ZBPs.

Some datasets from other devices, 3, 4 and 9, do show a coincidence between ZBP and LP-1 in magnetic field sweeps, in line with Figure 2B. However, as we demonstrate above for Device 1, this can be a result of acquiring data at an atypical setting of gate voltage where such coincidence appears. Recall that from each device we only see a few datasets on Zenodo. Taken together, additional data and paper data provide plenty of examples where the relationship between ZBP and LP-1 is either present or absent. However, Figure 2 of the Science-2020 paper itself only shows that the two phenomena coincide.

4.2 Even/odd pattern



The authors extend and generalize their experimental statements beyond the LP-1 coincidence. They suggest that whenever the number of flux quanta is even, 0 or 2, there is no ZBP. But when the number of quanta is odd, 1 or 3, there is a ZBP. This fits with their MZM narrative, and they make at least 20 statements throughout the paper, where they indicate that their data support this 'even/odd' pattern. We list the statements in Appendix A. We do not find support for the existence of such an even/odd pattern in the total data we considered.

The data to support the entire even/odd ZBP/LP pattern in a single graph is limited to one dataset from Device 4 that shows a pattern up to LP-3. However, in Device 3, the key verification device, and in Device 12, nominally identical to Device 1, there are no ZBPs in LP-3. In fact, the only dataset from Device 12 shows no peaks in any lobes. In Device 5, the 'bad' device which has no ZBPs in LP-1, we see broad ZBPs in LP-3. In other devices LP-3 is not visible.

26.
The data on the left is taken within the gate voltage presented in Fig. 2E, as discussed in the comments above. Likewise, we have already discussed that the topological phase does not have to span the whole 1st Little-Parks lobe. Thus, the data in the middle panel is also consistent with our theory, expectations as well as, interpretation of the data. The data in the right panel is for a wire with a thinner shell, hence a slightly larger gap, as commonly observed for Al. Combined with the slightly larger diameter, this would alter the ratio of coherence length to diameter. Our interpretation is that this is the important difference for device 5, which is never described as a bad device in our work.

In summary, all the three behaviors shown in the panels above can be understood and expected based on the supporting theory and are consistent with our interpretation of the data put forward in the paper.

27.
We repeat what we stated in previous pages: we do not expect a wire to be topological whenever n=1, independent of all other parameters. Theoretically, a variety of patterns can be found: no topological phase in the 1st lobe, presence of a topological phase only in part of the 1st lobe, and presence in the entirety of the 1st lobe. We find this expectation to be well reflected in the experimental evidence, as summarized by the statistics reported on the Zenodo repository.

28.
F&M choose to ignore the crucial sentence of our paper where we discuss this point explicitly. On page 5 we write:
"Mixing of different angular sectors, facilitated by the broken cylindrical symmetry that, in turn, is a consequence of the hexagonal cross section, lifts the restriction that the MZMs must have zero angular momentum (m_J = 0). In the case of broken angular symmetry […] the topological superconducting phase may also appear at even winding numbers".

Furthermore, Fig. S10 illustrates the possibility of having the topological phases in the 2nd Little-Parks lobe for a certain combination of parameters. It is of secondary importance, but still worth mentioning, that the parameters used in the simulations in Fig. 5 indicate a trivial phase in the 2nd lobe, yet a small change in these parameter is expected to push the wire into the topological regime.

We compare and contrast the behavior in different lobes when this is a visible feature of the data, but, well-aware that different patterns can be expected, we are careful not to present observed patterns as a general law that would apply to all data. In any case, the presence or absence of inter-lobe patterns is irrelevant to the main message of our work, that full-shell nanowires are a viable route for topological superconductivity.

29.
As reported in the summary table in the Zenodo repository.

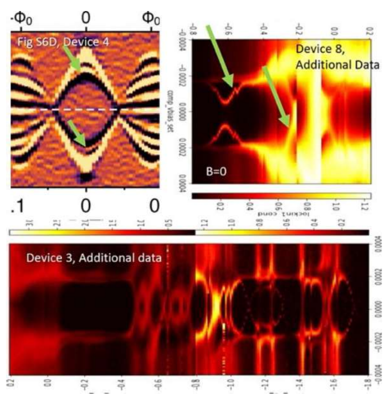
30.
As mentioned above, this device is not "bad". It simply has a clearly different cross-sectional area and shell thickness.

The even/odd pattern would imply that no ZBP is present in LP-2. However, we find for Device 1 a zero-bias peak in the gate voltage dependence within LP-2. This contradicts this statement in the supplementary materials:

'In the second lobe, with even number of phase windings, the spectrum for device 1 features an asymmetric superconducting density of states with the lowest energy subgap state centered around ~5 ueV, see Fig. S3.' SM, p3.

To illustrate this statement, the authors present a magnetic field dependence focused on LP-2 at the back gate set to V_BG=-1.05 V. The zero-bias peak in Figure S3B is at V_BG=-1.15 V, a different back gate voltage.

4.3 Empty gap within LP-0 (near zero magnetic field)



A statement regarding LP-0, repeated with variations several times in Science-2020, is stronger than the even/odd pattern would imply (i.e. no ZBPs in LP-0). The statement is that no subgap states at any bias are present in LP-0:

'*Our measurements reveal that tunneling into the core in the zeroth superconducting lobe, around zero flux, yields a hard proximity induced gap with no subgap features.*' Science-2020, p1.

The importance of the statement of 'no subgap features' in LP-0 for the narrative of the paper is high. If there are subgap features in LP-0, it leaves the possibility open that these features shift to zero energy in magnetic field due to its Zeeman/orbital effect, rather than 'discrete phase winding'. The notion that ZBP in LP-1 appears 'out of nowhere' would then tilt a reader towards believing that a discrete value of magnetic flux, within LP-1, is what generates that zero-bias peak.

Contrary to the statement above, we find in devices 1, 3, 4, 5, 8, 9 subgap features at zero magnetic field. The features are marked with green arrows for devices 1, 4 and 8. In Device 3, the states are so numerous that it is not practical to mark them all.

31.
The discrete phase winding is a direct consequence of the superconducting condensate response to the orbital effect induced by the magnetic field threading the superconducting wire.

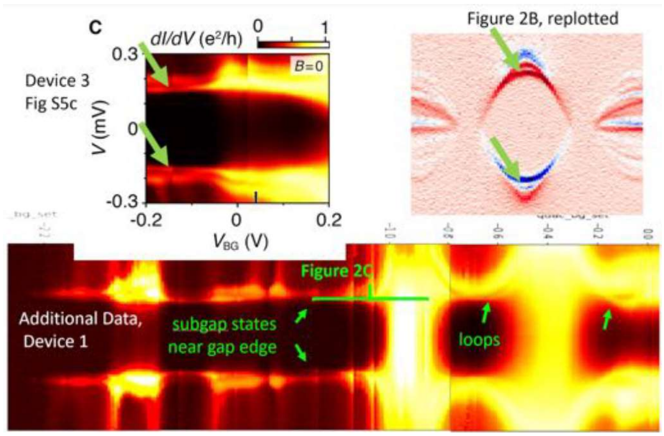
32.
Our statement quoted above is correct when one looks at data that reflects local density of states in the wire as opposed to the spectrum of local resonances. These two cases can be easily distinguished from the back-gate evolution of the spectrum (no dependence vs. strong dependence).

Local junction resoances occurred in our devices, as reported in Fig. S7 and page 3 of the Supplementary:
"For device 5, a discrete state crosses zero-energy [...] resembling a proximitized quantum dot state […]. We usually associate such state with a resonant level in the barrier and if possible, avoid it in the measurements".

We believe that this avoidance is reasonable to mitigate, though not eliminate, the spurious junction resonances. The focus of our investigation was therefore on gate ranges where there are no trivial resonances clearly dispersing already at zero magnetic field. These gate ranges are also the ones where the conductance is a faithful proxy of the density of states in the wire. They reveal a stark difference between the density of states in the 0^{th} lobe and all the other lobes. The latter are characterized by a dense sub-gap spectrum which is absent in the former.

The feature in the 0^{th} lobe just below the main gap, defined by the tallest coherence peaks, reflects a small difference between the parent gap in Al and the induced gap in InAs arising due to finite coupling between the two materials. This is what we meant by the induced gap. Notice, that this feature is gate independent and is visible in, for example, Figs. 2C and 2D for device 1. Given the totality of the evidence accumulated in our work, we find it illogical to suggest that our interpretation came 'out of nowhere', or that we should have abandoned our interpretation altogether just based on a relatively minor feature of the data which can be naturally explained staying within our interpretation.

In Device 4, and in the main Device 1, which is the basis for Figure 2, we identify subgap features that happen to be located very near the edge of the gap. As a reminder, 'the gap' is a horizontal peak in the back gate voltage dependence at approximately +/- 0.0002 V. We notice that these subgap features exist for those gate voltages that are used in Figure 2. In Figure 2 these are not apparent, and only can be identified if an additional data processing step is taken. In the replotted Figure 2B we take a numerical derivative in the vertical direction to identify a feature near zero field. This numerical derivative is the same procedure that the authors applied in Figure S6D for Device 4, which also shows similar features right below the gap.



In the additional gate-dependence data for Device 1, not shown in the paper, we see subgap states that are distinguishable from the gap without extra data processing. They appear as peaks at different V values than the gap. These subgap features appear either as peaks that track along the gap for a range of gate voltage, or as half-loop resonances. The gate voltage range of each of the two loops is greater than 0.2 V, a range comparable to the entire gate voltage range of Figure 2C, 2E.

The fact that the existence of subgap features was not disclosed or discussed in the paper, regardless of their ultimate origin which cannot be unambiguously elucidated based on the available data, is significant. Statements about LP-0 made in the paper lose part of their support and become either inaccurate or misleading.

4.4 More examples illustrate the large variety of observed phenomena

Device 9, revealed with additional data and referred to as 'nominally identical to device 1', shows that it is possible to see a ZBP correlated with LP-1 in a device that, at zero

33.
These features are accounted for within our interpretation as the gap induced in the InAs, slightly smaller than the parent Al gap (see the discussion above). As mentioned above, these features do not depend on gate voltage and thus, are not related to local junction states; they are visible when local junction states are absent.

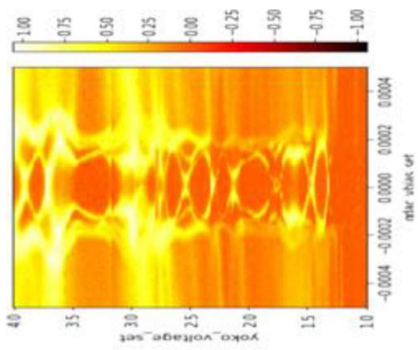
34.
See Figs. 2C and D.

35.
The "loops" are well understood voltage divider effects due to the finite resistance of the low-pass filters, where a portion of the applied voltage drops as the junction becomes less resistive. This is described in the "Materials and methods" section of the paper. In the tunneling regime, which is the focus of the first part of the paper, these effects can be neglected. Therefore, we chose not to apply the correction to the main text figures to minimize the amount of data processing that went into them. A comparison between the as taken and corrected data is shown in Fig. S4.

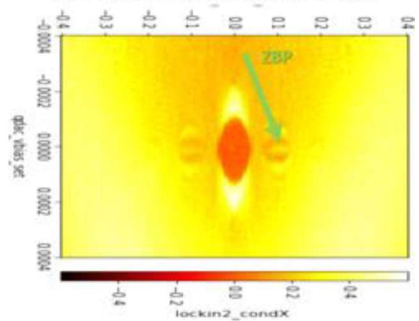
36.
In the main text, we mention both the induced gap (page 1, "Our measurements reveal that tunneling into the core in the zeroth superconducting lobe, around zero flux, yields a hard proximity induced gap with no sub-gap features") and the junction resonances (page 2, "The increase in conductance at V_{BG} ~ -1.2 V is likely caused by a resonance in the barrier").

37.
We agree with that this is a possibility. In order not to deceive ourselves by such scenarios we chose to measure in the regions without dispersing sub-gap states at zero magnetic field. Thus, we do not believe that the tunneling spectroscopy data presented in the paper can be explained this way.

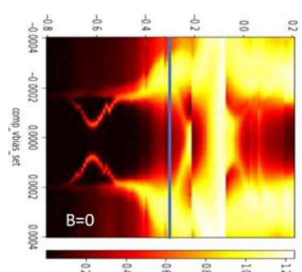
magnetic field, contains numerous states that are not confined near the gap edge, but instead cross V=0 throughout the gate voltage range. Thus, additional data also demonstrate that a zero-bias peak can be observed in the presence of ubiquitous subgap features. This raises further questions about the correlation of LP-1 and ZBP and how the data might look in other regimes not presented in the paper or in the additional data.



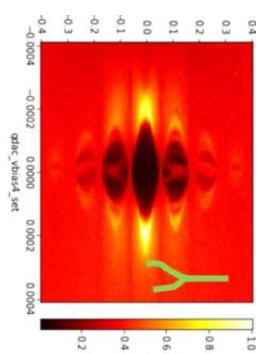
Device 9, "nominally identical to device 1"



Device 8 offers another illustration that a wide range of behaviors has been observed in the authors' experiments, and the coincidence of ZBP and LP-1 is not a representative behavior. At zero magnetic field, Device 8, nominally identical to device 1, exhibits two features, one a resonance that does not cross V=0, and appears at gate voltage V_BG = -0.3. Another one is a resonance that does cross V=0 at V_BG=-0.2 (a charge jump at the same gate voltage makes it harder to see). The authors set V_BG in between the two resonances (blue line), presumably in order to avoid them. However, when the magnetic field is turned on we see a fork-like resonance in LP-1: a pair of peaks merging into ZBP only half way through LP-1.



Device 8,
"nominally identical to device 1"
From Additional data



This is another example of possible behavior of subgap resonances. It is likely that if more magnetic field sweeps datasets were provided to us, e.g. at different gate voltages, more examples would be collected showing a rich variety of behavior, but not a correlation between ZBP and LP-1. It is possible that the authors

38.
There is nothing wrong with forked peaks since, as previously stated, the topological phase can occur only in part of the first lobe. Majorana zero modes can also split in energy due to finite size effects, which can become important for disordered systems or in some regions of the topological phase where the Majorana coherence length is large. We judged the discussion of such a feature not worth emphasizing in a first-announcement paper, but it is fully consistent with expectation and our interpretation.

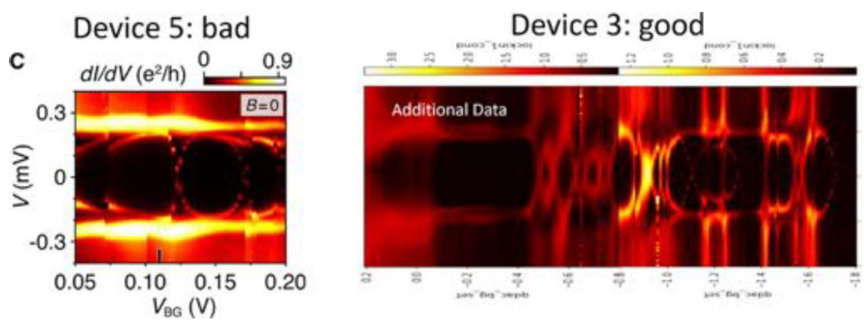
already have more data like that, in which case they should share these data. At the very minimum, additional data demonstrate a range of phenomena that greatly exceeds those presented in the Science-2020 paper.

4.5 Device 5: "bad" device with no ZBP but with Andreev Bound States

The authors present a device in the Science-2020 paper, Device 5, for which they do not show data with ZBP in LP-1. They explain the difference between Device 5 and other devices (1, 3, 4) as due to a thinner shell of Al, and/or thicker nanowire diameter in Device 5. We refer to Device 5 as 'bad' and to Devices 1, 3, 4 as 'good', with the meaning that 'bad' devices do not show ZBPs.

There is no evidence provided that the absence of ZBP is due to differences in the nanowire geometry. But we find even more significant the fact that Device 5, for which ZBP is not shown, is the only device for which the paper acknowledges the presence of subgap resonances in LP-0. This is how the authors describe them:

"For device 5, a discrete state crosses zero-energy around VBG = 0.12 V and then again at 0.17 V, resembling a proximitized quantum dot state, similar to the one previously studied in Ref. [84], see Fig. S7. We usually associate such state with a resonant level in the barrier and if possible avoid it in the measurements." SM, p3.



A *'proximitized quantum dot state'* is another name for an Andreev Bound State (ABS). As a reminder, Andreev Bound States are a widely known explanation for zero-bias peak, which is potent because these states can appear over parameter ranges much larger compared to MZM. A reader might infer that Andreev Bound States were only

39.
All the relevant data are available on the Zenodo repository. Among other things, it includes extended range gate sweeps at various magnetic field values as well as field sweeps at various gate voltage values for all devices.

40.
As mentioned before, we haven't used the word "bad" in our paper.

41.
This is a highly misleading sentence. The extended range gate sweeps for device 5 in the 1st lobe do not show zero-bias peaks and are available in the Zenodo repository.

42.
This is not true. As stated in the text multiple times, device 5 has a different Al shell thickness of 10 nm (compared to 30 nm shell of the other devices), which affect the superconducting properties. This difference is clearly visible by eye from the electron micrograph shown in Fig. S7 (device 5) and, for example, Fig. 2 (device 1).

Device 5 is presented as a device outside of the topological regime, it is also outside the destructive regime for related reasons. There is no notion of bad here. It is a non-topological, non-destructive wire, an interesting contrast highlighting variability.

found in this 'bad' Device 5. But as we already demonstrated, subgap features, some of which are likely Andreev Bound States, are visible in many Devices.

To illustrate this, we show side-by-side with data from Device 5, an analogous dataset from Device 3. In contrast to Device 5, which is a 'bad' device with ABS and no ZBP, this Device 3 plays a role of the verification device in the paper. Meaning, this is a 'good' device that is used to show that the findings from Device 1 can be reproduced. As we see from the data shown above, Device 3 is actually similar to Device 5. Both exhibit multiple subgap features that cross V=0. This can only be seen in the additional data for Device 3, and not in the Science-2020 paper, where the authors select regions with only subgap features near the gap edge, and not the ones that reach V=0, for supplementary Figure S5.

5. Discussion of the paper text and other figures

After the paper's figures, the main text of the paper is the most important factor in how the scientific claims are perceived by readers of the published paper, and before them by referees and editors when weighing the paper for publication. We already presented a case that individual statements from the main and supplementary text are incorrect. Here we discuss the paper as a whole.

In the experimental part of Science-2020, data descriptions as well as data interpretation are presented in simple and non-nuanced fashion. They project confidence in conclusions and stand in contrast with the complexity of phenomena revealed in additional data.

It is especially striking that an alternative explanation of ZBP, in terms of Andreev bound states or related phenomena, is absent from the main paper text entirely. No mention of this possibility is made in the text. Out of 82 references, only a single theoretical paper (Ref 75) deals with Andreev ZBPs, but the paper is not cited in this context. No experiments that demonstrate a ZBP due to non-Majorana origins are referenced. Contrarily, 6 experimental articles are referenced interpreting zero bias peaks through the Majorana hypothesis.

A reader is not informed of the alternative explanation, and if they know about it, their mind is directed away from it. An example of such misdirection is the description of Device 5 which shows Andreev bound states in supplementary materials, where this device is explained as distinct from Device 1 due to different nanowire cross-section. It is dismissed using confident language but without evidence, based on speculation.

43.
The "good" and "bad" terminology is introduced by F&M, and not used in our work. We used data from device 5 to illustrate the possible presence of barrier resonances in our devices. We did not say nor intend to say that they were unique to device 5.

We find that an interpretation of the totality of our data in terms of trivial ABSs is very difficult, especially when evidence from Coulomb-blockaded islands is taken into account. By contrast, we find the interpretation put forward in our paper to be natural, logical, and not contradicted by any dataset.

44.
We reiterate that F&M did not point out any factual mistakes in our paper nor did they provide an alternative interpretation consistent with the full data set (including both local and Coulomb-blockade spectroscopy).

Our statements were often quoted out of context, while relevant statements were omitted.

45.
The data cannot be explained by trivial ABSs. In particular, the entire second half of the paper, on Coulomb blockade, is crucial to our interpretation. One could perhaps claim that the phenomena we see in Fig. 2 could be explained by trivial instead of topological states, but the data in Fig. 6 and 7 is, to our knowledge, incompatible with those alternatives. By contrast, there is no data that is not naturally accounted for by our model.

46.
Device 5 was investigated to the same extent as the other devices. We looked for topological signatures but did not find them. The extended range gate sweeps in the 1st lobe presented in the Zenodo repository show no zero-bias peaks. This is why we classified the devices 5 as being in the trivial regime in the framework of our model. This difference can be explained by the structural properties of Device 5: different cross-section and Al shell thickness compared to, for example, device 1.

The main goal of our paper was not to show how to discriminate between Majorana zero modes and trivial Andreev bound states. It was to show that a new route to topological superconductivity is possible, based on both experimental and theoretical evidence. This explains the focus of the text on our model, rather than on already existing scenarios.

Distinguishing the Majorana hypothesis from the Andreev hypothesis is the main task in this research community when conducting experiments. The authors are well aware of widely discussed trivial zero-bias peaks due to Andreev bound states. They know about this from literature (first published in 2014), conferences (first presented in 2013) and many personal interactions. The 2016 Science paper from the same experimental group (Deng et al, Science 2016) discusses Andreev and Majorana states together. Most recently, the authors confirmed their awareness of the Andreev interpretation in April 2021 in their response to a previous version of this analysis.

47. We were also aware of the Kondo effect, weak antilocalization, class D and other possible interpretations of zero bias peaks.

If there is an alternative explanation, established for many years, at the very least this urges caution and extra rigor in making an ambitious Majorana claim in a high-impact journal. It should not be enough to offer a mere possibility that experiments may have a connection to Majorana, and ignore substantial evidence that the optimism is not based on reality. It should not be enough to show only a few datasets to substantiate your conclusion. Any Majorana theory provides plenty of opportunities to check and cross-check the experiment. After obtaining an interesting zero-bias peak, it is possible to further verify whether any given ZBP it is due to Majorana or if it is just an example of fine-tuned Andreev states by e.g. repeating magnetic field sweeps for a large number of different fixed gate voltages. This type of cross-check is at the core of our analysis, and it shows that multiple claims within the paper are inconsistent with the data.

48. No claims in the paper are inconsistent with the data. As the additional data in the Zenodo repository shows, we have performed these checks for the zero-bias peaks reported in the main text.

As discussed in previous comments related to Fig. 2E, we did not find evidence that contradicted our final interpretation of the data.

Furthermore, we devoted the entire second part of our study to measurements of Coulomb-blockaded devices that could allow us to provide additional evidence in favor or against our interpretation. The explicit motivation of this part of the work was that a body of evidence only based on NIS tunneling spectroscopy would not be compelling enough to put forward our interpretation in terms of a topological phase.

5.2 Comments on the theory part

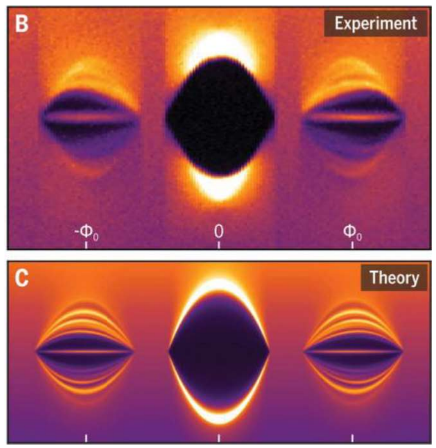
Science-2020 paper contains an equal theoretical contribution, to which FIgures 3,4,5 are dedicated. Originally, the theory part and the experimental paper were separate papers: they were posted on arXiv under separate identifiers (1809.05513 and 1809.05512). There was no overlap in the list of authors between the theory paper and the experimental paper. A version published in Science-2020 combined the author lists. The content of the two papers also got combined. Its two cores remain similar, meaning that the arXiv posting of the theory paper has strong overlap with the theory part of the joint Science-2020 paper.

We contend that the fact that the experimental part dedicated to the tunneling technique contains multiple incorrect statements, and its experimental conclusions where data are concerned are not supported by additional data, makes the Science-2020 paper invalid, in the form it was published (i.e. joint with the theoretical part).

49. By our count, the number of incorrect statements in the paper is zero. The data in additional files are consistent with the published data, and with our interpretation and claim.

There is therefore no need to consider the theory part in great detail. We limit our discussion to only a few remarks.

First, the theoretical model shows that ZBP correlated with LP-1 can appear in the topological regime, as well as in the non-topological regime (Figure S23). Whether this observation has any relationship to the experimental part is unclear, since theory considers an idealized model of the device. Nevertheless, the discussion of Figure 23 appears to be in direct contrast with the discussion of Figure 2 where no such possibility that a ZBP correlated with LP-1 need not be related to a topological state, is presented.



Second, and despite the fact that the theory is weak at associating ZBP with MZM, Figure 5 shows numerical simulations that closely resemble Figure 2. They are highly suggestive of a good match between experiment and theory. These simulations serve to convince a reader that theory does, in fact, provide strong support for the MZM explanation of the experimental data. As stated above, this is not the case.

Third, the theory part also makes a connection to the Coulomb blockade part of the paper, which we comment on below. The theory suggests that an 'exponential scaling' of the parameter extracted from the Coulomb blockade (peak oscillation amplitude) is indicative of the topological regime and is a better predictor of this regime than the coincidence of ZBP and LP-1. We have doubts about the experimental methodology of the CB technique, and about the relevance of the parameter extracted from it. The strength of the exponential scaling argument is also unclear. Devices of different length are different realizations of a system and to make a strong statement about scaling, it is necessary to generalize the observations by performing a lot more simulations. The question of how well the model describes the experimental system and whether another model cannot produce exponential scaling without MZM is an open question.

50.
A theoretical model can only approximate a real device. Our theory work primarily aimed at clarifying the conceptual basis for the existence of topological superconductivity in full-shell nanowires. We did not aim to quantitatively reproduce any experimental dataset.

51.
It is the exact contrary: there is no contrast, but rather a clear logical connection. The discussion of Fig. 23 serves the purpose of clarifying that a ZBP is not a sufficient signature of a Majorana zero mode. This motivates the second part of the work on Coulomb-blockaded islands, according to the same logic progression of the main text.

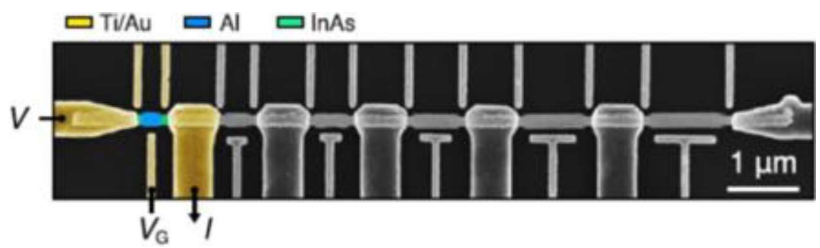
52.
Our point is that the experimental data is consistent with the presence of a topological phase, and that this is in accordance with theoretical expectations. In order to illustrate this, we have provided numerical evidence that simulating a device in the topological phase can yield conductance data that is qualitatively equivalent to the experimental data. Other behaviors are possible as well by tuning parameters, as discussed in the Supplementary Materials. Fig. 5 is a check for consistency, not for necessity, as appropriate to support our conclusions.

53.
These are speculative statements. One should not be discarding a large body of data without a valid justification. These data contradict F&M's assertion that the observed zero-bias peaks are due to trivial Andreev bound states.

54.
Because of the absence of alternative explanations of the exponential scaling observed in the data, we found it reasonable to interpret it in terms of the available one, namely the presence of zero modes at the ends of the wire. If new explanations are put forward in the future, the interpretation of this data can be subject to revisions and improvements, as it is always the case when science progresses.

5.3 Comment on Coulomb blockade section

The authors present another experimental technique based on measuring spacings of the so-called Coulomb peaks. Figures 6 and 7 are dedicated to this technique. Similar to our argument for not considering the theoretical part, we do not see a reason to consider the Coulomb blockade part. Since Figure 2 and its description misrepresent full data and contain serious errors, any arguments contributed by an additional technique do not change the fact that the paper is invalid. However, we will make several broad remarks about the Coulomb blockade technique.



Coulomb Blockade (CB) measurements on small superconducting islands are not widely used in Majorana studies. Other groups studied such devices. But only the Copenhagen-Microsoft group made Majorana observation claims based on this measurement technique, in papers such as Albrecht et al. Nature 2016, Sherman et al. Nature Nanotechnology 2017. We find several aspects of this technique questionable, and we are interested in re-analyzing all of the papers that use it for Majorana explanations, in a separate study.

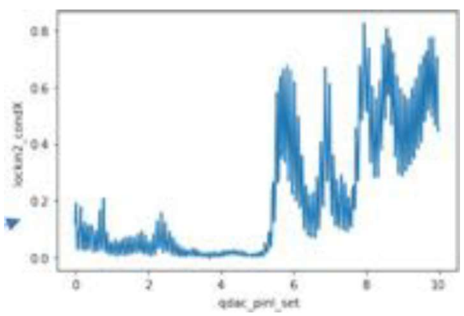
Figures 6 and 7 present data from Device 2, which is in fact 6 separate islands of Al of 6 different lengths. The results from all 6 islands are analyzed together as a length dependence of the topological regime. That means, each of the 6 nanowire segments contains MZM. Without looking at the data, let's cross-check this with what we already established from the tunneling technique.

We know that ZBPs, and hence Majorana modes, do not appear in every nanowire. Furthermore, finding a ZBP requires fine tuning of gate voltages. Based on this, it appears to be an unusually good device if it exhibits twelve Majorana zero modes, all at expected positions along the nanowire, at the ends of each Al island.
What is the likelihood of realizing such a device? If we assign a probability that a given segment has MZM to be 0.5, which we consider a high number, then the probability of

55.
This part of the paper is of critical importance as it strongly disfavors alternative interpretations, including those based on resonances in the junctions.

56.
These probability estimates are nonsensical, since one is not dealing with a random process. The segments are all of the same nanowire. They are not statistical within a wire. If the wire works, and barring fabrication errors, one would expect all segments to work. This plausible assumption was corroborated a-posteriori: if different segments were subject to strong variations in the wire parameters, we may not have been able to observe the exponential scaling reported in Fig. 7.

having 6 segments is 1.5%. It would require, on average, 64 nanowires to find a single one like Device 2. If Majorana probability per device is 7/9 (which matches the authors' count of devices with ZBPs vs. total working devices), then the probability of 6 topological segments in one wire is 22%. The authors present not one, but three such nanowires, two more in additional data. The coincidence appears too good to be true.



The CB technique the authors use relies on calculating mean distances between even and odd Coulomb peaks. To extract peak distances the authors use positions of between 6 and 22 peak pairs. But in a wider range of gates, shown in additional data, we see of order 100 peaks, perhaps more.

What is not known is whether patterns shown in the Science-2020 paper persist over larger peak ranges? Do energy oscillations survive averaging over 100 peaks? Do oscillations look the same if different sets of peaks are averaged? The authors show in Figs S12, S15 that they can also change the back gate, and that it is set to a large negative value. Since NIS devices are highly sensitive to back gate, how do peak statistics change in the full range of back gate? Are there examples where scaling is not exponential? These are the types of questions we would ask if and when we embark on re-analyzing all of the CB technique papers. We have other, even more basic questions as well. We did not proceed with this analysis now because our finding that Figure 2 is not representative of the devices studied is already sufficient to invalidate the conclusions of the paper.

5.4 Comment on related results from Austria

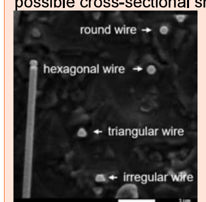
Shortly after the Science-2020 paper was published, a preprint on arxiv from the IST group in Austria reported that in the exact same nanowires no Majorana modes are observed, but only trivial Andreev bound states ("Flux-tunable Andreev bound states in hybrid full-shell nanowires", https://arxiv.org/abs/2008.02348). We do not base our post-publication analysis of the 2020 *Science* paper on this later preprint. We find that problems identified in Figure 2 and its discussion are significant enough to make the Science-2020 paper invalid. However, we comment on the IST results here anticipating a discussion of them may emerge.

57.
The data that we have analyzed was measured in an appropriately chosen Coulomb-blockaded regime, with clear peaks, but also conductance in order of noise floor in the valleys.

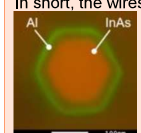
58.
We find that answering all possible open questions that researchers may come up with on this technique should not be a required burden before we can put forward an interpretation of the data. We gather (a finite amount of) data and make plausible inferences based on the evidence that we observed. It is our belief that this is how science works and progresses.

59.
The exponential scaling of even-odd Coulomb peaks confirms and strengthens our interpretation based on the NIS spectroscopy. These two parts of the experiment go hand in hand, and must be considered as a whole.

60.
We disagree with this statement that the the two studies were performed on the "exact same nanowires".
After the initial submition of our paper, we imaged the growth substrate of the measured wires using material-sensitive electron microscopy (same as Fig. 1A) and found a variety of possible cross-sectional shapes of the wires:



In short, the wires were usually hexagonal:



However, we also found different shapes such as round, triangular and irregular:

Therefore, the wires from the two studies are unlikely to be "exact same".

Furthermore, IST group's nanowires were from different parts of the wafer, and their experiments were performed more than a year later, during which time the aluminum shell likely oxidized further. These differences are relevant, because the ground state of the wire depends sensitively on the nanowire radius, thickness of the superconducting shell, cross-sectional shape, and interface properties.

The IST experiments show that the ZBP/LP-1 coincidence is a result of fine-tuning of the gate voltage settings. We conclude this based on a large volume of data, over 500 datasets, shared with us by the IST group.

The full-shell nanowires for both studies are grown by the same grower using the same growth equipment for both papers. Device fabrication including positioning of nanowires on silicon substrates, and deposition of electron-beam lithography patterned metal contacts (and gates) is generally similar. Though different cleanrooms were used to make devices, the processes appear to be not different in substantive ways. One way to see this is from the data themselves: devices from IST and Copenhagen exhibit similar low-temperature characteristics such as the induced superconducting gap, including its magnitude, hardness and its persistence in applied magnetic field; as well as similar Little-Parks oscillations that are specific to full superconducting shell nanowires.

The overall data quality is comparable, meaning that datasets of the same quality are present in the full IST data and in the Science-2020 paper, though they do not necessarily correspond to completely equivalent regimes. This however does not leave much room for claiming that the two studies are different in any significant way. Given the variety of data we found in additional Copenhagen data, we expect that full libraries of data show equivalent phenomenology.

5.5 Summary of communications with the authors of the paper

We find communications with the authors to be a significant factor in our post-publication analysis, since explanations from authors have enormous potential to influence our understanding of their paper and their experiments.

To recap the history briefly, upon learning of the IST replication issues, we asked for the full data underlying the experimental claims in Science-2020. Initially the authors refused to provide it, insisting that all data necessary to reproduce their manuscript were available within the paper. They shared a limited amount of data after the *Science* editor intervened, after we sent a 10-page memo summarizing our concerns and questions. On finding that the additional data was not consistent with the paper, we asked the authors further questions along the lines of the analysis above. We did receive a response from the authors to our analysis. However, the response was not extensive or satisfactory. We note that the amount of additional data that the authors provided upon our request, following the intervention of the *Science* editor, appears to be only a fraction of the total data collected. We have requested the full data.

61.
We contacted the authors of the IST study to compare techniques. It turns out that nearly every fabrication step was different. Different placement method, different substrate, different gate patterning, different oxide, different cooling method. It is difficult to ascertain exactly what effect these differences may have on the final measurements, but it is reasonable to assume that they have an impact. It is likely that the largest impact is in the behavior and microscopic properties of the NIS junctions. Further, even within our study, we have observed device-to-device variation of wire dimensions [device 4 (Fig. S6) has a core diameter of 160 nm, whereas, for example, device 1 (Fig. 2) has a core diameter of 130 nm]. This indicates that the growth variations have a significant effect too. All these elements must be considered when comparing different experiments.

62.
We disagree. There are numerous papers reporting similar-quality tunneling and Coulomb experiments on various systems. It doesn't mean that they can be directly compared with each other. Specific details of sample preparation and measurement techniques (and equipment) can and do matter, especially for the disordered mesoscopic devices that we are dealing with.

63.
Our previous communications (predating June 1st, the date of this document) with F&M were largely ignored and not incorporated in the current analysis. when analyzing and criticizing our work. In fact, in replying to this document, we find ourselves having to repeat verbatim clarifications already made in private.

64.
After a first private communication from F&M, our reply was to simply point out that the datasets included in the published paper were already available in the Zenodo repository. At the same time, we have provided considerable information to them, including, for instance:
"In a given device, a zero-bias peak is robust and reproducible in the n=1 lobe. However, wire-to-wire variation, wire aging, differences in etching, or conditions of oxide deposition can lead to differences between nominally similar full-shell devices. As the theory section shows, the topological phase is rather sensitive to variation in wire properties such as wire diameter and aluminum thickness. Indeed, as we showed both theoretically and experimentally in the paper, small geometrical variations can lead to the disappearance of the zero-bias peaks in the first lobe, see, for example, Fig. S7 in the supplementary material section."

Once the Editor communicated to us their interest for additional data, we provided the data in timely fashion.

65.
As F&M mention, there aren't many experimental knobs available to tune our devices. All the relevant NIS-junction conductance data measured as a function of source-drain voltage bias, gate voltage, and external magnetic field are available in the Zenodo repository. As mentioned above, we did not include flat traces of non-working devices, calibration curves, device tune-up line cuts, repetitive low-resolution, noisy, or aborted sweeps, because those data are irrelevant to our presentation or conclusions.

One thing we learned from the authors response is that they intended their paper to be merely suggestive of topological superconductivity. They also responded that they believe that “the topological phase can be present only in part of the 1st lobe and can also be present in the 2nd lobe.” While this may be consistent with the theory part of their manuscript, this is not how they described or represented the experimental data in the manuscript.

66.
In the manuscript, we do not find a single logical inconsistency between our descriptions of the experimental data and our descriptions of the theoretical results.

Some of the sentences quoted in this appendix applied to specific datasets and point out specific features which may not be universally required by the theory, but we felt were still worth pointing out since they are suggested by the data.

APPENDIX A - Relevant quotations from the Science-2020 paper

A.1 Statements about Majorana in the paper

1) ‘*We show experimentally and theoretically that the winding of the superconducting phase around the shell induced by the applied flux gives rise to MZMs at the ends of the wire.*’ Research Article Summary.

2) ‘*The topological phase […] is controlled by moving from zero to one phase twist around the superconducting shell.*’ Research Article Summary.

3) ‘*Two device geometries, measured in three devices each, showed similar results.*’ p1.

4) ‘*As the tunnel barrier is opened, the zero bias peak gradually evolves into a zero-bias dip. The increase of finite-bias conductance compared with zero-bias conductance as tunnel barrier decreases is in qualitative agreement with theory supporting MZMs...although the crossover from a peak to a dip occurs at lower conductance than expected.*’ p2.

5) ‘*Moreover, the full shell naturally protects the semiconductor from impurities and random surface doping, thus enabling a reproducible way of growing many wires with essentially identical electrostatic environments.*’ p6.

6) ‘*Although full-shell wires do not allow for direct gating of the electron density in the semiconducting core, we demonstrated that, using a careful design of the wire properties—for example, by choosing the appropriate radius— it is possible to obtain wires that harbor MZMs at a predictable magnetic field.*’ p6.

A.2 On tunneling spectroscopy at zero magnetic field:

1) '*Our measurements reveal that tunneling into the core in the zeroth superconducting lobe, around zero flux, yields a hard proximity induced gap with no subgap features.*' p1.

2) '*At zero field, a hard superconducting gap was observed throughout the zeroth superconducting lobe (Fig. 2, B and D).*' p2.

3) '*In a weak tunneling regime, for VBG < −1 V, a hard gap was observed, with D = 180 meV (Fig. 2, C and D). For VBG ~ −0.8 V, as the tunneling barrier is decreased, the subgap conductance is enhanced owing to Andreev processes. The increase in conductance at VBG ~ −1.2 V is likely caused by a resonance in the barrier.*' p2.

4) '*A hard gap is seen in the zeroth lobe,…*' and '*The zeroth lobe shows a hard superconducting gap,…*' Fig. 2, commenting on data from Device 1

5) '*For all four tunneling-spectroscopy devices (1, 3, 4 and 5) the zeroth lobe, where the winding number is 0, shows a hard gap and no subgap states are visible.*' SOM p3, commenting on all devices.

6) '*For device 5, a discrete state crosses zero-energy around VBG = 0.12 V and then again at 0.17 V, resembling a proximitized quantum dot state, similar to the one previously studied in Ref. [84], see Fig. S7. We usually associate such state with a resonant level in the barrier and if possible avoid it in the measurements.*' SOM p3, commenting on device 5.

7) '*The zeroth lobe shows a hard superconducting gap,…*' Fig S6, commenting on data from Device 4

8) '*The zeroth lobe shows a hard superconducting gap,…*' Fig S7, commenting on data from Device 5.

A.3 On tunneling spectroscopy within the first lobe of the Little-Parks oscillations

1) '*In the superconducting regions around one quantum of applied flux, corresponding to phase twists of* $\pm 2\pi$ *in the shell, tunneling spectra into the core show stable zero-bias peaks, indicating a discrete subgap state fixed at zero energy.*' Research Article Summary.

2) '*Upon reopening, a narrow zero-bias conductance peak was observed throughout the first gapped lobe (Fig. 2, B and F). Several flux-dependent subgap states are also visible, separated from the zero-bias peak in the first lobe.*' Research Article Summary.

3) '*In the first lobe, at B = 110 mT, the sweep of VBG showed a zero-energy state throughout the tunneling regime (Fig. 2E). The cut displayed in Fig. 2F shows a discrete zero-bias peak separated from other states by a softened gap, presumably owing to finite temperature and level broadening in the junction. As the tunnel barrier is opened, the zero-bias peak gradually evolves into a zero-bias dip.*' p2.

4)'*…the first lobes show a zero-bias peak,…*' Fig. 2, commenting on data from Device 1.

5) '*In the first lobe, with the phase winding of 2π, the spectrum for devices 1, 3 and 4 (all with 30 nm Al shell) displays a discrete, zero-energy state (see main-text Fig. 2, and Figs. S5 and S6),…*' **–** SOM p3, commenting on data from devices 1, 3 and 4.

6) '*…the first lobe shows zero-bias peak,…*' Fig. S5, commenting on data from device 3.

7) '*…the first lobes show subgap states including a zero-bias peak,…*' **–** Fig. S6, commenting on data from device 4.

A.4 On tunneling spectroscopy within the second lobe of the Little-Parks oscillations:

1) '*A second gapped lobe centered around* |*B*| *= 220 mT then appeared, containing several subgap states away from zero energy...*' p2, commenting on data from Device 1.

2) '*…and the second lobes show nonzero subgap states.*' Fig. 2, commenting on data from Device 1.

3) '*In the second lobe, with even number of phase windings, the spectrum for device 1 features an asymmetric superconducting density of states with the lowest energy subgap state centered around ~5 eV, see Fig. S3; For devices 3 and 4, multiple subgap states can be identified at finite voltage, but no zero-bias peak, see Figs. S5 and S6; For device 5, a qualitatively similar to the first lobe spectrum with several finite-energy states is observed, see Fig. S7.*' SOM p3, commenting on all devices.

4) '*The spectrum shows subgap states away from zero energy.*' Fig. S3, commenting on data from Device 1.

5) '*…the second lobe shows non-zero energy subgap states.*' Fig. S5, commenting on data from Device 3.

6) '*…the second lobes show non-zero energy subgap states.*' Fig. S6, commenting on data from Device 5.

7) '*…the higher-order lobes show multiple discrete states away from zero energy.*' Fig. S7, commenting on data from device 5, '*…higher-order lobes…*' meaning first lobe and onward.

A.5 On tunneling spectroscopy within the third lobe of the Little-Parks oscillations:

1) '*Device 4 with slightly bigger diameter, displays the third lobe, with odd number of phase windings. The spectrum features subgap states and a peak at zero bias, see Fig. S6.*' SOM p3, commenting on data from Device 4, the only device shown with a third lobe.

2) '*The third lobes show subgap states again with a peak at zero bias.*' Fig. S6, commenting on data from Device 4.

A.6 On device 5 where no ZBP was shown (some quotes already included earlier):

1) '*In the first lobe, with the phase winding of 2π,… …for device 5 (with 10 nm Al shell) the spectrum consists of multiple discrete, but finite energy subgap states, see Fig. S7.*' SOM text p3, commenting on device 5.

2) '*For device 5, a qualitatively similar to the first lobe spectrum with several finite-energy states is observed, see Fig. S7.*' SOM text p3, commenting on tunnelling spectroscopy in the second lobe for device 5.

3) '*For device 5, a discrete state crosses zero-energy around VBG = 0.12 V and then again at 0.17 V, resembling a proximitized quantum dot state, similar to the one previously studied in Ref. [84], see Fig. S7. We usually associate such state with a resonant level in the barrier and if possible avoid it in the measurements.*' SOM text p3, commenting on subgap resonances in device 5

4) '*Tunneling spectroscopy without zero-bias peaks in device with thinner Al shell (device 5).*' Fig. S7, caption title.

5) '*The zeroth lobe shows a hard superconducting gap, the higher-order lobes show multiple discrete states away from zero energy. No destructive regime is present in the thinner-shell device.*' Fig. S7, commenting on data from device 5.

6) '*…whereas for device 5 (with 10 nm Al shell) the spectrum consists of multiple discrete, but finite energy subgap states, see Fig. S7*.' SOM text p3, commenting on data from device 5 in comparison to devices 1,3,4.

Attachment 1: Correspondence with Science Regarding Posting Second Zenodo File

Oct 8, 2020

Dear Charlie and Roman,

I hope all is well.

As you know, I was cc'd on Sergey Frolov and Vincent Mourik's emails to you and Dr. Katsaros. Sergey followed up with me today to say that they've heard from you and that you pointed them to the Zenodo repository that's referenced in your paper. However, they're requesting that you supply them with a wider data set.

Specifically, they are requesting access to the data from all measured devices (and not only those shown in the paper). For each device, they are requesting access to the entire dataset starting from first characterization at low temperature up to the end of the experiment. The datasets should include the entire parameter space in which the device was measured.

We feel that this request is reasonable and in line with our editorial policies, which you can find at https://www.sciencemag.org/authors/science-journals-editorial-policies

It might also be a good idea to supply them with the statistics of the experiment, as you have done in response to one of the reviewers (I am attaching the document).

Ideally, we would like you to upload the additional data to the same Zenodo repository where the data from the paper are currently deposited so that they can be accessed by other researchers as well.

Questions/comments are welcome.

Best regards,

Jelena

Oct 22, 2020

Dear Jelena

Thanks for your email.

We were careful to include in the Zenodo repository all of the data that was used in the analysis of the paper or that was relevant for drawing conclusions either in the paper or the supplemental material. We believe that making this data available is consistent with Science's policy that: "All data used in the analysis must be available to any researcher for purposes of reproducing or extending the analysis."

Reviewing Science's editorial policies, we do not think that data from "all" measured devices or all parameters is consistent with those standards. The request from Mr. Frolov and Mr. Mourik does not appear to be meaningful or reasonable. We do not consider flat lines from dead devices, preliminary tests of alternative device designs not used in the paper, data from fabrication practice runs or calibration runs, data for subsequent experiments on different devices that have since been published elsewhere or may be published later, to be relevant or appropriate to include. Such data was not used in the analysis of our paper and is accordingly not necessary to reproduce or extend the analysis. We did not include the table from the referee response because it is not available in the paper. It is unclear for what purpose Mr. Frolov and Mr. Mourik are requesting this data, or how the request advances Science's editorial guidelines.

Moreover, it would create a considerable resource drain to retrieve the requested information and make it available. We are also concerned that requiring the production of this data sets a precedent for which there is no identifiable limiting principle. This presents definitional and other challenges that extend for both authors and Science well beyond the request presented here.

However, if you feel that the table of device statistics (or some other specific data) should be posted, even though it did not appear in the paper, please let us know and we will do our best to retrieve and prepare it. I am available to discuss this with you further if you would like and happy to jump on a quick call.

Sincerely,

Charlie Marcus, Roman Lutchyn

Oct 22, 2020

Dear Charlie and Roman,

Thanks for your response.

The data you posted on Zenodo satisfied our requirements for data transparency at the time of publication. However, our editorial policy also allows for post-publication requests for additional data from readers, and authors are expected to make a good-faith effort to comply with such requests.

We are not expecting you to release data from subsequent devices that were not part of this project, or flat-line data from non-working devices. However given that we are aware that there were additional working devices that were part of this project but not presented in the paper (based on your referee response), we do ask that you make the data for those additional devices available, as well as data for parameter regimes not shown in the paper. Releasing the statistics for the devices along the lines of the table in the referee response would also be helpful.

If you would prefer not to make these additional data part of the paper repository, you could also make them available to the requestors in another manner. However, a public release would send a stronger message and would be of more use to the community.

I can’t speak for Drs. Frolov and Mourik, or their motives. From our perspective, their request is not unreasonable and whether or not they are satisfied with what you end up releasing, I think it’s important to make an effort to be as transparent as possible.

Let me know your thoughts as well as the time frame for any data release.

Best regards,
Jelena

Oct 24, 2020

Dear Jelena,

Thanks. We will put together additional data, along the lines you suggest, and post it to Zenodo.

We agree that the best way to handle this request is to make the data available to all.

It will take a bit of digging to put the data together. I would expect that we can have the job done in about two weeks.

Best,

Charlie

Nov 9, 2021

Dear Jelena,

Thank you for your patience. We have now uploaded additional data to the Zenodo archive, closely following your recommendations. The as-published link to the Zenodo file will show both old and new data sets, denoted Version 1 and Version 2.

As described in the overview file “summary.pdf”, we provide a table summarizing all measured devices and data for the 25 working devices. These 25 devices comprise 9 NIS junctions and 16 Coulomb islands.

Of the 25 working devices, 12 (4 NIS junctions and 8 Coulomb islands) were discussed in the main text or supplementary materials document. For them, we provide the complete parameter ranges measured. We also provide data for 13 additional devices (5 NIS junctions and 8 Coulomb islands) not presented previously.

This additional data is organized into more than 130 new or expanded data sets, containing 300 MB of numerical data. The summary.pdf file describes how the files are organized. We also provide jupyter notebook files containing python code to load and plot all the datasets.

We hope that readers will find these additional data informative.

Regards,

Saulius Vaitiekenas,
Bernard van Heck,
Georg Winkler,
Charles Marcus
on behalf of all authors.

Nov 9, 2021

Dear All,

Thanks very much, this is greatly appreciated.

Best regards,

Jelena