

# Non-Equilibrium Charge Dynamics in Majorana-Josephson Devices

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We investigate the impact of introducing Majorana bound states, formed by a proximitized semi-conducting nanowire in the topological regime, into a current biased capacitive Josephson junction, thereby adding delocalized states below the superconducting gap. We find that this qualitatively changes the charge dynamics of the system, diminishing the role of Bloch oscillations and causing single-particle tunnelling effects to dominate. We fully characterize the resulting charge dynamics and the associated voltage and current signals. Our work reveals a rich landscape of behaviours in both the static and time-varying driving modes. This can be directly attributed to the presence of Majorana bound states, which serve as a pathway for charge transport and enable non-equilibrium excitations of the Majorana-Josephson device.

## I. INTRODUCTION

In recent years, there has been a growing appreciation of the role played by interactions in topologically non-trivial systems. In addition to changing the topological classification of systems<sup>1</sup>, interactions have been shown to modify topologically protected states, resulting in a range of exotic phenomena<sup>2–7</sup>. The relative simplicity of one-dimensional topological superconductors (TSCs) with a finite charging energy<sup>8–13</sup> is particularly attractive for studying interaction effects in topological matter. A recent experimental investigation of this system<sup>14</sup> has offered compelling evidence for the existence of Majorana Bound States<sup>15</sup> (MBSs) in condensed matter, whilst theoretical work indicates that it may host a delocalized many-body state arising from the interplay of interactions with MBSs<sup>16</sup>. Previous studies have shown how a Josephson coupling in this system affects its conductance properties<sup>17,18</sup>.

In this work, we exploit the topologically protected MBSs in the TSC to probe the non-equilibrium charge dynamics of a Josephson junction. The Josephson effect is one of the most prominent manifestations of superconducting phase coherence<sup>19</sup>. Whilst the effect owes its existence to microscopic quantum objects (Cooper Pairs), at the macroscopic level it is essentially classical in nature. There are, however, other phenomena associated with superconductors that do not admit such a classical description. In particular, it was realized over thirty years ago<sup>20</sup> that the competition between charging and Josephson energies in a Josephson junction results in a system whose behaviour is directly analogous to that of an electron in a periodic potential. Just as the electron's properties depend periodically on its momentum, with period given by the reciprocal lattice vector, the observables associated with the junction are  $2e$  periodic in charge, where  $e > 0$  is the magnitude of the electronic charge. This periodicity is, fundamentally, contingent upon charge-phase conjugation and constitutes a macroscopic quantum phenomenon. That such a state of af-

airs can exist is interesting in its own right, and some experimental progress has been made in demonstrating that remarkable effects, such as Bloch Oscillations, can indeed be observed in such systems<sup>21,22</sup>. However, the  $2e$  periodicity acts as a barrier to interrogation of the system, since for ideal superconductors all sub-gap charge perturbations must be in multiples of  $2e$  and therefore do not change the state of the system.

By introducing a pair of MBSs into the system, we are not only able to overcome this obstacle, but also exploit the non-locality inherent to the MBSs. Taken together, the MBSs constitute a single fermionic state at zero energy which, due to interactions, persists even in rather short systems<sup>23,24</sup>. The MBSs therefore allow single electrons from an external reservoir to tunnel into and out of the system, thereby permitting perturbations of the junction's electronic state in a way that is qualitatively distinct from the Cooper pair processes considered previously. Furthermore, the delocalized nature of the fermionic state corresponding to the two MBSs means that it permits current flow over an extended distance through the TSC, in contrast to the sub-gap quasiparticles that have been considered previously<sup>25–29</sup>. As we will show, it is this current through the TSC that allows controlled sub-gap perturbations of the Josephson junction. We develop the theoretical formalism necessary to characterize such MBS mediated single-particle processes, and discuss the consequences of their existence on the charge dynamics of the Josephson junction. We demonstrate that the system exhibits a rich variety of dynamic regimes which can be explored experimentally by varying its electrical inputs.

In Section II we develop the theoretical framework necessary to describe the dynamics of the Majorana-Josephson system. We then analyze these dynamics and present our results in Section III before providing a summary of our conclusions in Section IV. Unless explicitly noted otherwise, the system parameters given in Appendix A are used throughout this work.

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