Steps towards current metrology

Gianluca Rastelli & Ioan M. Pop

Two superconductors connected by a weak link form a Josephson junction, a nonlinear circuit element at the heart of many quantum devices. Quantized electrical current steps that were predicted decades ago have now been observed experimentally.

The tendency of coupled oscillating systems to synchronize is a common phenomenon in physics and biology. When a current-carrying Josephson junction is subject to microwave radiation, synchronization produces quantized 'Shapiro steps' in the voltage across the junction[1]. The dual process corresponds to steps in current expected to form across voltage-biased junctions[2]. Now, in work published in *Nature Physics*, Nicolò Crescini and colleagues[3] have observed the quantized current steps in a large system of Josephson junctions.

Consider the example of a particle sliding down a so-called washboard potential, at terminal velocity (Fig. 1). Although on average the velocity is constant, as the particle slides over the bumps in the potential its speed periodically rises and falls. A small harmonic drive of the slope with a frequency *f* can be used to influence the velocity modulations. This can lead to synchronization, which means that the particle slides, on average, from one minimum to another during a full oscillation of the drive, and the process repeats periodically. In this regime, the average speed can remain constant even if we slightly increase or decrease the overall downwards tilt of the washboard. In other words, the drive will autonomously accelerate or decelerate the slide, as needed.

Even though in practice many other factors should be considered, such as friction and thermal or quantum noise, they only affect the width of the bias region where synchronization occurs. Therefore, this type of phase-locking between the response of a physical system and a drive tone gives rise to flat response 'steps'. These are insensitive to small changes in bias and are a valuable resource for metrology.

Shapiro steps in a Josephson junction can be understood using an equivalent washboard potential where the particle coordinate is the superconducting phase, the periodic modulation of the potential is given by the Josephson effect and the slope is set by the current bias.

Electrical charge and magnetic flux are quantum mechanical conjugated variables and so theorists predicted that all phenomena observed in a Josephson junction for the phase dynamics can be translated in the charge dynamics using a duality transformation. In particular, they predicted the existence of dual Shapiro steps in current at integer multiples of the driving frequency[2]. By providing a quantized relationship between current and frequency, the dual Shapiro steps play a key role in closing the metrology triangle. This means that it is now in principle possible to perform experiments where voltage, frequency and current can all be defined by quantum effects, and one can perform consistency testes between their relationships.

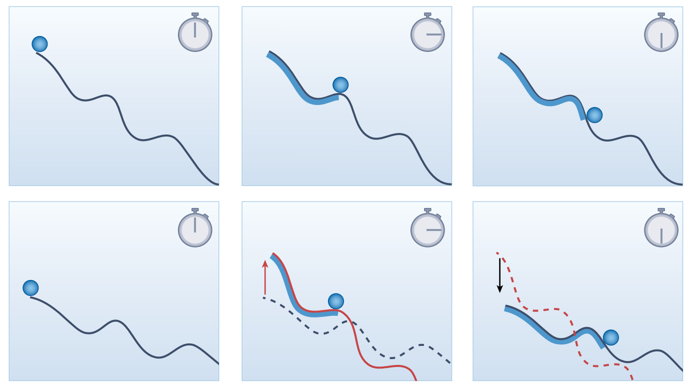

Fig. 1 | Illustration of synchronization. The top row shows a ball rolling on a fixed tilted washboard potential at three different moments in time. The bottom row shows the effect of a periodic modulation of the tilt. Even if the average tilt is different, under the right conditions, the rolling of the ball can synchronize with the modulation such that the average speed is the same as for the fixed tilt shown in the top row.

In the dual Josephson junction circuit, the charge of the junction plays the role of the fictitious particle moving in a periodic potential. When synchronized with an external voltage drive, a superconducting Cooper pair of electrons crosses the junction during one period of the drive, leading to quantized current steps.

Experimentalists have spent significant efforts on trying to measure the dual Shapiro steps. However, while it is relatively straightforward to produce superconducting circuits with the well-defined phase needed to observe Shapiro steps, fluctuations in charge are much stronger. Since synchronization requires a localized charge to slide on a modulated potential, dual Shapiro steps have remained elusive.

To suppress charge fluctuations, new electromagnetic environments needed to be engineered in order to increase their impedance well above a value known as the resistance quantum, 6.45 kΩ (ref. [4]). Experimental progress towards this goal was incremental, but with each attempt the community improved its understanding of the phase–charge duality[5] and of the environment of the dual potential[6], leading to increasingly realistic theoretical modelling of real-world devices[7,8]. The culmination of these efforts has been two measurements of dual Shapiro current steps reported by Crescini and co-workers[3] and a parallel effort using a superconducting nanowire[9].

Crescini and co-workers followed a strategy to create a high-impedance environment for a Josephson junction by embedding it in a chain of much larger junctions. Similar designs have been attempted in the past and have failed to show current steps, but the team introduced two important developments. Firstly, their search for the right parameter range to observe synchronization was significantly sped up compared to previous experiments by leveraging low-noise radio-frequency measurement techniques developed in the circuit quantum electrodynamics community. Secondly, they looked for the current steps at voltage biases far away from the regions expected from existing theoretical models. In fact, they only observe current steps at voltages corresponding to about five times the superconducting gap in aluminium, which means that several large junctions in the environmental array carry this voltage drop. This unexpected observation hints at the subtle role played by dissipation in synchronization processes, and it will likely inform further studies.

The measurements of dual Shapiro steps by Crescini and co-workers are a breakthrough with important implications for the quantum metrology of electrical currents. It will be very interesting to address the remaining open questions regarding the role of dissipation and the observation of current steps at sub-gap voltages. Additionally, in order to further increase charge localization, the small Josephson junction could be engineered to be even smaller, or it could be replaced by a disordered superconducting nanowire, similarly to ref. [9], or by a granular aluminium nanojunction[10].

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Competing interests

The authors declare no competing interests.