Most physical systems depend on external parameters which, at special values, give additional symmetries to the system. At these points, quantum degeneracies may occur. When the parameters are easily tunable, one can explore quantum states not only at the degeneracy points but over the entire parameter space. Even when it is away from a symmetry point, the system is sensitive to the point’s presence. The reason is simple: at a degenerate point absolute quantum phases cannot be defined. From a topological point of view, a degeneracy is a defect in the wavefunction phase. This topology has important consequences such as the quantization of physical quantities (e.g. the quantum Hall effect). For quantum circuits, the quantized quantity is the charge transferred when performing an adiabatic cycle by varying gate voltage and magnetic flux values. This quantization is geometric and does not depend on the precise shape of the cycles used. In this fashion, a quantized current can be generated. Such a current can be used in metrology as an electrical current standard, critical to the redefinition of the International System of Units.

The circuit studied here, a “Cooper-pair pump”, represented in Fig. 1, has three Josephson junctions in series which separate two superconducting islands. The three tunable parameters are the two gate-induced charges $n_{g1}$ and $n_{g2}$ on the islands and the phase difference $\phi$ across the three junctions. The lowest quantum states are degenerate at isolated points $T_{pq}$ ($n_{g1}=2/3+p$, $n_{g2}=2/3+q$, $\phi=\pi[2\pi]$, where $p$ and $q$ are integers) in this three-dimensional parameter space. An integer topological charge can be associated with the phase defects at these points.

The most interesting consequence of this non-trivial topology is the quantization of the charge transferred during the adiabatic evolution of the circuit’s ground state over any families of cycles which completely enclose the degenerate points. This is achieved using periodic cycles which cover densely a surface which encloses one or more degeneracies. The most convenient cycles are helices covering the surface of a cylinder of height $2\pi$ (the cylinder axis is the phase difference across the pump). Over one cycle, the charge transferred is an integer (the number of turns) multiple of $2e$. When the cycles are repeated at a frequency $\nu$, the current $I_p$ generated is exactly $I_p=2ep\nu$. Thus, the current can be used as a metrological current source and ultimately as an absolute standard for the International System of Units.

There are several challenges to be met on the way to this goal. Since the current is generated by the adiabatic evolution of the circuit’s ground state, the operating frequencies must be limited in order to remain adiabatic. This limits the pumped current to a few tens of pico-amperes. The “topological” nature of the current generated protects the circuit against low frequency noise sources. The effect of other noise sources is the subject of ongoing studies.

This research is part of a European Future and Emerging Technologies programme devoted to studies of the adiabatic evolution of electronic circuits.

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Further reading