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The dc SQUID as a Quantum Limited Amplifier

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The Josephson tunnel junction consists of two superconductors separated by a thin insulating barrier through which, at low electrical currents, Cooper pairs of electrons can tunnel without producing a voltage. When the applied current is increased above a value known as the critical current, however, a voltage is developed. The dc Superconducting QUantum Interference Device (SQUID) consists of two Josephson junctions connected in parallel on a superconducting loop. The SQUID is operated by passing a current through the two junctions. When an external magnetic field is applied to induce a magnetic flux in the loop, the critical current of the SQUID oscillates as a function of the flux with a period of one flux quantum, $h/2e$. Here, h is the Planck constant and e the electronic charge. With appropriate electronics one can detect changes in flux of a millionth of a flux quantum—or even less—in a bandwidth of 1 Hz. To make an amplifier one inductively couples the SQUID loop to a superconducting input circuit in series with an oscillating voltage source and appropriate circuitry, and detects the amplified voltage developed across the current-biased SQUID. I discuss in detail the theory of intrinsic noise in the SQUID, which originates as Nyquist noise in the shunt resistor connected across each Josephson junction. The noise at the signal frequency arises from two components of noise generated in the shunt resistors: one at the signal frequency and the other at the much higher Josephson frequency $2eV/h$, where V is the bias voltage of the SQUID, mixed down to the signal frequency by the nonlinearity of the junctions. For a single junction with appropriate design parameters and bias current, I illustrate the second term with the direct observation of zero-point fluctuations. The theory of the noise temperature for a quantum-limited SQUID amplifier yields hf/k at signal frequency f, where k is the Boltzmann constant. Finally, I show results for a SQUID amplifier operating at 50 mK with a measured noise temperature close to the quantum limit.

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