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Quantum transitions of a small Josephson junction array

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Abstract

We have experimentally studied a small Josephson junction array in the presence of microwave irradiation. The array has comparable energy scales for single-charge effects and the Josephson effect, resulting in a discrete set of macroscopic eigenenergy levels. Excitation of the array by low-power microwaves is possible at frequencies where the photon energy matches the level spacing. The microwave frequency and amplitude dependence show that the excitation mechanism involves resonant quantum coherent dynamics of the array.

Keywords: Josephson effect; Macroscopic quantum mechanics; Microwave spectroscopy; Single-charge effects

1. Introduction

The appearance of discrete energy levels (DEL) when a degree of freedom is confined by a potential is a distinct quantum mechanical effect. In circuits of extremely underdamped Josephson junctions DEL that result from macroscopic degrees of freedom can be studied experimentally. These systems are equivalent to a particle, with a mass proportional to the junction capacitance C, whose phase coordinate γ (the phase degree of freedom of the Josephson junction) is confined by the Josephson potential — $E_J \cos\gamma$. Recently, the DEL of a device with a single superconducting grain coupled to leads via tunnel junctions have been demonstrated in experiments using microwave spectroscopy [1–3]. With such a circuit excited to a superposition of two energy states coherent charge oscillations have been observed [4].

2. Results

Here we study the quantum transitions between DEL of the array depicted in Fig. 1 [5]. For the junctions the ratio of the Josephson coupling E_J to the energy scale for single-charge effects $E_C = e^2/2C$ was $E_J/E_C = 0.2$, with $E_C/h = 28$ GHz. The level spacing between the DEL can be tuned continuously by inducing a gate charge $n_g = C_g V_g/2e$ on the islands. The array was studied by measuring the switching current I_{SW} from the supercurrent branch in the IV (effectively the escape of a particle in the tilted washboard potential in Fig. 1). This method can be used for spectroscopy since I_{SW} is strongly reduced when the array is in an excited state [1]. Note however that the analysis is complicated. For the ground band the relation $I_{bias} = (2e/\hbar)\partial E/\partial\delta$ between the bias current and the phase difference across the array δ is close to the form $I_{bias} \propto \sin\delta$, as shown in Fig. 1. From this picture it is clear that the level spacing ΔE changes, and the resonance condition $\Delta E = hf$ can be met, while adiabatically ramping the current for a switching current measurement.

Fig. 2 presents I_{SW} as a function n_g, measured in the presence of CW-microwaves. Additional low levels in I_{SW} around half-integer values of n_g are due to the presence of an unpaired quasiparticle on one or both islands, effectively changing n_g with $\frac{1}{2}$ for that island [6]. Arrows indicate n_g-values where I_{SW} is strongly reduced, which is clearly frequency dependent. The dips move closer to $n_g = 0$ with increasing frequency f, in agreement with a larger level spacing ΔE between the ground state and the first excited state at $n_g = 0$ where Coulomb blockade effects are maximal. For the reasons mentioned above the width of the dips cannot be interpreted as the lifetime of the excited states. When n_g is applied with an asymmetry of $\Delta n_g = 0.15$ the level spacing between the first and

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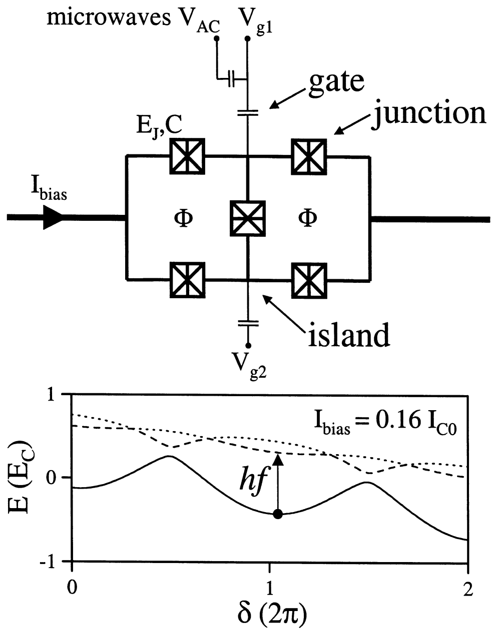

Fig. 1. Top: Schematic of the array. Here we only consider the case of symmetrically induced gate charges for the top and bottom island $n_g = C_g V_g/2e$, and a magnetic flux $\Phi = 0$ applied to the loops. Bottom: The lowest three bands of the array as a function of the phase δ across the array, here calculated for $E_J/E_C = 0.3$ and $n_g = 0.37$ using [6]. At finite bias current the bands are tilted ($I_{C0} = (2e/\hbar)E_J$).

second excited state is larger, and transitions to both the first and second excited state could be distinguished.

Measurements of the Bessel function behavior of the Shapiro-step heights in the voltage biased IV were used to calibrate the microwave amplitude V_{AC}. This was possible without any change to the array's electromagnetic environment. This showed that the data of Fig. 2 is typically recorded for $V_{AC} < hf/2e$, corresponding to an oscillating matrix element for transitions between the levels that is much smaller than the level spacing. This, together with the clear frequency dependence of the dips, indicates that the excitation mechanism involves resonant quantum coherent dynamics, similar to AC-pulse-induced Rabi dynamics in NMR.

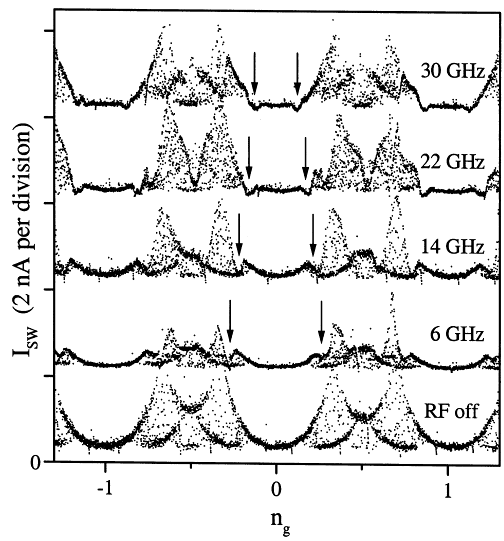

Fig. 2. Measurements of the $2e$-periodic modulation of the switching current I_{SW} by the dimensionless gate charge n_g, measured with different microwave frequencies, at a temperature of 10 mK. Data sets are 2 nA offset for clarity.

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