Classical to Quantum Crossover Behavior of Drexel's First Solid-state Qubit

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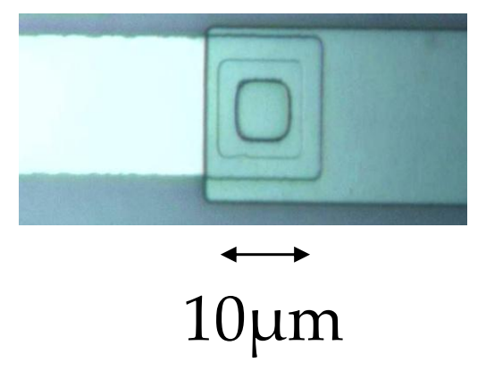
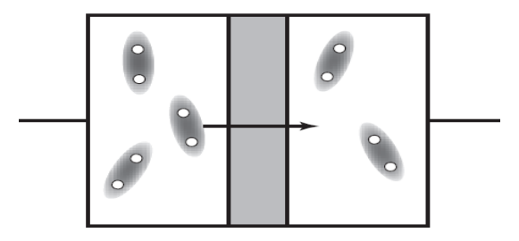
Abstract

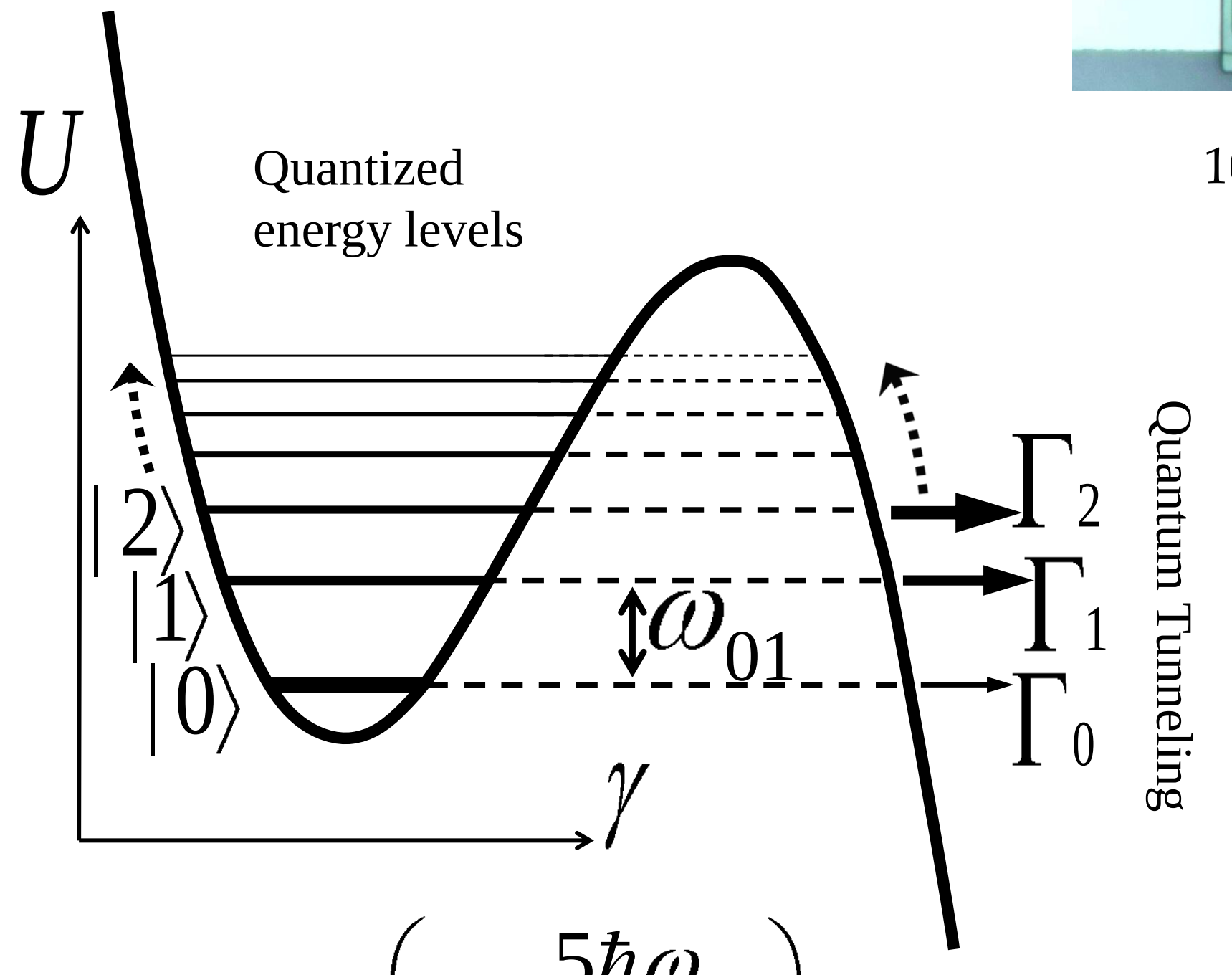
At very low temperatures, a solid-state device called the Josephson junction acts like an artificial atom with distinct quantum energy levels. These energy levels, which form the basis of a "qubit state", can be measured using microwaves. We examine the microwave activation of a current-biased Josephson junction near the crossover temperature $T_{cr} = hf/2\pi k_b$. *We report on experiments that demonstrate how the device transitions from the quantum regime behavior to that of a classical nonlinear oscillator.* In the quantum regime, we excite the device from the ground state to first excited state with microwaves at the resonant frequency. The quantum features, in the form of peaks in escape rate enhancements, are visible until the junction is heated up to the crossover temperature T_{cr}, at which point the line widths of the energy levels overlap and become indistinguishable from one another. The result is a step-like structure that is characteristic of escape rate enhancements in the classical regime. Well above this temperature, the junction behaves classically when resonantly activated with microwaves.

Theory

The superconducting Josephson junctions is a solid state device made with two superconductors separated by a thin oxide layer. All of the electrons coalesce into one common ground state that can be described by a single wave equation, allowing for tunneling across the classically forbidden region of the oxide layer.



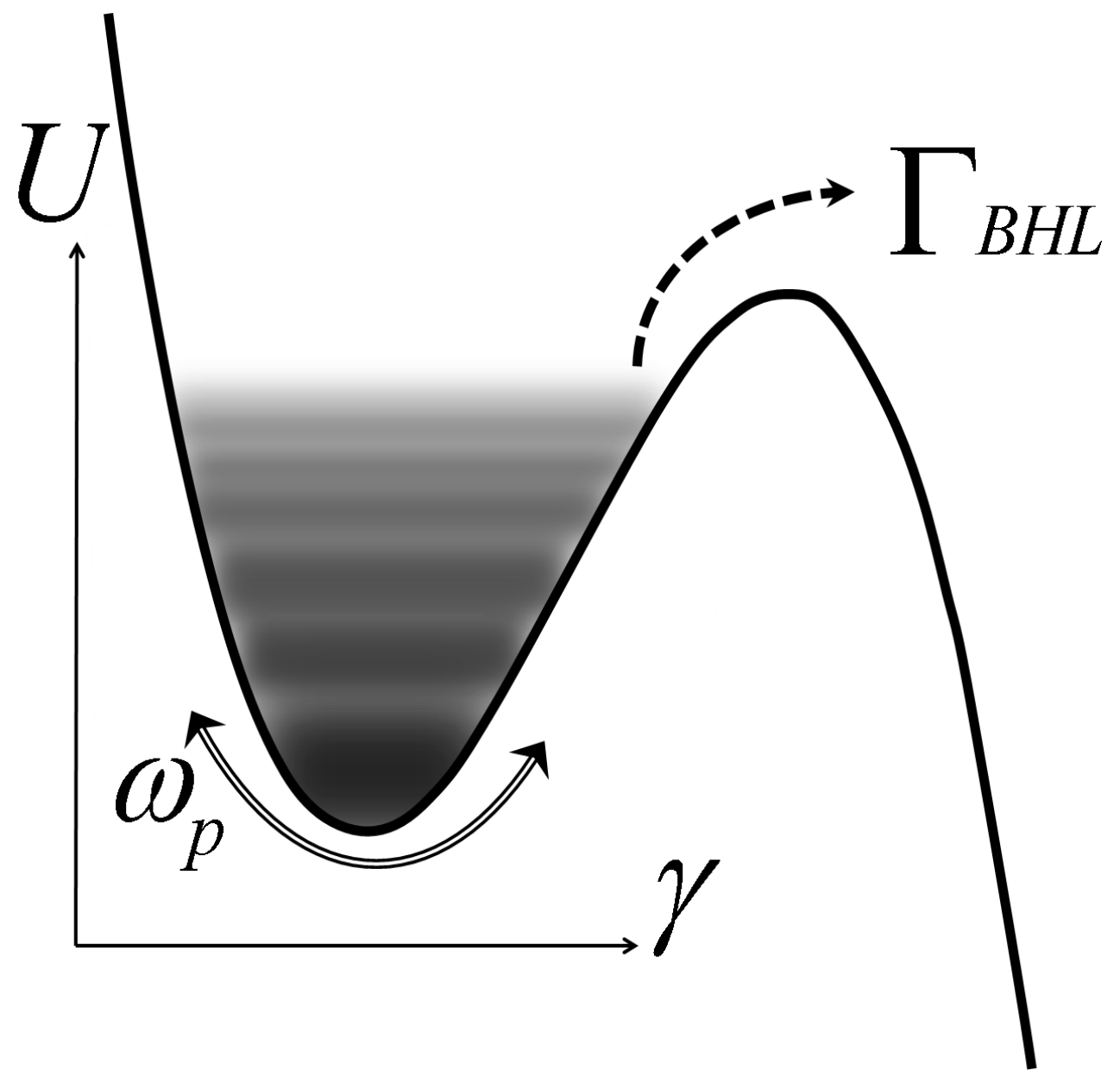




$$\omega_{01} \cong \omega_p\left(1-\frac{5\hbar\omega_p}{36\Delta U}\right)$$

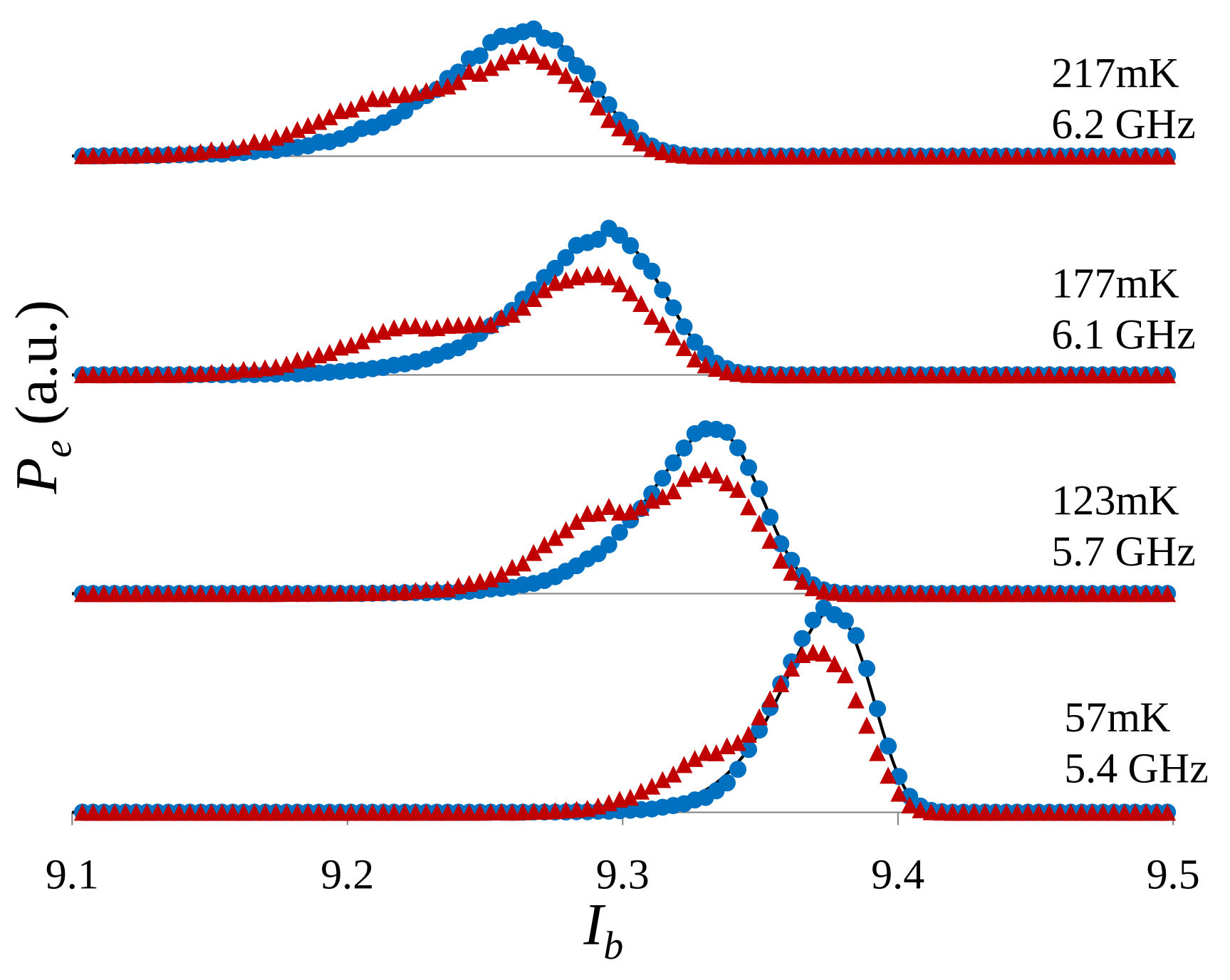
At low temperatures, only the lowest states are populated and thermal escape out of the well is minimized. The primary escape mechanism is tunneling through the barrier. If microwaves are applied at the resonance frequency, ω_{01}, the first excited state becomes populated, and an enhancement in the escape rate is observed.

At higher temperatures, more energy states become thermally populated, allowing the system to exist in a superposition of energy states. The system can then behave as though there were a continuum of energy states available. Under resonant activation, this system behaves classically.



$$\omega_p = \sqrt{\frac{2\pi I_0}{\Phi_0 C_j}}\left[1-\left(\frac{I_b}{I_0}\right)^2\right]^{\frac{1}{4}}$$

High Temperatures



Histograms of the escape events as a function of bias current, offset for clarity.

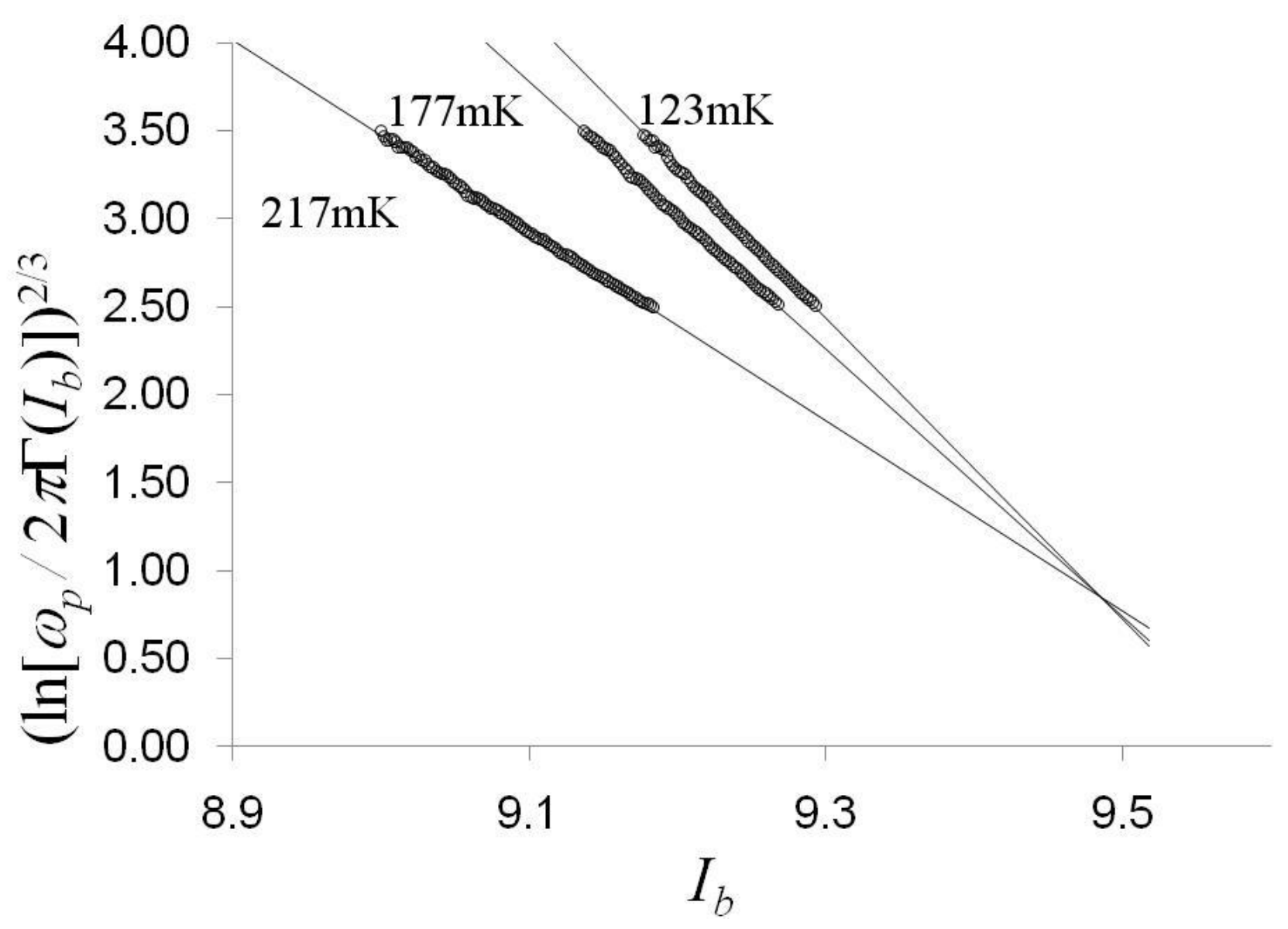
In order to analyze the data, we first determine the parameters of our system.

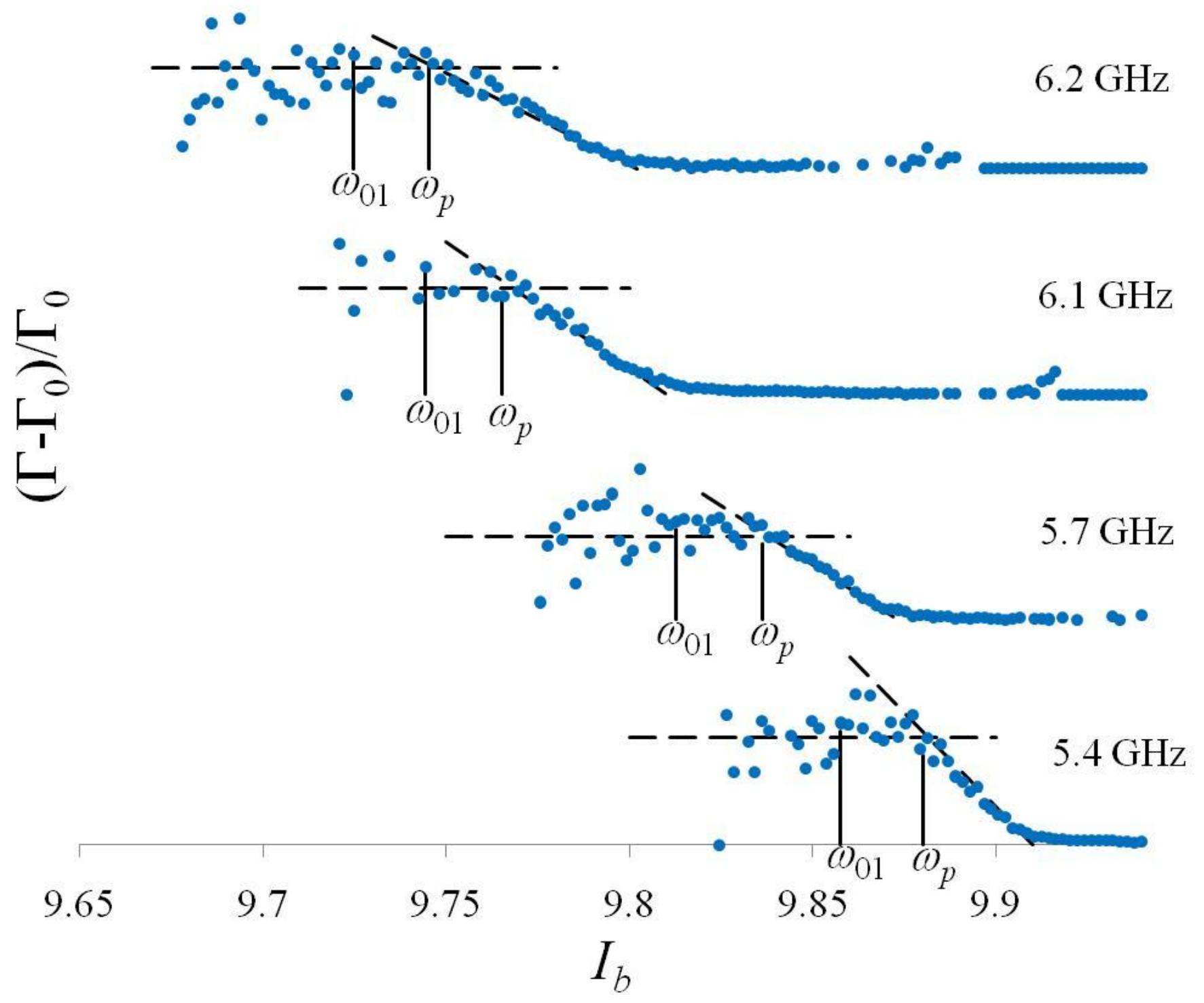
In the limit that the system is above the crossover temperature the total escape rate is governed by the equation

$$\Gamma_{BHL} = a_t\frac{\omega_p}{2\pi}\exp\left(-\frac{\Delta U}{k_b T}\right)$$

$$a_t = 4/[\sqrt{1+5Qk_bT/9\Delta U}+1]^2$$

In order to find the critical current for the junction, $(\ln[\omega_p/2\pi\Gamma(I_b)])^{2/3}$ is plotted as a function of bias current. The linear fits intersect at the theoretical critical current at about $I_b = 9.485\mu A$





Escape rate enhancement plots.

The non-Lorentzian shape is indicative of classical behavior.

The elbow in the enhancements shown here clearly line up with ω_p, indicating classical resonance.

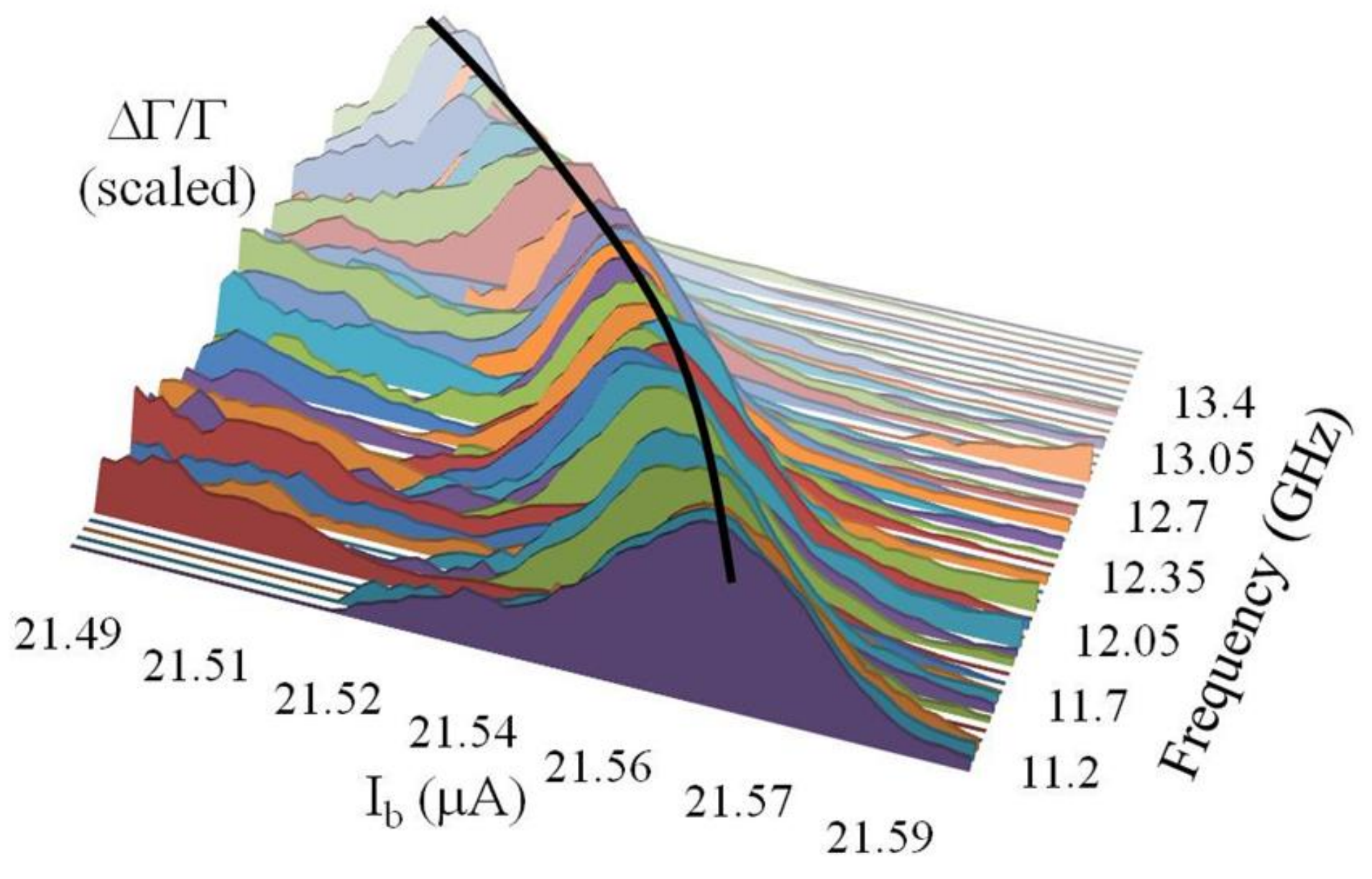
QUANTUM TO CLASSICAL CROSSOVER

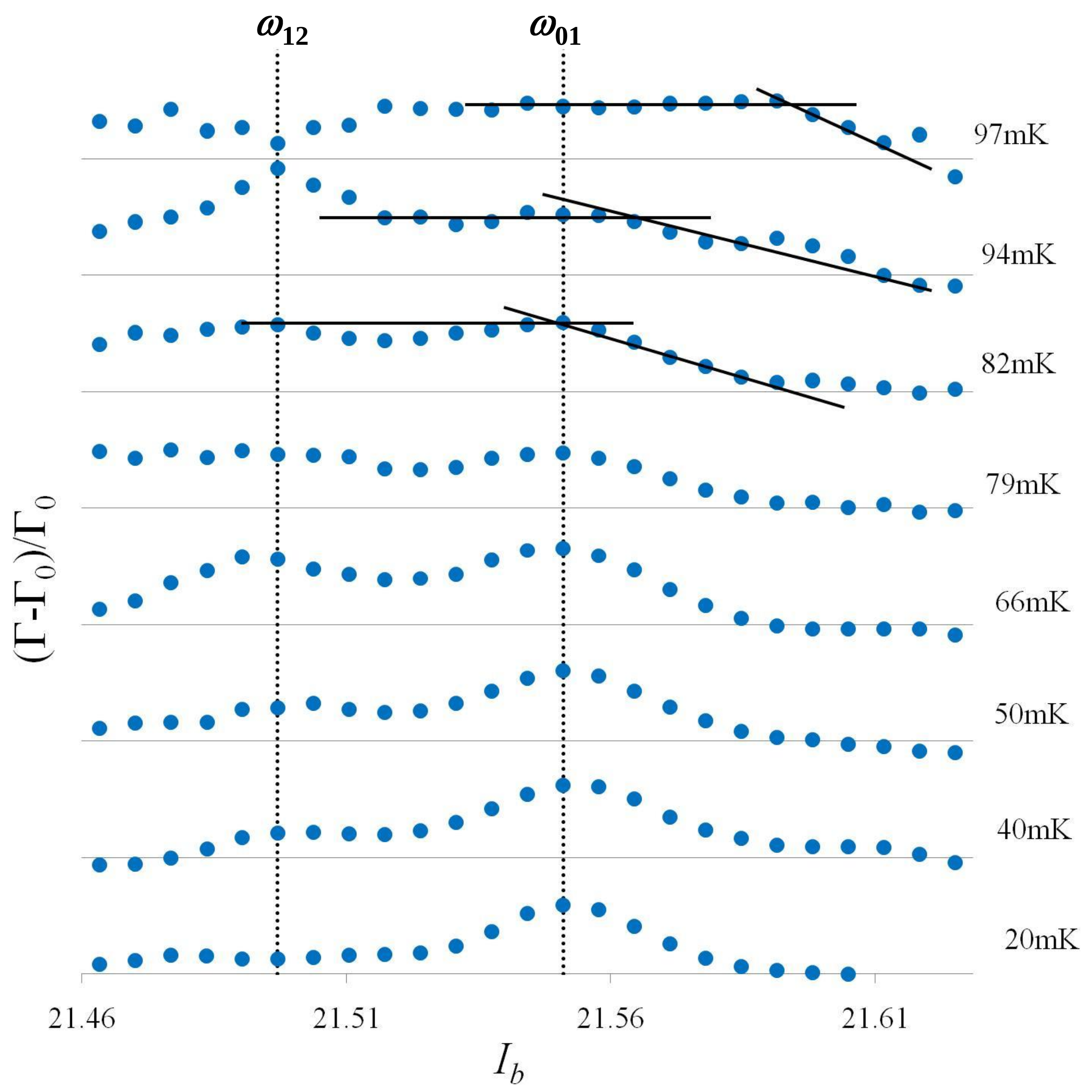
In the second experiment we must determine the parameters again.

Escape rate enhancement plots for the data at base temperature in our second experiment at various frequencies.

The enhancements show a clearly quantum signature.

Using this frequency vs. current plot we can derive C_j and I_b for this experiment.





Escape rate enhancement plots for the data at increasing temperatures in our second experiment. The driving frequency is being held at 12GHz.

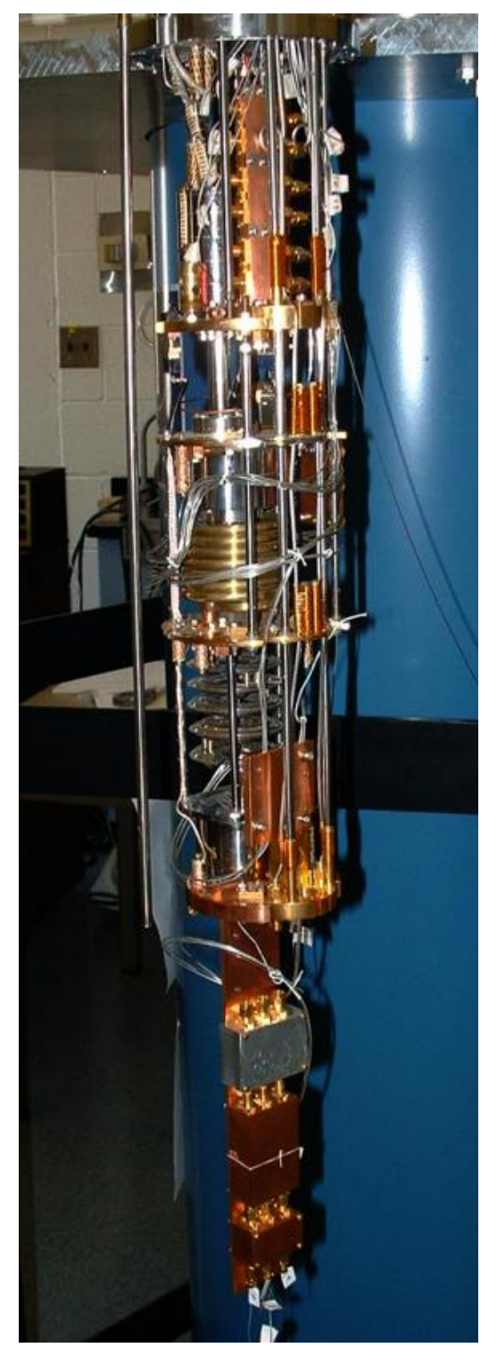
The bias currents corresponding to a resonance with ω_{01} and ω_p are shown.

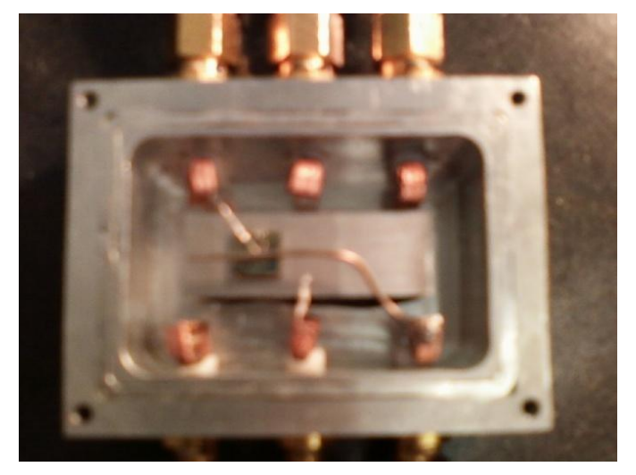
At temperatures near the base temperature of the fridge, there is an enhancement corresponding to the ω_{01} transition.

As the temperature increases the ω_{02} transition becomes visible due to thermal excitations into the first excited state.

At temperatures near the crossover, 92mK, the peaks widen enough to form the step-like structure as seen in the first experiment.

Summary and Future Work





In conclusion, we have presented experimental data that shows evidence of the crossover from classical to quantum behavior.

In the high temperature regime, the escape enhancement is governed by the classical plasma frequency.

At lower temperatures the enhancement will become governed by the resonances corresponding to the quantum energy level spacings.

In the future, we will investigate a more detailed look into the interplay of classical and quantum dynamics in Josephson junctions.

We will collect data within the crossover region itself in order to provide insight into the nature of the transition.