Final Report
Superconducting Qubits for Quantum Computation
Contract MDA904-98-C-A821/0000

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1. Summary of year one results.

The following results were presented in detail in our technical report for year one and will only be summarized here.

- The band gap in a Bloch transistor was measured at the degeneracy point, demonstrating the coherent superposition on the 0 and 1 pair charge states on the island of the transistor [1].
- Work was undertaken to upgrade our experimental apparatus for the study of SQUID qubits. This involved:
    - Improved shielding of the sample from the measurements magnetometer.
    - Development of better DC SQUID magnetometers to permit further decoupling of the magnetometer from the sample in order to reduce the influence of the measuring apparatus on the sample.
    - Installing the microwave lines into the sample cell in order to be able to induce transitions to excited energy levels of the sample SQUID. This will be needed for our initial measurements of coherence in SQUIDs and later for manipulating the state of the qubit.
- A theoretical analysis of the dynamics of Rabi transitions was undertaken, which showed that an adiabatic level-crossing approach to controlling the state of the qubit should be superior.
- The effects of electron-phonon interactions of decoherence in Josephson junctions have been analyzed and found to be small.
- An improved theory of tunneling between the flux wells of a SQUID has been developed. A density matrix approach is used which permits the inclusion of coherence among the states as well as separate decoherence rates for in-well and inter-well interactions.
- A new concept for a coupled flux-charge qubit has been developed and analyzed. An important feature of this qubit is that it contains essentially two qubits (one using charge states and the other using flux states) in the same device. The coupling between these two qubits can be switched on and off *in situ*.

2. Summary of results for the final six-month period.

- Our apparatus upgrade for the experiment to attempt to demonstrate the coherent superposition of different flux states of a SQUID has been completed:
  - A higher sensitivity magnetometer has been fabricated and installed. The coupling of the magnetometer to the sample has been reduced in order to minimize the decoherence induced by the measurement itself.
  - As a result of these improvements it has been possible to move the normal metal shield around the sample (which is also a source of decoherence) further from the sample. We calculated that this new configuration should reduce the damping to the point that we will be able to observe a significant degree of coherence between flux states of the SQUID.
  - The sample cell has been modified to permit radiation to be couple to the sample in the frequency range of 1 to 100 GHz while, at the same time shielding the sample from the rf generated by the magnetometer.
  - As of the end of this contract, this new setup has been tested and found to perform essentially as predicted. We expect to shortly begin a data run in which we would expect to demonstrate the existence of a coherent superposition of flux states of the SQUID.
- The density matrix theory of inter-well transitions has been extended to the case – corresponding to our proposed experiment -- where the system is first excited to a state that is near enough to the barrier to be split into its symmetric and anti-symmetric components due to the coherent superposition of different fluxoid states. The inter-well transition rate for the system has been calculated as a function of the frequency of the applied radiation. For sufficiently low damping, the splitting between the symmetric and anti-symmetric states is clearly resolved (see Fig.1). This paper is now nearly ready for submission[2].
- An analysis of a two level quantum system under continuous observation has been carried out[3]. It is found that under suitable conditions a resonance can be observed in the output spectrum of the system at a frequency corresponding to the energy difference between the two states. This shows that the coherent oscillations between the two levels can be maintained even though the system is under continuous observation. This effect is weak, however. The maximum amplitude of the coherent peak, assuming a quantum-limited detector, can only be 4 times the noise floor of the measurement.
- A further analysis has been carried out of the data obtained from our initial experiments which used incoherent tunneling to probe the level structure of the fluxoid wells[4]. It was discovered that for certain values of the control parameters, where the resonant tunneling rates were low, we observed clear evidence for inter-well transition due to the sequential absorption of two photons (see Fig. 2). In this case, the system was first excited to a resonant level in the initial well. When a second intermediate state, above the barrier, was separated from this initial resonant level by the photon energy, a second photon was absorbed sending the system above the barrier. From this second intermediate state, it had a roughly 50% probability of decaying into the opposite fluxoid well. While the probability of such double absorption is low, the very high probability of a transition once it occurs makes this the dominant transition process under some conditions. The

relevance of this process for the development of SQUID qubits is that, in a system which is not designed to avoid it, it can serve as a rapid source of decoherence, which must be avoided.

3. Conclusions and recommendations for further work.

The experimental apparatus has been upgraded to the point where, if the predictions of theory are correct, it will be possible to demonstrate the existence of the coherent superposition of different fluxoid states. A solid theoretical framework for the analysis of such experiments has been developed. So far, the prospects for the development of successful SQUID qubits seem quite promising. A continuation of the work toward that goal is being carried out under a grant through ARO, with funding from NSA.

Note that, in accordance with our NSA contract, publications resulting from work done under this contract do not acknowledge NSA support.

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[1] *Observation of Coherent Charge-State Mixing in Asymmetric Bloch Transistors*, D. J. Flees, S. Han, and J. E. Lukens, J. Supercond., **12**, 813 (1999)

[2] *Macroscopic Resonant Tunneling of Magnetic Flux*, D. V. Averin, J. R. Friedman and J. E. Lukens, preprint

[3] *Continuous Weak Measurement of Quantum Coherent Oscillations*, A. N. Korotkov and D. V. Averin, submitted for publication.

[4] *Observation of Cascaded Two-Photon-Induced Transitions between Fluxoid States of a SQUID*, Siyuan Han, R. Rouse, and J. E. Lukens, Phys. Rev. Lett., **84**, 1300 (2000)

Figure Captions

Fig. 1. The rate for the photon-assisted resonant tunneling of flux between the two wells of the SQUID potential as a function of the difference ν between the photon energy and the mean of the resonant levels. "a" is a measure of the rf amplitude, ε measures the tilt of the potential and Γ is the in-well relaxation rate in units of the tunnel splitting Δ.

Fig. 2. Measured amplitudes of the resonantly activated tunneling peaks (dots) with representative error bars compared with the calculated amplitudes including only single photon absorption (dashed line) and cascaded 2-photon absorption (solid line). Several of the calculated peaks are identified with their corresponding processes by **T** (tunneling from [0,3]) or **C** (cascaded 2-photon absorptions to a second resonant level above the barrier).