Macroscopic Quantum Superposition States, Squeezing and Entanglement in SQUID Rings

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In this paper we consider the behaviour of a quantum regime SQUID ring (here, one Josephson weak link enclosed by a thick superconducting ring) from the viewpoint of generating superpositions of macroscopically distinct states and in the squeezing of coherent states [1,2]. We show that because of the Josephson coupling term in the SQUID ring Hamiltonian both are possible. On this basis we consider that the SQUID ring constitutes a strong contender for application in future quantum circuit technologies. In order to make our calculations correspond to a more realistic situation we also consider the effect on the SQUID ring of a dissipative (decohering) external environment, taking the standard open systems approach commonly used in the field of Quantum Optics. We show that even with such a decohering environment in place it is still possible to utilise SQUID ring for creating superpositions and squeezing provided the dissipation is not too great.

As another example of applying the techniques familiar to the field of quantum optics, we consider the problem of entangling a SQUID ring coupled inductively to an electromagnetic field oscillator mode. We demonstrate by solving the time dependent Schrödinger equation that we can create a state of maximal entanglement between them. We show that this state can be generated and controlled through the application of a time dependent external magnetic flux bias applied to the ring. When this flux is adiabatically ramped through an avoided crossing we are able to create a reasonably good approximation to a maximally entangled state. However, we find that this state of entanglement can be enhanced considerably by using a non-adiabatic flux pulse. We extend these calculations to include the effects of dissipative environments coupled to the SQUID ring. We demonstrate that even including such decohering environments it is possible to maintain a sufficient degree of entanglement over time scales that would be required for quantum technologies.

[1] J. R. Friedman, V. Patel, W. Chen, S. K. Tolpygo, and J. E. Lukens, Nature (London) **406**, 43 (2000).
[2] M. J. Everitt, T. D. Clark, P. B. Stiffell, A. Vourdas, J. F. Ralph, R. J. Prance, and H. Prance, "Superconducting analogs of quantum optical phenomena: Macroscopic quantum superpositions and squeezing in a superconducting quantum-interference device ring", Phys. Rev. A Scheduled Issue **69**(4) (1 Apr 2004).