

Probing Nanomagnetism with Quantum-Limited Resolution

We are trying to demonstrate superconducting magnetometers with sufficient sensitivity to observe time domain behavior of individual nanomagnets. In analogy with single charge detectors, we have dubbed this measurement device the single Bohr magneton detector (SBD). The SBD consists of three superconducting Josephson junctions in a loop. The electronic transport properties of the circuit are affected by the magnetic flux in the loop. The three junction SBD is optimized for measurement of nanometer sized particles. In the SBD, one of the three junctions is a micrometer sized conventional aluminum/aluminum oxide/aluminum tunnel junction. The other two junctions are weak-link type junctions formed by single-walled carbon nanotubes bridging superconducting electrodes [3]. The nanotube weak-links are envisioned to be ~ 1 nm in diameter and ~ 50 nm in length. This geometry allows for strong magnetic coupling of the magnetometer to nanomagnets which can be attached to the nanotubes or placed within close proximity. The large junction is used to readout the magnetic flux present in the loop.

The operation of nanotube based Josephson junctions have recently been demonstrated by two European groups [3,4]. A two junction superconducting quantum interference (SQUID) magnetometer is shown in Figure 1. The critical current of the SQUID, though near ideal in its magnetic flux modulation, has a magnitude of only a few nanoamps [4], making precision measurements prohibitively slow. The addition of a third junction with microamp critical current imposes the nanoamp magnetic modulation on top of a large current which can be readily read out with fast microwave techniques. This scheme is suggested in analogy with the Quantronium circuit, studied by Siddiqi, and shown in Figure 2 [5]. This circuit also consists of three Josephson junctions, one with a critical current of about 1 microamp, coupled to two small junctions with nanoamp critical currents. These junctions are all aluminum oxide tunnel junctions. The Quantronium circuit is in fact a superconducting qubit and hence a pseudospin $\frac{1}{2}$ system. The “spin” states of the Quantronium circuit can be read out within ~ 10 ns using a novel microwave readout scheme which is also proposed for readout of the SBD.

Each junction can be thought of as an inductor. The total inductance of the three junction loop is hence dependent on the magnetic signal of the nanomagnet. Shunted with an on-chip capacitor, this circuit forms an oscillator with a resonant frequency in the GHz range. With the aid of microwave pulses, this frequency can be determined in ~ 10 ns. Moreover, this technique, pioneered by Siddiqi and co-workers at Yale, does not switch the superconductor into the normal state as does a conventional shunted SQUID, but allows the SQUID to remain in the zero voltage, nondissipative state. This eliminates any spurious heating effects.

The nanomagnets to be studied with the SBD are single-molecule magnets (SMMs). SMMs consist of ~ 100 atoms, and are roughly a few nanometers in spatial extent. The core consists of several strongly exchange coupled transition metal atoms, giving the molecule a rigid overall spin S which can be varied from $1/2$ to a currently achieved maximum value of $83/2$. There are several techniques for depositing SMMs onto metallic

nanocircuits. SMMs can be doped into isostructural spin neutral crystals so that the density of molecular magnets in a given volume can be continuously varied. Additionally, there are several species of SMMs that can be deposited intact on a surface by spraying with a dilute solution which is subsequently evaporated. Finally, functional groups can be attached to the SMMs to bind to the carbon surface of the nanotube weak links.

The transition frequency between the magnetic sublevels of SMMs is typically in the 1-20 GHz range. Microwave radiation to manipulate the spin state can be readily coupled via metallic, on-chip transmission lines. With appropriate microwave control pulses, coherent superpositions of magnetic sub-levels can be prepared. By varying the spin S of the molecules, we plan to address a fundamental question at the heart of quantum mechanics: Can a superposition be made of arbitrarily macroscopic objects? Nothing in the linear theory of quantum mechanics causes the collapse of a superposition as long as all interactions are known and controlled. By varying a single control parameter – the spin S – SMMs can potentially realize quantum superpositions of varying complexity, directly testing the limits of superposition.

Such coherent control of molecule-based quantum spins will provide us with deep insight into the most fundamental aspects of quantum mechanics and open the door to exciting new interdisciplinary applications that marry sensitive nanoelectronics with molecular based active elements. The techniques developed here will permit new experiments in nuclear magnetic resonance (NMR), electron-spin resonance (ESR), and nuclear quadrupole resonance (NQR) at the single molecule limit. Moreover, this research will provide the means to store and manipulate information quantum mechanically in individual magnetic molecules, ultimately enabling us to realize true quantum machines whose operation is based on the laws of quantum electrodynamics rather than classical electromagnetism.

References

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