Cavity Quantum Spin Resonance

Controlling spin relaxation with a cavity

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Recommended and Commentary by Steven M. Girvin, Yale University

In 1946 Purcell [1] predicted that spins placed in the coil of a resonant circuit would have an enhanced spontaneous emission rate. Using a superconducting resonant circuit of small mode volume and high quality factor Q, Bienfait et al. have succeeded in dramatically shortening the spin relaxation time by a factor of nearly 10^9 finally achieving the limit in which the spontaneous radiative emission rate exceeds the non-radiative 'spin-lattice' relaxation rate. This is an important advance which will allow fast reset of spins used as qubits and could have potential applications in improving dynamical nuclear polarization via the Overhauser effect. It is particularly interesting that the fast radiative damping can be turned on and off by using a magnetic field to vary the detuning of the spin frequency relative to the circuit resonance.

When we first learn about the quantum eigenstates of the hydrogen atom, we are told that the 2p excited eigenstate is a stationary state lying 3/4 of a Rydberg above the 1s ground state. Later we discover that the 2p state lives for only about 1 nanosecond before decaying back to the ground state via 'spontaneous' emission of an ultraviolet photon. The decay is caused by the zero-point flucutations of the quantized electromagnetic vacuum which arise because the electric and magnetic fields are canonically conjugate and thus subject to the uncertainty principle. The matrix element for the emission of a photon by an atom is given by the transition electric dipole moment multiplied by the RMS zero-point fluctuations of the vacuum electric field.

The spontaneous emission rate can be determined from Fermi's Golden Rule using the square of this matrix element multiplied by the photon density of states.

The spontaneous emission rate can be modified by placing the atom inside a cavity which acts as a filter standing between the atom and the vacuum noise. If the filter is resonant with the atom, it enhances the electric field fluctuations and thus enhances the spontaneous emission rate. Conversely, if the filter resonance is detuned from the atom transition frequency, the filter shields the atom from the relevant spectral components of the vacuum noise and the spontaneous emission rate is correspondingly reduced. Fermi's Golden Rule gives for the spontaneous emission rate

$$\Gamma = g^2(-2)\mathrm{Im}G(\omega), \tag{1}$$

where g is the matrix element for photon emission (the 'vacuum Rabi coupling'), ω is the atom transition frequency and G is the filter response function

$$G(\omega) = \frac{1}{(\omega - \omega_{\mathrm{R}}) + i\kappa/2}. \tag{2}$$

Here ω_{R} is the cavity resonance frequency and the linewidth is κ. Thus we have

$$\Gamma = g^2 \frac{\kappa}{\Delta^2 + (\kappa/2)^2}, \tag{3}$$

where $\Delta \equiv \omega - \omega_{\mathrm{R}}$ is the detuning between the qubit and the cavity resonance. In the limit of large detuning ($\Delta \gg \kappa$) we have [2]

$$\Gamma \sim \frac{g^2}{\Delta^2}\kappa. \tag{4}$$

This can be interpreted as the qubit and cavity hybridizing to form a polariton. The qubit-like polariton has a probability $(g/\Delta)^2$ of being a photon which in turn decays at rate κ. For large detuning, the qubit decay rate is strongly suppressed by the presence of the cavity which is filtering out the vacuum noise at the qubit transition frequency. For superconducting qubits, it is sometimes the case that qubit natural lifetime γ^{-1} is considerably shorter than that of the cavity. In such a situation the hybridization produces a kind of 'reverse Purcell' effect in which the cavity decay becomes enhanced by an amount $\kappa_\gamma \equiv (g/\Delta)^2\gamma$ so that $\kappa_{\mathrm{eff}} = \kappa + \kappa_\gamma$.

For the resonant case of zero detuning, we have [2,3] from Eq. (3)

$$\Gamma = 4\frac{g^2}{\kappa}, \tag{5}$$

which is *inversely* proportional to the cavity decay rate. We can understand this as the resonant enhancement of the photon density of final states for the qubit to decay into. In electrical engineering language, the resonator acts as a transformer to impedance match the vacuum to the atom. Of course if κ becomes so small that $g > \kappa$, Fermi's Golden Rule breaks down. The upper and lower polaritons are equal coherent superposition of qubit and cavity excitations and the cavity-induced decay rate therefore saturates at $\kappa/2$.

In practice, the lifetime enhancement effect associated with large detuning is difficult to observe at optical frequencies. This is because a Fabry-Perot cavity consisting of two mirrors separated by a distance even as small as 1 cm (say) still has $\sim 10^4$ wavelengths between the mirrors. The atom thus mostly decays into modes (spatial directions) not trapped between the mirrors. (In addition the free spectral range of the cavity (i.e. the mode spacing) is small so it is difficult to detune all the cavity modes far from the atom.) On the other hand it is now routine to see lifetime enhancements of a factor of 10^3 for superconducting qubits surrounded on all sides by the the superconducting walls of a (small) 3D cavity whose size is comparable to the wavelength [4].

In principle, the excited state of a spin in a magnetic field can spontaneously emit a radio-frequency photon via a magnetic dipole transition. However the corresponding matrix element (given by the Bohr or nuclear magneton multiplied by the zero-point fluctuation magnetic field) is very small, as is the density of photon states at radio frequencies. The result is that the spontaneous emission lifetime is enormously and unobservably long. In 1946 Purcell predicted that spins placed in the coil of a resonant circuit would have an enhanced spontaneous emission rate as described above and Bienfait et al. have succeeded admirably in dramatically shortening the spin relaxation rate so that it is dominated by spontaneous emission of photons. This advance as well as the use of nearly ideal quantum-limited amplifiers (developed for use with superconducting qubits) are bringing us closer and closer to the regime of single-spin resonance detection.

Interested readers are urged to read the beautiful summary of the Bienfait et al. paper by Johanna Miller in *Physics Today* [5].

References:

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