Coupling small spin ensembles to superconducting on-chip resonators: towards a hybrid architecture for quantum information

M. D. Jenkins,[1] P. Hermosilla,[2] M. C. Pallarés,[2] A. Lostao,[2,3] C. Sánchez-Azqueta,[4] J. Majer,[5] D. Zueco,[6,3] and F. Luis[6,*]

[1] Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, Delft 2628 CJ, The Netherlands
[2] Laboratorio de Microscopías Avanzadas. Instituto de Nanociencia de Aragón, Universidad de Zaragoza, 50018 Zaragoza, Spain
[3] Fundación ARAID, Campus Río Ebro, 50018 Zaragoza, Spain
[4] Departamento de Ingeniería Electrónica y Comunicaciones, Universidad de Zaragoza, 50009 Zaragoza, Spain
[5] Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, 1020 Vienna, Austria
[6] Instituto de Ciencia de Materiales de Aragón, CSIC - Universidad de Zaragoza, 50009 Zaragoza, Spain
[*] fluis@unizar.es

Cavity quantum electrodynamics (QED) studies the interaction of photons in resonant cavities with either natural or "artificial" atoms, such as quantum dots and superconducting qubits, having a nonlinear and discrete energy level spectrum.[1] A major goal is to maximize the coupling strength g_1 of the atom to the cavity, making it larger than the decoherence rates of both the cavity and the atom (strong coupling regime). Attaining this regime for individual spin qubits would open the possibility of developing an all-magnetic quantum processor.[2] This goal remains, however, very challenging because the interaction of each spin with the photon's magnetic field is much weaker than the typical decoherence rates of the resonator and of most magnetic qubits. Strong coupling has been observed only in the case of macroscopic spin ensembles, containing $N > 10^{12}$ spins, for which the effective collective coupling g_N is enhanced by a factor $N^{1/2}$ with respect to that of a single spin.[3,4] The microwave magnetic field of a coplanar superconducting resonator can be enhanced locally via the fabrication of nanoscopic constrictions at its central line.[5] In this communication, we report the results of experiments performed on small spin ensembles directly deposited onto such nanobridges. The samples consist of DPPH free radicals, each having a spin s = 1/2 with a fully isotropic gyromagnetic factor g = 2 and a negligibly small inhomogeneous broadening.[6] Molecular ensembles were deposited using either a micropipette or, for the smallest ones, the tip of an atomic force microscope (AFM).[7] The number of spins N lying inside the area of the constriction was accurately determined from Scanning Electron Microscopy and AFM experiments. The maximum transmission, near the ground resonator's mode at $\omega/2\pi$ = 1.5 GHz, and the effective Q factor decrease sharply when the field brings the spins into resonance with the circuit. From these experiments, the collective coupling constant has been determined for samples with N varying between 10^8 and 10^{16} spins. The results show that $g_N \propto N^{1/2}$ and that the average single-spin coupling $g_1 = g_N/N^{1/2}$ is enhanced by more than two orders of magnitude (from 0.5 Hz up to 200 Hz) near the constrictions. Furthermore, the dependence of g_1 on the width of the central line agrees quantitatively with theoretical predictions.[8]

These results show that the coupling of spin qubits to quantum superconducting circuits can be enhanced via a combination of top-down and bottom up nanolithography techniques. The strong coupling regime might, therefore, be attained for especially designed molecular spin qubits that can show T_2^{-1} values as small as 1 kHz.[9] Furthermore, reaching this limit for individual spins, a pre-requisite for the development of a magnetic quantum processor, will then also be feasible provided that nanofabrication techniques are pushed down to w < 10 nm.

[1] R. J. Schoelkopf and S. M. Girvin, *Nature* **451** (2008) 669
[2] M. D. Jenkins, D. Zueco, O. Roubeau, G. Aromí, J. Majer and F. Luis, *Dalton Trans.* **45** (2016) 16682.
[3] D. I. Schuster *et al*, *Phys. Rev. Lett.* **105** (2010) 140501
[4] R. Amsüss *et al*, *Phys. Rev. Lett.* **107** (2011) 060502
[5] M. D. Jenkins et al, *Applied Physics Letters* **105** (2014) 162601
[6] N. D. Yordanov, *Appl. Magn. Res.* **10** (1996) 339
[7] M. J. Martínez-Pérez, E. Bellido, R. de Miguel, J. Sesé, A. Lostao, C. Gómez-Moreno, D. Drung, T. Schurig, D. Ruiz-Molina, and F. Luis, *Applied Physics Letters* **99** (2011) 032504
[8] M. D. Jenkins, T. Hümmer, M. J. Martínez-Pérez, J. J. García-Ripoll, D. Zueco and F. Luis, *NJP* **15** (2013) 095007
[9] J. M. Zadrozny, J. Niklas, O. G. Poluektov and D. E. Freedman, *ACS Cent. Sci.* **1** (2015) 4