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# Single electron-spin-resonance detection by microwave photon counting

1. **Single electron-spin-resonance detection by microwave photon counting**
   Authors: Z. Wang, L. Balembois, M. Rancic, E. Billaud, M. Le Dantec, A. Ferrier, P. Goldner, S. Bertaina, T. Chaneliere, D. Esteve, D. Vion, P. Bertet, and E. Flurin
   *Nature* **619**, 276–281 (2023)

2. **Practical Single Microwave Photon Counter with $10^{-22}$ W/$\sqrt{\text{Hz}}$ sensitivity**
   Authors: L. Balembois, J. Travesedo, L. Pallegoix, A. May, E. Billaud, M. Villiers, D. Estéve, D. Vion, P. Bertet, and E. Flurin
   arXiv:2307.03614

*Recommended with a Commentary by Steven M. Girvin, Yale University*

AMO (atomic, molecular and optical) physicists have long been able to detect single atoms via their resonance fluorescence despite the fact that only a tiny fraction of the emitted photons typically strike the detector. In these remarkable new papers, Wang et al. and Balembois et al. are able to detect the electron spin resonance (ESR) of single rare-earth ions embedded in a host solid ($\sim 3$ ppb $Er^{3+}$ in $CaWO_4$) by counting individual microwave fluorescence photons with very high efficiency. This advance opens new windows for potential applications in chemistry, biology, quantum computation/communication and fundamental physics ranging from probing individual spins in single molecules to substantially accelerating axion dark matter searches.

Typical commercial ESR systems that measure the magnetic field associated with electron spins have a detection sensitivity of about $10^{13}$ spins/$\sqrt{\text{Hz}}$. Using the quantum-limited microwave linear amplifiers developed for circuit QED measurements of superconducting qubits, one can do much better, reaching single-shot sensitivities of $\sim 10^2$ spins [1]. The big advantage however for photon counting techniques over linear amplifiers is that they do not suffer from the large background caused by amplified vacuum fluctuations because photon counters (nominally) only click if there is a photon present.

The single microwave photon detector used in these experiments is based on a transmon qubit coupled to a high $Q$ buffer mode containing the photon to be detected and a low $Q$ waste mode. The transmon is driven by a pump and acts as a 4-wave mixer that takes in the photon to be detected plus a pump photon and outputs an excitation of the transmon and a photon dumped into the waste mode. The low $Q$ of the waste mode makes the process irreversible, preventing the time-reversed process that would subsequently de-excite the transmon. The jump of the transmon into its excited state is then measured by standard dispersive coupling techniques used to read out superconducting qubits. This novel scheme offers a low dark count rate $\alpha \sim 10^2$/s and high quantum efficiency $\eta \sim 45\%$.

It is interesting to note that the spontaneous emission lifetime for microwave fluorescence in free space is of order $\sim 10^3$ years. Hence a critical feature of this experiment is the use of the high $Q$ buffer mode to resonantly (Purcell) enhance [2] the fluorescence rate to $\sim 10^3$/s so that it dominates over the non-radiative spin-lattice relaxation rate. Unlike an ordinary magnetic ESR experiment which relies on the spin coherence, this scheme does not since fluorescence radiation is incoherent. However it presents a new opportunity for probing and coherently controlling slow nuclear spin dynamics which in turn could be used to study molecular structure, or create long-term quantum memories.

# References


[1] 'Electron spin resonance spectroscopy with femtoliter detection volume,' V. Ranjan, S. Probst, B. Albanese, T. Schenkel, D. Vion, D. Esteve, J. J. L. Morton, and P. Bertet, *Appl. Phys. Lett.* **116**, 184002 (2020).

[2] 'Cavity Quantum Spin Resonance,' S. M. Girvin, *https://doi.org/10.36471/JCCM_April_2016_02*