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## **Magnetic Resonance Force Microscopy and the spin bath : towards single-spin massive-resonator entanglement and the spoiling influence of the spin bath**

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### **Citation**

Voogd, J. M. de. (2018, February 20). *Magnetic Resonance Force Microscopy and the spin bath : towards single-spin massive-resonator entanglement and the spoiling influence of the spin bath*. *Casimir PhD Series*. Retrieved from <https://hdl.handle.net/1887/61001>

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**Note:** To cite this publication please use the final published version (if applicable).

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**Issue Date:** 2018-02-20

## Bibliography

- A. Abragam and L. C. Hebel. The Principles of Nuclear Magnetism. *American Journal of Physics*, 29, 860–861, December 1961.
- B. Anderson and J. Payne. *The Spectroscope and Gemmology*. GemStone Press, Woodstock, Vt., 2 edition edition, October 2006.
- M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt. Cavity optomechanics. *Reviews of Modern Physics*, 86, 1391–1452, December 2014.
- C. R. Ast, B. Jäck, J. Senkpiel, M. Eltschka, M. Etzkorn, J. Ankerhold, and K. Kern. Sensing the quantum limit in scanning tunnelling spectroscopy. *Nature Communications*, 7, 13009, October 2016.
- H. Atmanspacher. Quantum Approaches to Consciousness. In E. N. Zalta, editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, summer 2015 edition, 2015.
- N. Bar-Gill, L. M. Pham, A. Jarmola, D. Budker, and R. L. Walsworth. Solid-state electronic spin coherence time approaching one second. *Nature Communications*, 4, 1743, April 2013.
- A. Bassi, K. Lochan, S. Satin, T. P. Singh, and H. Ulbricht. Models of wave-function collapse, underlying theories, and experimental tests. *Reviews of Modern Physics*, 85, 471–527, April 2013.
- G. P. Berman, F. Borgonovi, V. N. Gorshkov, and V. I. Tsifrinovich. *Magnetic Resonance Force Microscopy and a Single-Spin Measurement*. WORLD SCIENTIFIC, September 2006.
- F. Bloch. Nuclear Induction. *Physical Review*, 70, 460–474, October 1946.
- N. Bloembergen, E. M. Purcell, and R. V. Pound. Relaxation Effects in Nuclear Magnetic Resonance Absorption. *Physical Review*, 73, 679–712, April 1948.

- L. Boyer, F. Houze, A. Tonck, J.-L. Loubet, and J.-M. Georges. The influence of surface roughness on the capacitance between a sphere and a plane. *Journal of Physics D: Applied Physics*, 27, 1504, July 1994.
- D. Braak. Integrability of the Rabi Model. *Physical Review Letters*, 107, 100401, August 2011.
- V. B. Braginsky, F. Y. Khalili, and K. S. Thorne. *Quantum Measurement*. Cambridge University Press, Cambridge, 1 edition edition, May 1995.
- P. R. Briddon and R. Jones. Theory of impurities in diamond. *Physica B: Condensed Matter*, 185, 179–189, April 1993.
- N. C. Bruce, A. García-Valenzuela, and D. Kouznetsov. Rough-surface capacitor: approximations of the capacitance with elementary functions. *Journal of Physics D: Applied Physics*, 32, 2692, 1999.
- N. C. Bruce, A. García-Valenzuela, and D. Kouznetsov. The lateral resolution limit for imaging periodic conducting surfaces in capacitive microscopy. *Journal of Physics D: Applied Physics*, 33, 2890, 2000.
- A. Bruno, G. de Lange, S. Asaad, K. L. van der Enden, N. K. Langford, and L. Di-Carlo. Reducing intrinsic loss in superconducting resonators by surface treatment and deep etching of silicon substrates. *Applied Physics Letters*, 106, 182601, May 2015.
- R. Budakian, H. J. Mamin, and D. Rugar. Suppression of spin diffusion near a micron-size ferromagnet. *Phys. Rev. Lett.*, 92, 037205, Jan 2004.
- A. O. Caldeira and A. J. Leggett. Influence of Dissipation on Quantum Tunneling in Macroscopic Systems. *Physical Review Letters*, 46, 211–214, January 1981.
- A. O. Caldeira and A. J. Leggett. Quantum tunnelling in a dissipative system. *Annals of Physics*, 149, 374–456, September 1983.
- J. Cardellino, N. Scozzaro, M. Herman, A. J. Berger, C. Zhang, K. C. Fong, C. Jayaprakash, D. V. Pelekhov, and P. C. Hammel. The effect of spin transport on spin lifetime in nanoscale systems. *Nature Nanotechnology*, 9, 343–347, May 2014.
- S. Carroll. *Spacetime and Geometry: An Introduction to General Relativity*. Pearson, San Francisco, September 2003.
- L. Chen, J. G. Longenecker, E. W. Moore, and J. A. Marohn. Long-lived frequency shifts observed in a magnetic resonance force microscope experiment following microwave irradiation of a nitroxide spin probe. *Appl. Phys. Lett.*, 102, 132404, 2013.

- B. W. Chui, Y. Hishinuma, R. Budakian, H. J. Mamin, T. W. Kenny, and D. Rugar. Mass-loaded cantilevers with suppressed higher-order modes for magnetic resonance force microscopy. *2*, 1120–1123, June 2003.
- P. K. Day, H. G. LeDuc, B. A. Mazin, A. Vayonakis, and J. Zmuidzinas. A broadband superconducting detector suitable for use in large arrays. *Nature*, 425, 817–821, October 2003.
- C. L. Degen, M. Poggio, H. J. Mamin, C. T. Rettner, and D. Rugar. Nanoscale magnetic resonance imaging. *Proc. Natl. Acad. Sci. U. S. A.*, 106, 1313–7, 2009a.
- C. L. Degen, M. Poggio, H. J. Mamin, C. T. Rettner, and D. Rugar. Nanoscale magnetic resonance imaging, appendix b. *Proceedings of the National Academy of Sciences*, 106, 1313–1317, February 2009b.
- L. Diósi. Models for universal reduction of macroscopic quantum fluctuations. *Physical Review A*, 40, 1165–1174, August 1989.
- L. Diósi. Gravity-related spontaneous wave function collapse in bulk matter. *New Journal of Physics*, 16, 105006, 2014.
- L. Diósi. Testing Spontaneous Wave-Function Collapse Models on Classical Mechanical Oscillators. *Physical Review Letters*, 114, 050403, February 2015.
- M. W. Doherty, N. B. Manson, P. Delaney, F. Jelezko, J. Wrachtrup, and L. C. L. Hollenberg. The nitrogen-vacancy colour centre in diamond. *Physics Reports*, 528, 1–45, July 2013.
- F. Donati, S. Rusponi, S. Stepanow, C. Wäckerlin, A. Singha, L. Persichetti, R. Baltic, K. Diller, F. Patthey, E. Fernandes, J. Dreiser, Ž. Šljivančanin, K. Kummer, C. Nistor, P. Gambardella, and H. Brune. Magnetic remanence in single atoms. *Science*, 352, 318–321, April 2016.
- D. M. Eigler and E. K. Schweizer. Positioning single atoms with a scanning tunnelling microscope. *Nature*, 344, 524–526, April 1990.
- A. Einstein. Die Feldgleichungen der Gravitation. *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften (Berlin)*, Seite 844-847., 1915.
- Element Six Technologies. *The Element Six CVD Diamond Handbook*. The De Beers Group of Companies, 2015.
- A. Endo, C. Šfiligoj, S. J. C. Yates, J. J. A. Baselmans, D. J. Thoen, S. M. H. Javadzadeh, P. P. van der Werf, A. M. Baryshev, and T. M. Klapwijk. On-chip filter bank spectroscopy at 600-700 GHz using NbTiN superconducting resonators. *Applied Physics Letters*, 103, 032601, July 2013.

- K. M. C. Fu, C. Santori, P. E. Barclay, I. Aharonovich, S. Praver, N. Meyer, A. M. Holm, and R. G. Beausoleil. Coupling of nitrogen-vacancy centers in diamond to a GaP waveguide. *Applied Physics Letters*, 93, 234107, December 2008.
- L. Fumagalli, G. Ferrari, M. Sampietro, I. Casuso, E. Martínez, J. Samitier, and G. Gomila. Nanoscale capacitance imaging with attofarad resolution using ac current sensing atomic force microscopy. *Nanotechnology*, 17, 4581–4587, September 2006.
- L. Fumagalli, G. Ferrari, M. Sampietro, and G. Gomila. Dielectric-constant measurement of thin insulating films at low frequency by nanoscale capacitance microscopy. *Applied Physics Letters*, 91, 243110, December 2007.
- C. Gardiner and P. Zoller. *Quantum Noise: A Handbook of Markovian and Non-Markovian Quantum Stochastic Methods with Applications to Quantum Optics*. Springer, Berlin ; New York, 3rd ed. 2004 edition edition, October 2004.
- S. R. Garner, S. Kuehn, J. M. Dawlaty, N. E. Jenkins, and J. A. Marohn. Force-gradient detected nuclear magnetic resonance. *Applied Physics Letters*, 84, 5091–5093, June 2004.
- F. J. Giessibl, S. Hembacher, M. Herz, C. Schiller, and J. Mannhart. Stability considerations and implementation of cantilevers allowing dynamic force microscopy with optimal resolution: the qplus sensor. *Nanotechnology*, 15, S79, 2004.
- G. Gomila, J. Toset, and L. Fumagalli. Nanoscale capacitance microscopy of thin dielectric films. *Journal of Applied Physics*, 104, 024315, July 2008.
- G. Gomila, G. Gramse, and L. Fumagalli. Finite-size effects and analytical modeling of electrostatic force microscopy applied to dielectric films. *Nanotechnology*, 25, 255702, 2014.
- A. M. J. den Haan. *Nuclear magnetic resonance force microscopy at millikelvin temperatures*. Leiden University, March 2016.
- A. M. J. den Haan, G. H. C. J. Wijts, F. Galli, O. Usenko, G. J. C. van Baarle, D. J. van der Zalm, and T. H. Oosterkamp. Atomic resolution scanning tunneling microscopy in a cryogen free dilution refrigerator at 15 mK. *Rev. Sci. Instrum.*, 85, 035112, 2014.
- A. M. J. den Haan, J. J. T. Wagenaar, J. M. de Voogd, G. Koning, and T. H. Oosterkamp. Spin-mediated dissipation and frequency shifts of a cantilever at millikelvin temperatures. *Physical Review B*, 92, 235441, December 2015.

- P. J. Hajduk, D. A. Horita, and L. E. Lerner. Theoretical Analysis of Relaxation During Shaped Pulses. I. The Effects of Short  $T_1$  and  $T_2$ . *Journal of Magnetic Resonance, Series A*, 103, 40–52, June 1993.
- D. Haneman. Electron paramagnetic resonance from clean single-crystal cleavage surfaces of silicon. *Phys. Rev.*, 170, 705–718, 1968.
- J. G. E. Harris, R. Knobel, K. D. Maranowski, A. C. Gossard, N. Samarth, and D. D. Awschalom. Damping of micromechanical structures by paramagnetic relaxation. *Appl. Phys. Lett.*, 82, 3532–3534, 2003.
- E. C. Heeres, A. J. Katan, M. H. van Es, A. F. Beker, M. Hesselberth, D. J. van der Zalm, and T. H. Oosterkamp. A compact multipurpose nanomanipulator for use inside a scanning electron microscope. *Rev. Sci. Instrum.*, 81, 023704, 2010.
- C. T. Herbschleb, P. C. van der Tuijn, S. B. Roobol, V. Navarro, J. W. Bakker, Q. Liu, D. Stoltz, M. E. Cañas Ventura, G. Verdoes, M. A. van Spronsen, M. Bergman, L. Crama, I. Taminiau, A. Ofitserov, G. J. C. van Baarle, and J. W. M. Frenken. The ReactorSTM: Atomically resolved scanning tunneling microscopy under high-pressure, high-temperature catalytic reaction conditions. *Review of Scientific Instruments*, 85, 083703, August 2014.
- S. Hudlet, M. Saint Jean, C. Guthmann, and J. Berger. Evaluation of the capacitive force between an atomic force microscopy tip and a metallic surface. *The European Physical Journal B - Condensed Matter and Complex Systems*, 2, 5–10, March 1998.
- IBM Corp. A boy and his atom: The world's smallest movie, May 2013. URL <http://ibm.co/ZyRmCT>.
- M. Imboden and P. Mohanty. Evidence of universality in the dynamical response of micromechanical diamond resonators at millikelvin temperatures. *Physical Review B*, 79, 125424, March 2009.
- C. J. Isham. *Canonical Quantum Gravity and the Problem of Time*. NATO ASI Series. Springer, Dordrecht, 1993.
- B. Jäck, M. Eltschka, M. Assig, A. Hardock, M. Etzkorn, C. R. Ast, and K. Kern. A nanoscale gigahertz source realized with Josephson scanning tunneling microscopy. *Applied Physics Letters*, 106, 013109, January 2015.
- JPE Precision Point. Precision Point - Fit a plane through data points, 2013. URL <http://www.janssenprecisionengineering.com/page/fit-a-plane-through-data-points/>.

- G. Jug, S. Bonfanti, and W. Kob. Realistic tunnelling states for the magnetic effects in non-metallic real glasses. *Philosophical Magazine*, 96, 648–703, March 2016.
- V. Kaajakari, T. Mattila, A. Oja, and H. Seppa. Nonlinear limits for single-crystal silicon microresonators. *Journal of Microelectromechanical Systems*, 13, 715–724, October 2004.
- H. P. Kleinknecht, J. R. Sandercock, and H. Meier. An experimental scanning capacitance microscope. *Scanning Microscopy*, 2, 1839–1844, 1988.
- S. Kolkowitz, A. C. Bleszynski Jayich, Q. P. Unterreithmeier, S. D. Bennett, P. Rabl, J. G. E. Harris, and M. D. Lukin. Coherent Sensing of a Mechanical Resonator with a Single-Spin Qubit. *Science*, 335, 1603–1606, March 2012.
- H. Kovacs, D. Moskau, and M. Spraul. Cryogenically cooled probes - a leap in NMR technology. *Progress in Nuclear Magnetic Resonance Spectroscopy*, 46, 131–155, May 2005.
- S. Kuehn, R. F. Loring, and J. A. Marohn. Dielectric fluctuations and the origins of noncontact friction. *Phys. Rev. Lett.*, 96, 156103, 2006.
- S. Kuehn, S. A. Hickman, and J. A. Marohn. Advances in mechanical detection of magnetic resonance. *The Journal of chemical physics*, 128, 052208, February 2008.
- S. Kurokawa and A. Sakai. Gap dependence of the tip-sample capacitance. *Journal of Applied Physics*, 83, 7416–7423, 1998.
- Š. Lányi. Effect of tip shape on capacitance determination accuracy in scanning capacitance microscopy. *Ultramicroscopy*, 103, 221 - 228, 2005.
- Š. Lányi and M. Hruškovic. Analysis of lateral resolution and contrast of scanning capacitance microscopes. *Surface Science*, 566-568, Part 2, 880 - 884, 2004. Proceedings of the 22nd European Conference on Surface Science.
- S. Lányi and M. Hruškovic. The resolution limit of scanning capacitance microscopes. *Journal of Physics D: Applied Physics*, 36, 598, 2003.
- A. Laraoui, J. S. Hodges, and C. A. Meriles. Nitrogen-Vacancy-Assisted Magnetometry of Paramagnetic Centers in an Individual Diamond Nanocrystal. *Nano Letters*, 12, 3477–3482, July 2012.
- B. M. Law and F. Rieutord. Electrostatic forces in atomic force microscopy. *Physical Review B*, 66, 035402, June 2002.



- D. Lee, K. W. Lee, J. V. Cady, P. Ovarthaiyapong, and A. C. Bleszynski Jayich. Topical review: spins and mechanics in diamond. *Journal of Optics*, 19, 033001, 2017.
- D. T. Lee, J. P. Pelz, and B. Bhushan. Instrumentation for direct, low frequency scanning capacitance microscopy, and analysis of position dependent stray capacitance. *Review of Scientific Instruments*, 73, 3525–3533, September 2002.
- D. T. Lee, J. P. Pelz, and B. Bhushan. Scanning capacitance microscopy for thin film measurements. *Nanotechnology*, 17, 1484, 2006.
- S. Lee, E. W. Moore, and J. A. Marohn. Unified picture of cantilever frequency shift measurements of magnetic resonance. *Physical Review B*, 85, 165447, April 2012.
- B. P. Lemke and D. Haneman. Low-temperature epr measurements on *in situ* vacuum-cleaved silicon. *Phys. Rev. Lett.*, 35, 1379–1382, Nov 1975.
- J. H. N. Loubser and J. A. van Wyk. Electron spin resonance in the study of diamond. *Reports on Progress in Physics*, 41, 1201, 1978.
- H. J. Mamin, R. Budakian, B. W. Chui, and D. Rugar. Detection and manipulation of statistical polarization in small spin ensembles. *Phys. Rev. Lett.*, 91, 207604, 2003.
- N. B. Manson and J. P. Harrison. Photo-ionization of the nitrogen-vacancy center in diamond. *Diamond and Related Materials*, 14, 1705–1710, October 2005.
- F. Marquardt, J. P. Chen, A. A. Clerk, and S. M. Girvin. Quantum Theory of Cavity-Assisted Sideband Cooling of Mechanical Motion. *Physical Review Letters*, 99, 093902, August 2007.
- W. Marshall, C. Simon, R. Penrose, and D. Bouwmeester. Towards Quantum Superpositions of a Mirror. *Physical Review Letters*, 91, 130401, September 2003.
- P. Mohanty, D. A. Harrington, K. L. Ekinci, Y. T. Yang, M. J. Murphy, and M. L. Roukes. Intrinsic dissipation in high-frequency micromechanical resonators. *Physical Review B*, 66, 085416, August 2002.
- B. A. Myers, A. Das, M. C. Dartailh, K. Ohno, D. D. Awschalom, and A. C. Bleszynski Jayich. Probing Surface Noise with Depth-Calibrated Spins in Diamond. *Physical Review Letters*, 113, 027602, July 2014.
- Y. V. Nazarov and Y. M. Blanter. *Quantum Transport: Introduction to Nanoscience*. Cambridge University Press, Cambridge, 2009.

- J. M. Nichol, E. R. Hemesath, L. J. Lauhon, and R. Budakian. Nanomechanical detection of nuclear magnetic resonance using a silicon nanowire oscillator. *Physical Review B*, 85, 054414, February 2012.
- D. G. Norris, H. Lüdemann, and D. Leibfritz. An analysis of the effects of short  $T_2$  values on the hyperbolic-secant pulse. *Journal of Magnetic Resonance (1969)*, 92, 94–101, March 1991.
- Y. Okazaki, I. Mahboob, K. Onomitsu, S. Sasaki, and H. Yamaguchi. Quantum point contact displacement transducer for a mechanical resonator at sub-Kelvin temperatures. *Applied Physics Letters*, 103, 192105, November 2013.
- T. H. Oosterkamp and J. Zaanen. A clock containing a massive object in a superposition of states; what makes Penrosian wavefunction collapse tick? *arXiv:1401.0176 [quant-ph]*, December 2013. arXiv: 1401.0176.
- D. P. Pappas, M. R. Vissers, D. S. Wisbey, J. S. Kline, and J. Gao. Two Level System Loss in Superconducting Microwave Resonators. *IEEE Transactions on Applied Superconductivity*, 21, 871–874, June 2011.
- R. N. Patel, T. Schröder, N. Wan, L. Li, S. L. Mouradian, E. H. Chen, and D. R. Englund. Efficient photon coupling from a diamond nitrogen vacancy center by integration with silica fiber. *Light: Science & Applications*, 5, e16032, February 2016.
- P. K. Peddibhotla. *Magnetic resonance force microscopy : harnessing nuclear spin fluctuations*. University of Basel, 2013.
- R. Penrose. On Gravity's role in Quantum State Reduction. *General Relativity and Gravitation*, 28, 581–600, May 1996.
- R. Penrose. On the Gravitization of Quantum Mechanics 1: Quantum State Reduction. *Foundations of Physics*, 44, 557–575, May 2014.
- W. A. Phillips. Tunneling states in amorphous solids. *Journal of Low Temperature Physics*, 7, 351–360, 1972.
- L. S. C. Pingree, E. F. Martin, K. R. Shull, and M. C. Hersam. Nanoscale impedance microscopy—a characterization tool for nanoelectronic devices and circuits. *IEEE Transactions on Nanotechnology*, 4, 255–259, March 2005.
- M. Poggio and C. L. Degen. Force-detected nuclear magnetic resonance: recent advances and future challenges. *Nanotechnology*, 21, 342001, 2010.
- D. M. Pozar. *Microwave Engineering, 4th Edition*. Wiley, November 2011.

- N. V. Prokof'ev and P. C. E. Stamp. Theory of the spin bath. *Reports on Progress in Physics*, 63, 669, 2000.
- Quantum Design. Coupling Magnetic Signals to a SQUID Amplifier, December 2001. URL <http://www.qdusa.com/techsupport/index.html>.
- I. I. Rabi. *Science: the Center of Culture*. World Publishing Company, first edition. edition edition, January 1970.
- L. Rademaker, T. van der Reep, N. van den Broeck, B. van Waarde, J. M. de Voogd, and T. H. Oosterkamp. The Instability of a Quantum Superposition of Time Dilations. *arXiv:1410.2303 [quant-ph]*, October 2014. arXiv: 1410.2303.
- L. Robledo, H. Bernien, I. van Weperen, and R. Hanson. Control and Coherence of the Optical Transition of Single Nitrogen Vacancy Centers in Diamond. *Physical Review Letters*, 105, 177403, October 2010.
- S. B. Roobol, M. E. Cañas-Ventura, M. Bergman, M. A. van Spronsen, W. G. Onderwaater, P. C. van der Tuijn, R. Koehler, A. Ofitserov, G. J. C. van Baarle, and J. W. M. Frenken. The ReactorAFM: Non-contact atomic force microscope operating under high-pressure and high-temperature catalytic conditions. *Review of Scientific Instruments*, 86, 033706, March 2015.
- T. Roskopf, A. Dussaux, K. Ohashi, M. Loretz, R. Schirhagl, H. Watanabe, S. Shikata, K. M. Itoh, and C. L. Degen. Investigation of surface magnetic noise by shallow spins in diamond. *Phys. Rev. Lett.*, 112, 147602, 2014.
- M. J. Rost, L. Crama, P. Schakel, E. van Tol, G. B. E. M. van Velzen-Williams, C. F. Overgaww, H. ter Horst, H. Dekker, B. Okhuijsen, M. Seynen, A. Vijftigschild, P. Han, A. J. Katan, K. Schoots, R. Schumm, W. van Loo, T. H. Oosterkamp, and J. W. M. Frenken. Scanning probe microscopes go video rate and beyond. *Review of Scientific Instruments*, 76, 053710, May 2005.
- M. J. Rost, G. J. C. van Baarle, A. J. Katan, W. M. van Spengen, P. Schakel, W. A. van Loo, T. H. Oosterkamp, and J. W. M. Frenken. Video-rate scanning probe control challenges: setting the stage for a microscopy revolution. *Asian Journal of Control*, 11, 110–129, March 2009.
- D. Rugar, H. J. Mamin, P. Guethner, S. E. Lambert, J. E. Stern, I. McFadyen, and T. Yogi. Magnetic force microscopy: General principles and application to longitudinal recording media. *Journal of Applied Physics*, 68, 1169–1183, August 1990.
- D. Rugar, C. S. Yannoni, and J. A. Sidles. Mechanical detection of magnetic resonance. *Nature*, 360, 563–566, December 1992.

- D. Rugar, R. Budakian, H. J. Mamin, and B. W. Chui. Single spin detection by magnetic resonance force microscopy. *Nature*, 430, 329–332, 2004.
- R. Schlegel, T. Hänke, D. Baumann, M. Kaiser, P. K. Nag, R. Voigtländer, D. Lindackers, B. Büchner, and C. Hess. Design and properties of a cryogenic dip-stick scanning tunneling microscope with capacitive coarse approach control. *Review of Scientific Instruments*, 85, 013706, January 2014.
- M. Schlosshauer, A. P. Hines, and G. J. Milburn. Decoherence and dissipation of a quantum harmonic oscillator coupled to two-level systems. *Physical Review A*, 77, 022111, February 2008.
- T. Sleator, E. L. Hahn, C. Hilbert, and J. Clarke. Nuclear-spin noise and spontaneous emission. *Physical Review B*, 36, 1969–1980, August 1987.
- C. P. Slichter. *Principles of Magnetic Resonance*, volume 1 of *Springer Series in Solid-State Sciences*. Springer Berlin Heidelberg, Berlin, Heidelberg, 1990.
- W. V. Smith, P. P. Sorokin, I. L. Gelles, and G. J. Lasher. Electron spin resonance of nitrogen donors in diamond. *Phys. Rev.*, 115, 1546–1552, Sep 1959.
- Y. J. Song, A. F. Otte, V. Shvarts, Z. Zhao, Y. Kuk, S. R. Blankenship, A. Band, F. M. Hess, and J. A. Stroscio. Invited Review Article: A 10 mK scanning probe microscopy facility. *Review of Scientific Instruments*, 81, 121101, December 2010.
- B. C. Stipe, H. J. Mamin, T. D. Stowe, T. W. Kenny, and D. Rugar. Magnetic dissipation and fluctuations in individual nanomagnets measured by ultrasensitive cantilever magnetometry. *Phys. Rev. Lett.*, 86, 2874–2877, 2001a.
- B. C. Stipe, H. J. Mamin, C. S. Yannoni, T. D. Stowe, T. W. Kenny, and D. Rugar. Electron spin relaxation near a micron-size ferromagnet. *Phys. Rev. Lett.*, 87, 277602, 2001b.
- P. Strehlow, M. Wohlfahrt, A. G. M. Jansen, R. Hau Eisen, G. Weiss, C. Enss, and S. Hunklinger. Magnetic Field Dependent Tunneling in Glasses. *Physical Review Letters*, 84, 1938–1941, February 2000.
- S. Takahashi, R. Hanson, J. van Tol, M. S. Sherwin, and D. D. Awschalom. Quenching spin decoherence in diamond through spin bath polarization. *Phys. Rev. Lett.*, 101, 047601, Jul 2008.
- Y. Tao, J. M. Boss, B. A. Moores, and C. L. Degen. Single-crystal diamond nanomechanical resonators with quality factors exceeding one million. *Nat. Commun.*, 5, 3638, 2014.

- A. Tayebi and V. Zelevinsky. The Holstein polaron problem revisited. *Journal of Physics A: Mathematical and Theoretical*, 49, 255004, 2016.
- R. P. Taylor, G. F. Nellis, S. A. Klein, D. W. Hoch, J. Fellers, P. Roach, J. M. Park, and Y. Gianchandani. Measurements of the material properties of a laminated piezoelectric stack at cryogenic temperatures. In *Advances in Cryogenic Engineering*, volume 824, pages 200–207. AIP Publishing, 2006.
- C. J. Terblanche and E. C. Reynhardt. Room-temperature field dependence of the electron spin-lattice relaxation times of paramagnetic P1 and P2 centers in diamond. *Chemical Physics Letters*, 322, 273–279, May 2000.
- O. Usenko. *Development and testing of the gravitational wave antenna MiniGRAIL in its full-featured configuration*. Leiden University, May 2012.
- O. Usenko, A. Vinante, G. Wijts, and T. H. Oosterkamp. A superconducting quantum interference device based read-out of a subattonewton force sensor operating at millikelvin temperatures. *Applied Physics Letters*, 98(13):133105, 2011.
- A. Venkatesan, K. J. Lulla, M. J. Patton, A. D. Armour, C. J. Mellor, and J. R. Owers-Bradley. Dissipation due to tunneling two-level systems in gold nanomechanical resonators. *Physical Review B*, 81, 073410, February 2010.
- P. Vettiger, M. Despont, U. Drechsler, U. Durig, W. Haberle, M. I. Lutwyche, H. E. Rothuizen, R. Stutz, R. Widmer, and G. K. Binnig. The "Millipede";- More than thousand tips for future AFM storage. *IBM Journal of Research and Development*, 44, 323–340, May 2000.
- A. Vinante, G. Wijts, O. Usenko, L. Schinkelshoek, and T. H. Oosterkamp. Magnetic resonance force microscopy of paramagnetic electron spins at millikelvin temperatures. *Nature Communications*, 2, 572, December 2011a.
- A. Vinante, G. Wijts, O. Usenko, L. Schinkelshoek, and T. H. Oosterkamp. Magnetic Resonance Force Microscopy of paramagnetic electron spins at millikelvin temperatures. *ArXiv.org*, December 2011b. arXiv: 1105.3395v2.
- A. Vinante, A. Kirste, A. M. J. den Haan, O. Usenko, G. Wijts, E. Jeffrey, P. Sonin, D. Bouwmeester, and T. H. Oosterkamp. High sensitivity SQUID-detection and feedback-cooling of an ultrasoft microcantilever. *Applied Physics Letters*, 101, 123101, September 2012.
- A. Vinante, M. Bahrami, A. Bassi, O. Usenko, G. Wijts, and T. H. Oosterkamp. Upper Bounds on Spontaneous Wave-Function Collapse Models Using Millikelvin-Cooled Nanocantilevers. *Physical Review Letters*, 116, 090402, March 2016.

- J. M. de Voogd, M. A. van Spronsen, F. E. Kalff, B. Bryant, O. Ostojić, A. M. J. den Haan, I. M. N. Groot, T. H. Oosterkamp, A. F. Otte, and M. J. Rost. Fast and reliable pre-approach for scanning probe microscopes based on tip-sample capacitance. *Ultramicroscopy*, 181, 61–69, October 2017a.
- J. M. de Voogd, J. J. T. Wagenaar, and T. H. Oosterkamp. Dissipation and resonance frequency shift of a resonator magnetically coupled to a semiclassical spin. *Scientific Reports*, 7, 42239, February 2017b.
- B. E. Vugmeister. Spin diffusion and spin-lattice relaxation in paramagnetic crystals. *physica status solidi (b)*, 90, 711–718, December 1978.
- B. van Waarde. *The lead zeppelin : a force sensor without a handle*. Leiden University, November 2016.
- J. J. T. Wagenaar. *Magnetic resonance force microscopy for condensed matter*. Leiden University, July 2017.
- J. J. T. Wagenaar, A. M. J. den Haan, J. M. de Voogd, L. Bossoni, T. A. de Jong, M. de Wit, K. M. Bastiaans, D. J. Thoen, A. Endo, T. M. Klapwijk, J. Zaanen, and T. H. Oosterkamp. Probing the Nuclear Spin-Lattice Relaxation Time at the Nanoscale. *Physical Review Applied*, 6, 014007, July 2016.
- J. van Wezel and T. H. Oosterkamp. A nanoscale experiment measuring gravity's role in breaking the unitarity of quantum dynamics. *Proc. R. Soc. A*, 468, 35–56, January 2012.
- G. Wijts. *Magnetic resonance force microscopy at milliKelvin temperatures*. Leiden University, September 2013.
- J. A. van Wyk. Carbon-12 hyperfine interaction of the unique carbon of the P<sub>2</sub> (ESR) or N<sub>3</sub> (optical) centre in diamond. *Journal of Physics C: Solid State Physics*, 15, L981, 1982.
- J. A. van Wyk, E. C. Reynhardt, G. L. High, and I. Kiflawi. The dependences of ESR line widths and spin - spin relaxation times of single nitrogen defects on the concentration of nitrogen defects in diamond. *Journal of Physics D: Applied Physics*, 30, 1790, 1997.
- J. Q. You and F. Nori. Superconducting circuits and quantum information. *Physics Today*, 58, 42–47, November 2005.

## List of publications

J. M. de Voogd, G. Welker, M. de Wit, and T. H. Oosterkamp. [Section 4.3](#)  
Change in linear response of ultra sensitive magnetic probe reveals spin density of diamond bulk and surface spins. *In preparation*, 2017.

J. M. de Voogd, M. A. van Spronsen, F. E. Kalff, B. Bryant, O. Ostojić, A. M. J. den Haan, I. M. N. Groot, T. H. Oosterkamp, A. F. Otte, and M. J. Rost. [Chapter 7](#)  
Fast and reliable preapproach for scanning probe microscopes based on tip-sample capacitance. *Ultramicroscopy*, 181, 61-69, October 2017.

J. M. de Voogd, J. J. T. Wagenaar, and T. H. Oosterkamp. [Chapter 2](#)  
Dissipation and resonance frequency shift of a resonator magnetically coupled to a semiclassical spin. *Scientific Reports*, 7, 42239, February 2017.

J. J. T. Wagenaar, A. M. J. den Haan, J. M. de Voogd, L. Bossoni, T. A. de Jong, M. de Wit, K. M. Bastiaans, D. J. Thoen, A. Endo, T. M. Klapwijk, J. Zaanen, and T. H. Oosterkamp. Probing the Nuclear Spin-Lattice Relaxation Time at the Nanoscale. *Physical Review Applied*, 6, 014007, July 2016.

A. M. J. den Haan, J. J. T. Wagenaar, J. M. de Voogd, G. Koning, and T. H. Oosterkamp. Spin-mediated dissipation and frequency shifts of a cantilever at milliKelvin temperatures. *Physical Review B*, 92, 235441, December 2015.

Chapter 3

L. Rademaker, T. van der Reep, N. van den Broeck, B. van Waarde, J. M. de Voogd, and T. H. Oosterkamp. The Instability of a Quantum Superposition of Time Dilations. *arXiv:1410.2303 [quant-ph]*, October 2014.

Section 5.2



