MEASURING RANDOM SPIN FLUCTUATIONS FOR PERTURBATION-FREE PROBES OF SPIN DYNAMICS AND MAGNETIC RESONANCE

S. A. Crooker, D. G. Rickel (NHMFL-LANL); A. V. Balatsky, D. L. Smith (Theory Division, LANL)

Introduction

In magnetic systems, fundamental noise can exist in the form of random spin fluctuations. In his seminal 1946 paper on nuclear induction, Felix Bloch noted that random, statistical fluctuations of $N$ paramagnetic spins should generate measurable noise of order $N^{1/2}$ spins, even in zero magnetic field. By the fluctuation-dissipation theorem, this “spin noise” alone contains detailed information about the spin system itself. (The fluctuation-dissipation theorem states that the response of a system to an external perturbation -- i.e., the susceptibility -- can be described by its spectrum of fluctuations while in thermal equilibrium). We use optical techniques to passively and sensitively “listen” to the magnetization noise in a classical, equilibrium ensemble of paramagnetic alkali atoms [1]. Correlation spectra of the measured spin noise reveals the complete magnetic structure of the atomic $^2S_{1/2}$ ground state (g-factors, nuclear spin, isotope abundance ratios, hyperfine splittings, nuclear moments, and spin coherence lifetimes) -- without having to excite, optically pump, or otherwise drive the system away from thermal equilibrium.

Results and Discussion

A linearly polarized laser, detuned from any atomic absorption, is focused through a cell containing rubidium or potassium vapor (Fig. 1a). Random magnetization fluctuations along $z$ impart small polarization (Faraday) rotation fluctuations $\delta \theta_F(t)$ on the laser, which are sensitively measured with a balanced photodiode bridge. Helmholtz coils provide a small transverse magnetic field $B$ along $x$, about which all magnetization fluctuations $\delta M_z$ must precess. The detuned laser ensures that atoms are not optically pumped or excited in any way. The spin correlation function, $S(t) = \langle M_z(0)M_z(t)\rangle$, has a Fourier transform $S(\omega)$ that is related simply to the power spectrum of $\delta \theta_F(t)$. A typical noise spectrum is shown in Fig. 1b. The sharp peaks at $\Omega = 869$ and 1303 kHz are due to random spin fluctuations which are precessing in the small 1.85G transverse magnetic field, effectively generating spontaneous spin coherences between ground-state Zeeman sublevels. These coherences precess with g-factors $\sim 1/3$ and $1/2$, which are the ground-state g-factors of the stable isotopes $^{85}$Rb and $^{87}$Rb. Coupling of the nuclear spin $I$ to the $J=1/2$ valence electron splits the $^2S_{1/2}$ atomic ground state into two hyperfine levels with total spin $F = I \pm J$ and g-factor $|g_F| \approx g_j / (2I + 1)$, where $g_j \approx 2$ is the free electron g-factor. Thus, the nuclear spin of $^{85}$Rb ($I=5/2$) and $^{87}$Rb ($I=3/2$) may be directly measured from spin fluctuations in thermal equilibrium. Strikingly, the measured spin noise actually increases when the diameter of the probe laser shrinks (Fig. 2). This result may be understood by considering that the Faraday rotation imposed on light passing through an intentionally-magnetized system is independent of beam area, so that the effective measurement sensitivity (rotation angle per unit polarized spin, $\theta_F/N$) is larger for narrower beams. Therefore, fluctuations of order $N^{1/2}$ spins induce correspondingly more signal. These data suggest the utility of noise spectroscopy for passive probes of small systems, where the absolute amplitude of measured fluctuations actually increases when probe size is reduced, as long as measurement sensitivity increases correspondingly.

References