NUCLEAR SPIN NOISE SPECTRA FOR EXTREMEY SMALL BATHS

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INTRODUCTION

The nuclear spin noise (NSN) is the main source of loss of information for quantum information applications in solid-state systems. The spin qubit, so called central spin (CS) interacts with backround nuclear spins in semiconductor matrix via hyperfine interaction which results in the decoherence of information stored in CS. Our work addresses noise frequency content of the spin environment due to the site dependent dipole-dipole interaction which is conditioned on CS. Moreover, we investigate the basic dependencies on typical interactions such as quadrupolar and Zeeman in extremely tiny baths to shed ligth on how noise spectra get syntesized under relatively complex Hamiltonians. Cluster-Correlation Expansion (CCE) is employed since it yields consistent result for predicting many-body dynamics of even large spin baths as in self-assembled quantum dots.

$$H^{(\pm)} = \underbrace{H_Z}_{\text{Zeeman}} + \underbrace{H_Q}_{\text{Quadrupolar}} + \underbrace{H_{hf}^{(\pm)}}_{\text{Hyperfine}} + \underbrace{H_{dd}^{(\pm)}}_{\text{Dipole-dipole}}$$

$H_Z = \sum_i B^i_{eff} I_i^z$ (B^i_{eff} effective B-field acting on the ith spin site)

$H_Q = \sum_i \frac{f_{Q_i}}{6}\{3(I_i^z)^2 + \frac{\eta_i}{2}[(I_i^+)^2 + (I_i^-)^2]\}$ (f_{Q_i} is the Quadrupolar coupling constant)

$H_{hf}^{(\pm)} = \pm\sum_i A_i I_i^z$ (A_i is the hyperfine coupling constant)

$H_{dd} = \pm\sum_{i<j} \frac{\mu_0}{4\pi}\frac{\gamma_i\gamma_j\hbar^2}{r_{ij}^3}\{A+B+C+D+E+F\}$ (A, B, C, D, E, F is the dipolar alphabet)

$I_i \bar{D}_{ij} I_j$

$A = (3\cos^2\theta - 1) I_i^z I_j^z$

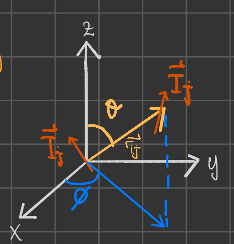
$B = \frac{1-3\cos^2\theta}{4}(I_i^+ I_j^- + I_i^- I_j^+)$

$C = -\frac{3}{4}\sin\theta\cos\theta\, e^{-i\phi}(I_i^+ I_j^z + I_i^z I_j^+)$

$D = -\frac{3}{4}\sin\theta\cos\theta\, e^{i\phi}(I_i^- I_j^z + I_i^z I_j^-)$

$E = -\frac{3}{4}\sin^2\theta\, e^{-2i\phi}(I_i^+ I_j^+)$

$F = -\frac{3}{4}\sin^2\theta\, e^{2i\phi}(I_i^- I_j^-)$



A) Basic Spectra Under DD Interaction

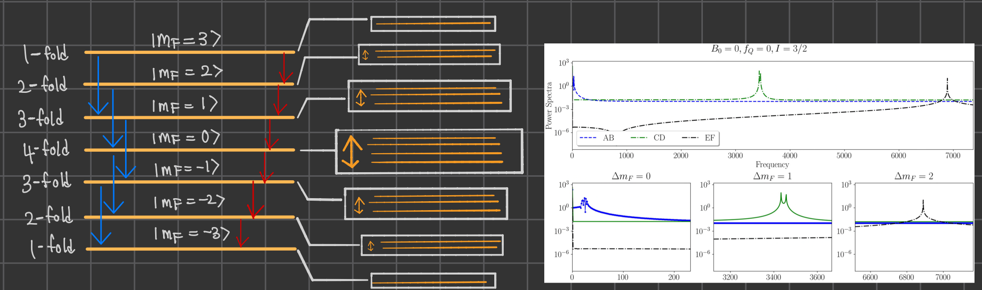


Figure: Basic energy level splitting of 2 spin-3/2 system and corresponding power spectra. Here we turn on and off dipolar alphabet terms. Blue line shows the noise spectra of A and B terms which implies intraband transitions (i.e. transitions which $\Delta m_F = 0$.), Green line shows the spectra content for C and D terms and lastly, Black line shows the spectra for E and F terms. Here note that C and D terms induce single quantum transitions and E and F terms responsible for double quantum transitions.

B) DD + Zeeman Interaction

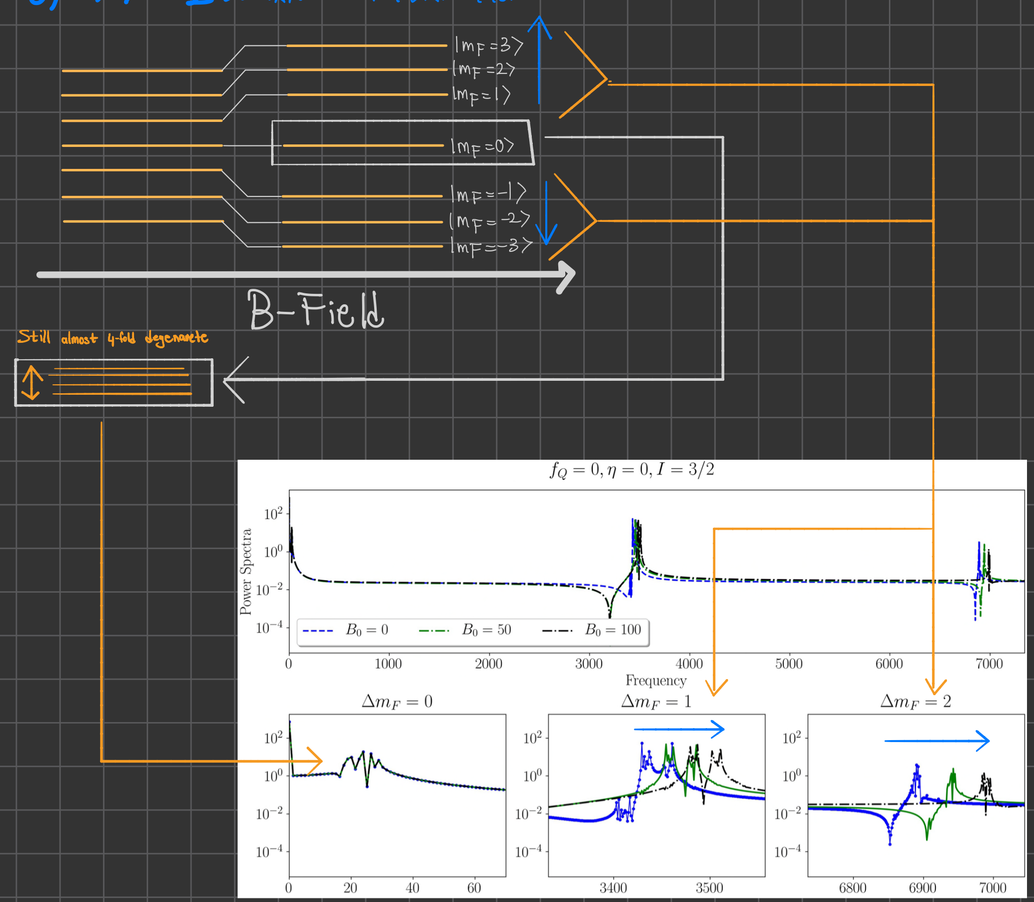


Figure: Nuclear spin noise spectra under Zeeman splitting. Since $|m_F=0\rangle$ states immune to B-field and $|m_F\pm3\rangle$, $|m_F\pm2\rangle$, $|m_F=\pm1\rangle$ states shifted, frequency content for intrabath transitions ($\Delta m_F=0$) stay without any change, yet power spectra related single and double quantum transitions swipe right in the noise spectra.

C) Noise Spectra For Different CCE Orders

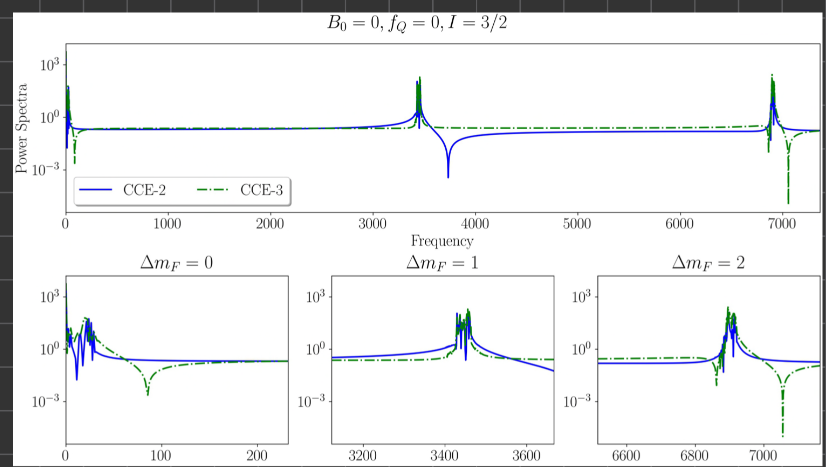
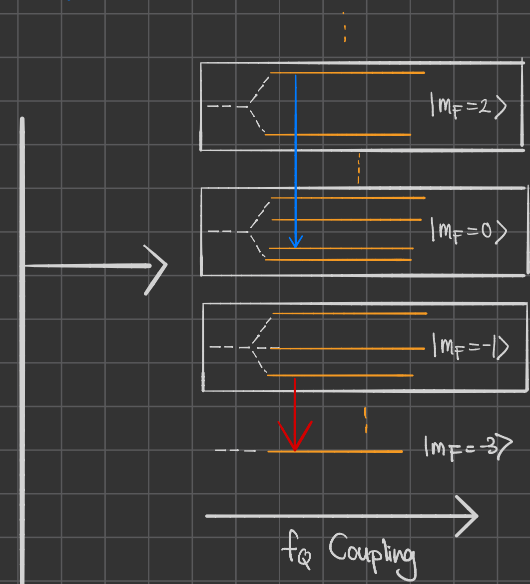


Figure: CCE-2 and CCE-3 noise spectra for N=8 spin-3/2 particles. Here note that while CCE-2 covers high frequency content more preciesely when comperad to low frequencies, this is due to basic nature of CCE-method.

D) DD + Quadrupolar Interaction ($\eta=0$)



* As quadrupolar interaction coupling increases, the degeneracies starts to be lifted in $|m_F=0\rangle$ and $|m_F=\pm1\rangle$ states.
* Whreas the states $|m_F\pm2\rangle$ and $|m_F=\pm3\rangle$ states are just pushed downwords and upwerds.
* Some less probable transitions become more probable for both single and double quantum transitions

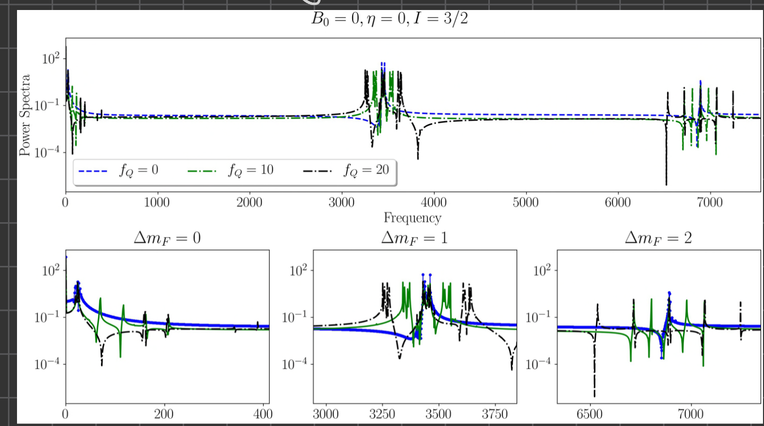


Figure: Spin Noise Spectra for various Quadrupolar couplings. Quadrupolar interaction makes some transitions possible and lifts degeneracies at $|m_F=0\rangle$, $|m_F\pm1\rangle$ states.

E) DD + Quadrupolar Interaction ($\eta\neq0$)

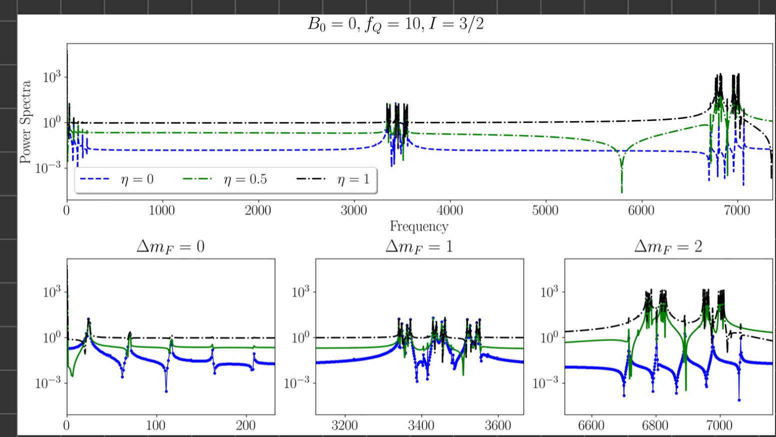


Figure: Spin noise spectra for different η values, energy levels are same with $\eta=0$ case, so that frequency content stays same for $\Delta m_F = 0$ & $\Delta m_F = 1$ transitions. However, case in which $\eta\neq0$ induces more $\Delta m_F=2$ transitions due to the quadratic nature of Quadrupolar interaction.

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