Theory of magnon pumping-induced manipulation of electron spins in diamond

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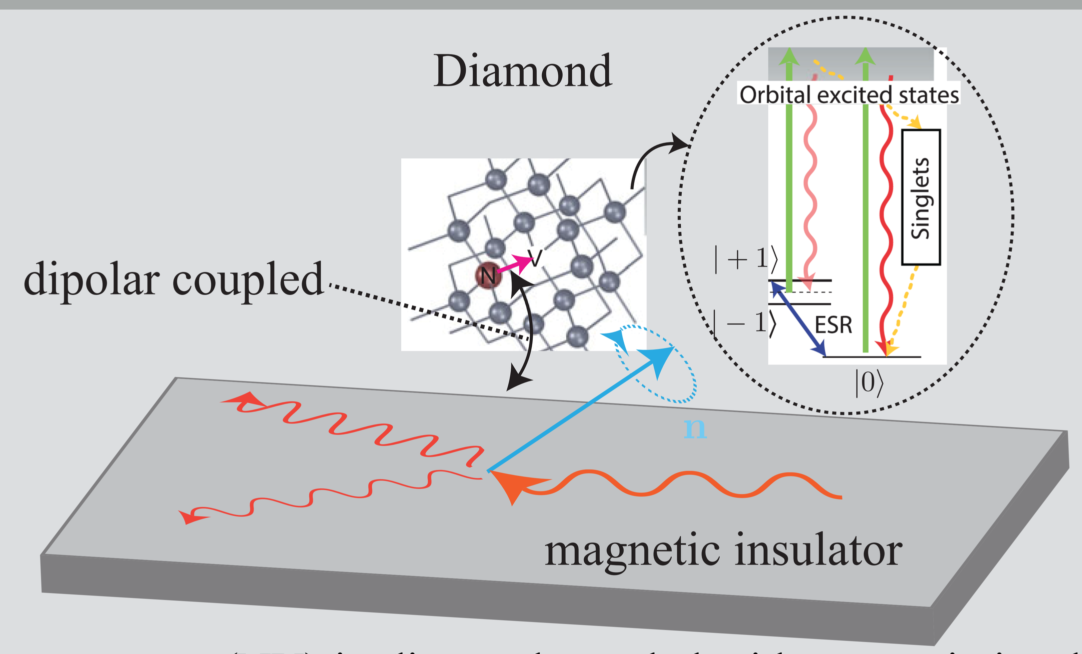
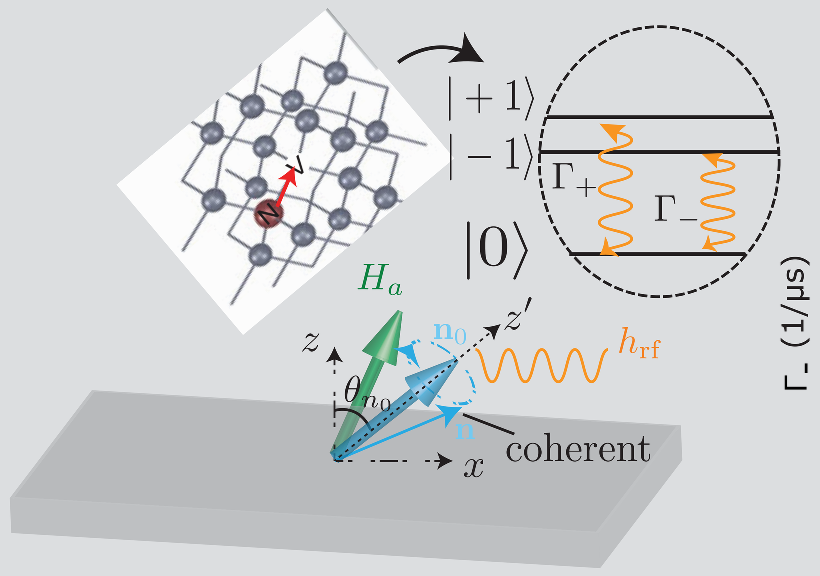
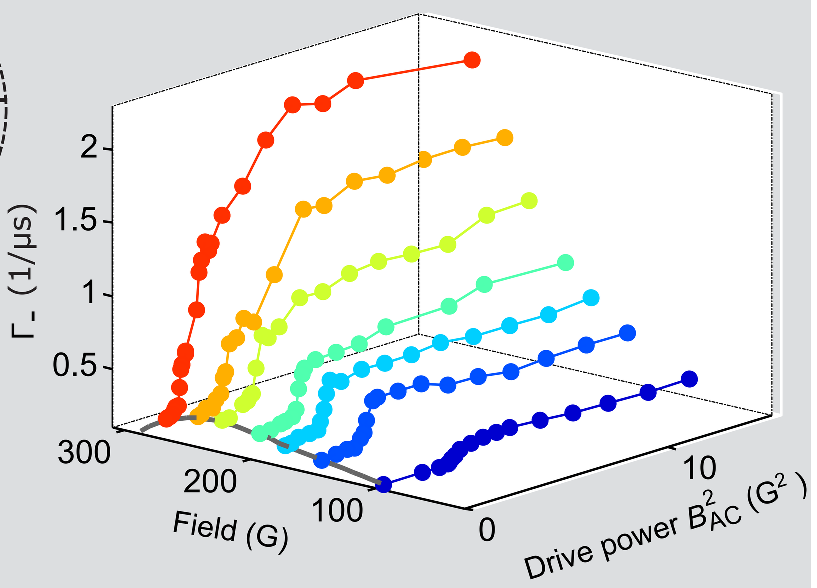
Nitrogen Vacancy+Magnetic Insulators : a novel quantum spintronic system



- Nitrogen vacancy (NV) in diamond coupled with magnetic insulators (MI) have recently emerged as a novel spintronic system, where transfer of spin information between insulators have been demonstrated [1].
- NV center acts as a spin 1 quantum system, which can be read optically (inset of above figure).
- The NV spin interacts, via dipole-dipole coupling, with magnetic insulator's total spin density. This spin density, in turn, comprise of a coherent piece (blue arrow) and incoherent magnons (red wavy lines), respectively, representing the average of spin density operator and fluctuations around it,.
- The NV/MI system thus provide novel opportunities for detecting insulator dynamics. Reciprocally, new avenues for manipulating NV spin arise via controlling spin density of magnetic insulators

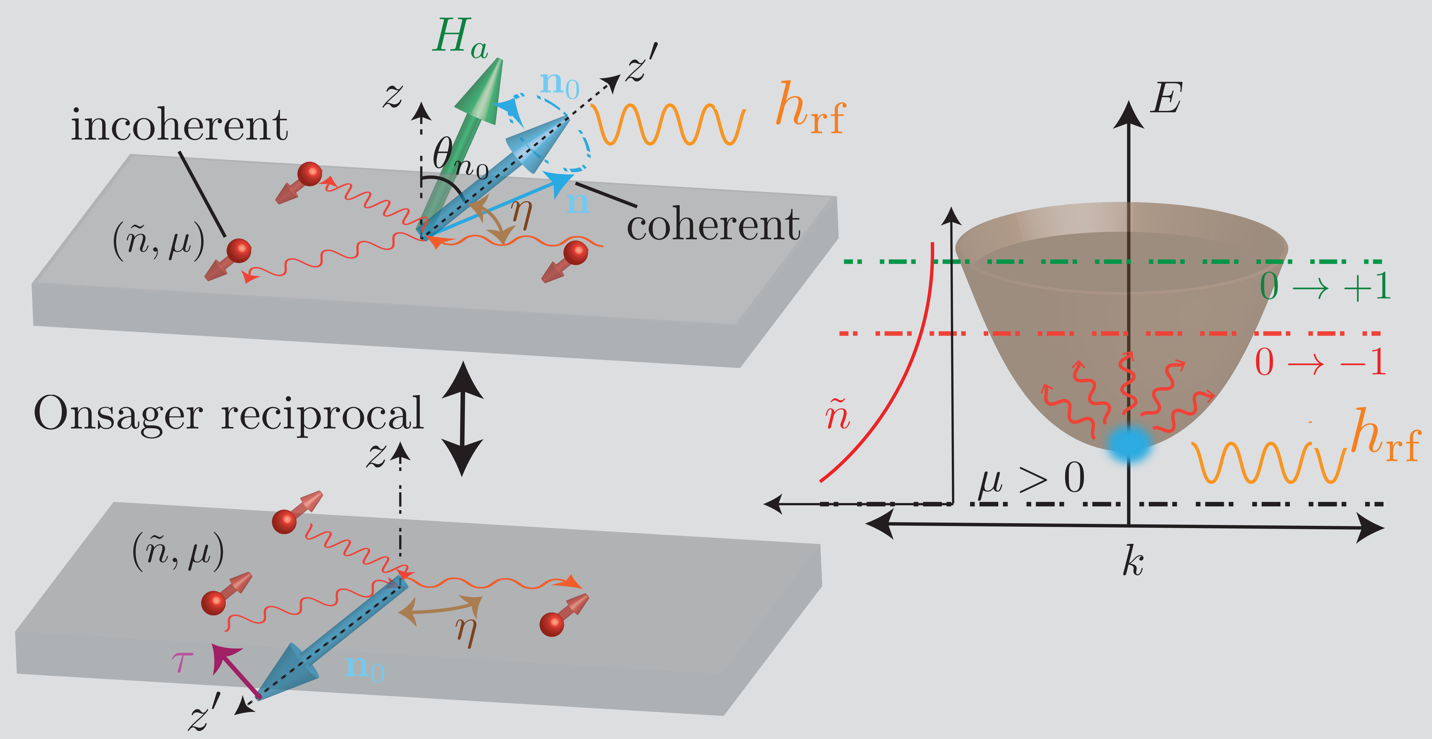
FMR-induced non-resonant coupling





- It was shown recently that when coherent spin density is driven by an AC magnetic field, both the populations [1] and the transition rates [2] of the NV spin states are manipulated.
- In contrast to the direct on-resonance microwave driving of the NV spin, this manipulation occurs even when the frequency of the coherently precessing magnet is well separated from the magnetic resonance of the NV spin.

Proposed coupling mechanism



- **Pumping of incoherent magnons by precessing coherent spin density:** An incoherent magnon scatters off a time-dependent coherent spin density, producing two incoherent magnons. The scattering occurs due to a non zero coupling between the coherent piece and the incoherent magnons arising from the breaking of SU(2) symmetry, due to a finite easy-plane anisotropy of YIG thin films [3].
- The pumping of magnons is balanced by the loss of magnons to the lattice, establishing a new quasi-equilibrium **with a raised effective chemical potential** for the incoherent magnons. Consequently, the number of magnons and the corresponding dipolar field noise is increased at the levels resonant with the NV spin transitions, enhancing the transition rates.
- Importantly, the **pumping process is Onsager reciprocal to thermomagnonic torques** studied intensively in the field of spincaloritronics 4]. Whereby, the coherent piece absorbs excess incoherent magnons resulting in the transfer of angular momentum fed into the thermal magnons via application of temperature gradients.

Theory: symmetry-based two-fluid phenomenology

- Hydrodynamic variables describing the magnetic insulator

$$s\mathbf{n} \equiv s(n_x, n_y, n_z) \quad \& \quad \tilde{n}$$

coherent spin density — incoherent magnon density

- Free energy:

$$\mathcal{F}(\mathbf{n}, \tilde{n}) \equiv \frac{A|\nabla \mathbf{n}|^2}{2} + K n_z^2/2 + \mu\tilde{n}$$

exchange — anisotropy — chemical potential

- Linear response equation of motion:

$$\begin{pmatrix} \dot{\mathbf{n}} \\ \dot{\tilde{n}} \end{pmatrix} = \begin{pmatrix} \mathbf{L}^{\mathbf{nn}} & \mathbf{L}^{\mathbf{n}\tilde{n}} \\ \mathbf{L}^{\tilde{n}\mathbf{n}} & \mathrm{L}^{\tilde{n}\tilde{n}} \end{pmatrix} \begin{pmatrix} \mathbf{H} \\ \mu \end{pmatrix} \qquad \mathbf{H} \equiv \delta_{\mathbf{n}}\mathcal{F}_n$$

- Apply Onsager reciprocity, and demand equation of motion to be invariant under symmetries of the system, namely U(1) about the z-axis and mirror about xz plane

$$\hbar\dot{\mathbf{n}} = \frac{\hbar}{s}\mathbf{H}\times\mathbf{n} - \hbar(\alpha + \eta n_z^2)\mathbf{n}\times\dot{\mathbf{n}} + \mu\eta n_z \mathbf{n}\times\mathbf{n}\times\mathbf{z}$$

damping-like thermal torque

$$\dot{\tilde{n}} = \sigma\nabla\cdot\mathbf{j} - (\alpha' + \eta n_z^2)\frac{s\mu}{\hbar^2} + \eta\frac{s}{\hbar}n_z\mathbf{z}\cdot\mathbf{n}\times\dot{\mathbf{n}}$$

magnon pumping by coherent dynamics

Experiment vs Theory : linear regime

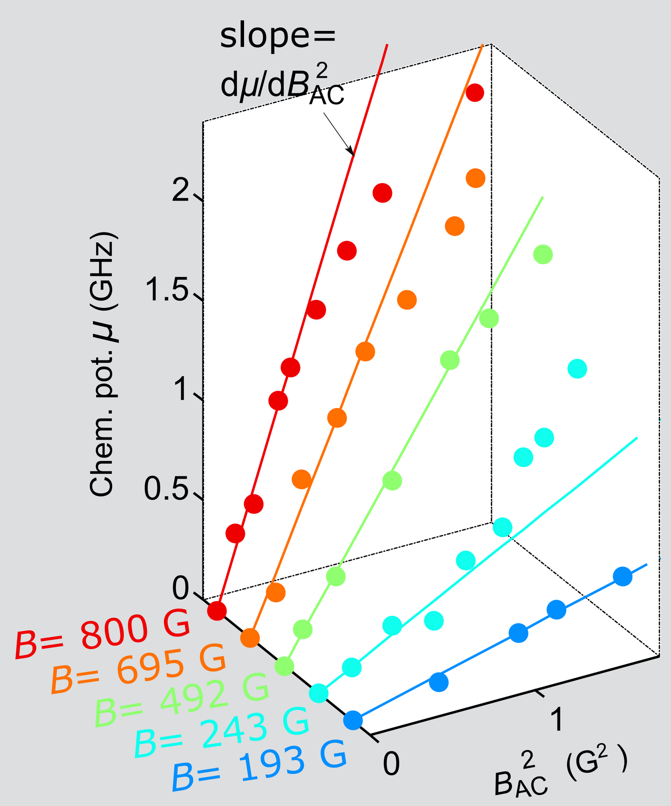
- Chemical potential can be extracted from measured transition rates using [2]

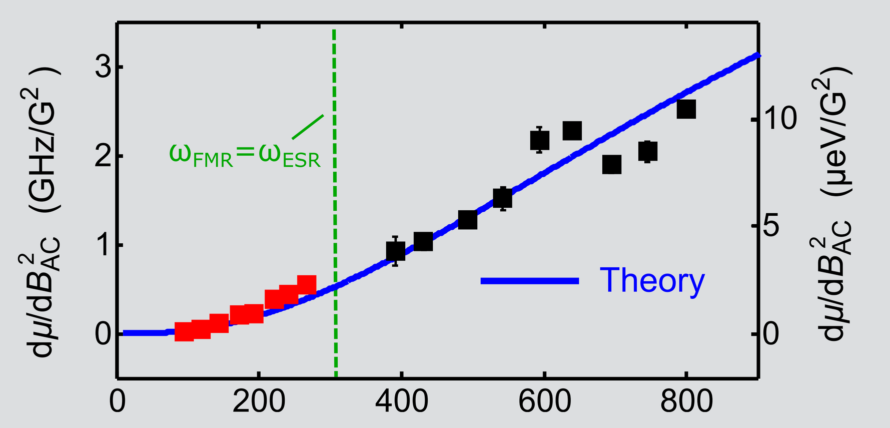
$$\Gamma_{\pm} = \frac{k_B T}{\hbar\omega_{\pm} - \mu}\int_k f(E(k), T, \theta)$$

- Chemical potential can be extracted from two fluid phenomenology, by averaging magnon evolution equation over precession cycle. In non-adiabatic pumping regime

$$\mu = \tilde{\eta}\hbar\frac{\Omega_{\mathrm{rf}}^2\omega_H}{4\omega_1^2\alpha^2}\cos^2\theta_n \qquad \tilde{\eta} = \frac{\eta\pi^2}{\alpha\mathcal{I}}\left(\frac{T_c}{T}\right)^{3/2}$$

$$\mathcal{I} \sim 1$$





$$\Omega_{\mathrm{rf}} \equiv \gamma h_{\mathrm{rf}}$$
$$\omega_H \equiv \gamma[H_a\cos(\theta_n - \theta) - 4\pi M_s\cos^2\theta_n]$$
$$\omega_1 \equiv \omega_H + 2\pi\gamma M_s\sin^2\theta_n$$

- **Theory accurately predicts the observed angular dependence of chemical potential**
- **Quantitative measurement of thermo-magnonic torque parameter indicates coupling between magnons and coherent spin density comparable to coupling to lattice, i.e.** $\eta \sim 7\times 10^{-5} \sim \alpha$

References

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[4] Bauer et. al. Nat. Mat. **11**, 391 (2012)