Quenching of dynamic nuclear polarization by spin-orbit coupling in GaAs quantum dots

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The central-spin problem is a widely studied model of quantum decoherence. Dynamic nuclear polarization occurs in central-spin systems when electronic angular momentum is transferred to nuclear spins and is exploited in quantum information processing for coherent spin manipulation. However, the mechanisms limiting this process remain only partially understood. Here we show that spin-orbit coupling can quench dynamic nuclear polarization in a GaAs quantum dot, because spin conservation is violated in the electron-nuclear system, despite weak spin-orbit coupling in GaAs. Using Landau-Zener sweeps to measure static and dynamic properties of the electron spin-flip probability, we observe that the size of the spin-orbit and hyperfine interactions depends on the magnitude and direction of applied magnetic field. We find that dynamic nuclear polarization is quenched when the spin-orbit contribution exceeds the hyperfine, in agreement with a theoretical model. Our results shed light on the surprisingly strong effect of spin-orbit coupling in central-spin systems.
Motivation

Landau-Zener sweeps

\[ H(\epsilon) = \begin{pmatrix} \frac{\epsilon}{2} - B & \Delta_{ST}(t) \\ \Delta_{ST}^*(t) & -1/2\sqrt{\epsilon^2 - 4t_c^2} \end{pmatrix} \] in \{T^+, S\} basis.

Landau-Zener:

\[ P_{LZ}(t) = 1 - \exp\left(\frac{-2\pi|\Delta_{ST}(t)|^2}{\hbar\beta}\right) \approx \frac{2\pi|\Delta_{ST}(t)|^2}{\hbar\beta} \rightarrow P_{LZ}(t)/\beta \propto |\Delta_{ST}(t)|^2 \]

\[ \beta = d(E_S - E_{T^+})/dt \quad \beta \gg \Delta_{ST} \]

\[ \delta \beta(t) \rightarrow \text{Saturation due to charge noise} \]
Singlet mixing at $\epsilon_{ST}$:

$$|S > = \cos \theta |(1,1)S > + \sin \theta |(0,2)S >$$

Singlet mixing angle: $\theta = \arctan(B/t_c)$

Nuclear: only differences $\delta B_\perp$ btw. dots: $(1,1)T \leftrightarrow (1,1)S$

Spin orbit: During tunneling, only $B_{SO,z} \perp z$: $(1,1)T \leftrightarrow (0,2)S$

$$\Delta_{ST}(t) = \Delta_{HF}(t) + \Delta_{SO} = \delta B_\perp(t) \cos(\theta) + \Omega_{SO} \sin(\theta) \sin(\phi)$$
Spin orbit contribution

\[ \sigma_{ST} = \sqrt{\langle |\Delta_{ST}(t)|^2 \rangle} \propto \sqrt{P_{LZ}(t)/\beta} \]

\[ \Delta_{ST}(t) = \delta B_{\perp}(t) \cos(\theta) + \Omega_{SO} \sin(\theta) \sin(\phi) = \Delta_{HF}(t) + \Delta_{SOI} \]

\[ \Omega_{SO} = 461 \pm 10 \text{neV}(18 \text{mT}) \rightarrow \lambda_{so} \approx 3.5 \mu m, \]

\[ \sqrt{\langle |\delta B_{\perp}(t)|^2 \rangle} = 34 \pm 1 \text{neV} (1.3 \text{mT}) \]
Dynamical properties of $P_{LZ}(t)$

\[ P_T = P_{LZ}(t) \quad P_T = P_{LZ}(t) \cdot e^{\tau/T_1} \quad P_T(t + \tau) = (1 - P_{LZ}(t) \cdot e^{-\tau/T_1}) \cdot P_{LZ}(t + \tau) + P_{LZ}(t) e^{-\tau/T_1} (1 - P_{LZ}(t + \tau)) \]

\[ P_S(t + \tau') \]

- Autocorrelation of the LZ probability:
  \[ \langle P_T(t + \tau) \rangle \propto R_{PP}(\tau) = \langle P_{LZ}(t) P_{LZ}(t + \tau) \rangle \]
- As $P_{LZ} \propto |\Delta_{ST}(t)|^2 \rightarrow S_P(\omega) \propto S_{|\Delta_{ST}|^2}(\omega)$
- $\Delta_{HF}(t)$ arises from precessing nuclear polarization and therefore contains Fourier components of the Larmor frequencies of Ga-69, Ga-71 and As-75.
- $\Delta_{HF}(t) = \sum_{\alpha=1}^{3} \Delta_{\alpha} e^{2\pi i f_{\alpha} t + \theta_{\alpha}}, \alpha = \text{species}$
- Only HF ($\phi = 0$):
  \[ |\Delta_{ST}(t)|^2 = \left| \sum_{\alpha=1}^{3} \Delta_{\alpha} e^{2\pi i f_{\alpha} t + \theta_{\alpha}} \right|^2 \]
  only contains $f_i - f_j \neq i$ components
- With SOI ($\phi \neq 0$):
  \[ |\Delta_{ST}(t)|^2 = |\Delta_{HF}(t) + \Delta_{SOI}|^2 \]
  contains $\Delta_{SOI} e^{2\pi i f_{i} t + \theta_{\alpha}}$ (absolute Larmor frequency) terms!
Dynamic nuclear polarization

\((1,1)S \leftrightarrow (1,1)T_0\) Oscillations \(\rightarrow \delta B_z\)

- LZ sweeps «pump» on the nuclear bath due to hyperfine driven
  \(|S \leftrightarrow |T\rangle\)
- SOI is not flipping nuclear spin
- Competition between SOI and hyperfine:
  \(
  \Delta_{ST}(t) = \delta B_z(t) \cos(\theta) + \Omega_{SO} \sin(\theta) \sin(\phi) = \Delta_{HF}(t) + \Delta_{SOI}
  \)
- DNP efficiency given by \(\sigma_{HF}/\sigma_{ST}\)

\[\beta \rightarrow <P_{LZ}> = 0.4\]
Summary

• LZ sweeps on S-T+ transition as a tool for measuring $\Omega_{SO}$
• High bandwidth correlation measurements as a tool for nuclear spin dynamics
• dDNP is very sensitive on $\angle(\vec{B}, \Omega_{SO})$ and can be quenched completely
• dDNP efficiency $\sim \Delta_{HF}/(\Delta_{SOI} + \Delta_{HF})$
Singlet Hybridization

Singlet mixing angle

atan(B/tc) (°)

B (T)

Singlet Hybridization

(0,2)S

(1,1)S