Spin Exchange Dynamics in Chromium Dipolar Quantum Gases

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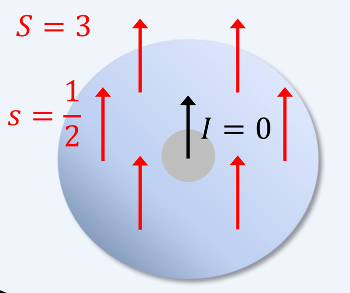
We study out-of-equilibrium spin exchange dynamics in a chromium dipolar Bose-Einstein condensate and a 3D deep optical lattice through tilting the atomic spins by an angle θ with respect to the external magnetic field. Comparisons with numerical simulations provide insight into the origin of the dynamics and the quantum state obtained during the evolution of the system.

Spin dynamics with ^{52}Cr

Total angular momentum: $\vec{F} = \vec{L} + \vec{S} + \vec{I}$

For ^{52}Cr : $L = 0$, $S = 3$ and $I = 0$ → only spin angular momentum

"Magnetic" atoms
purely electronic spin



Cr (S = 3), Er (J = 7), Dy (J = 10)

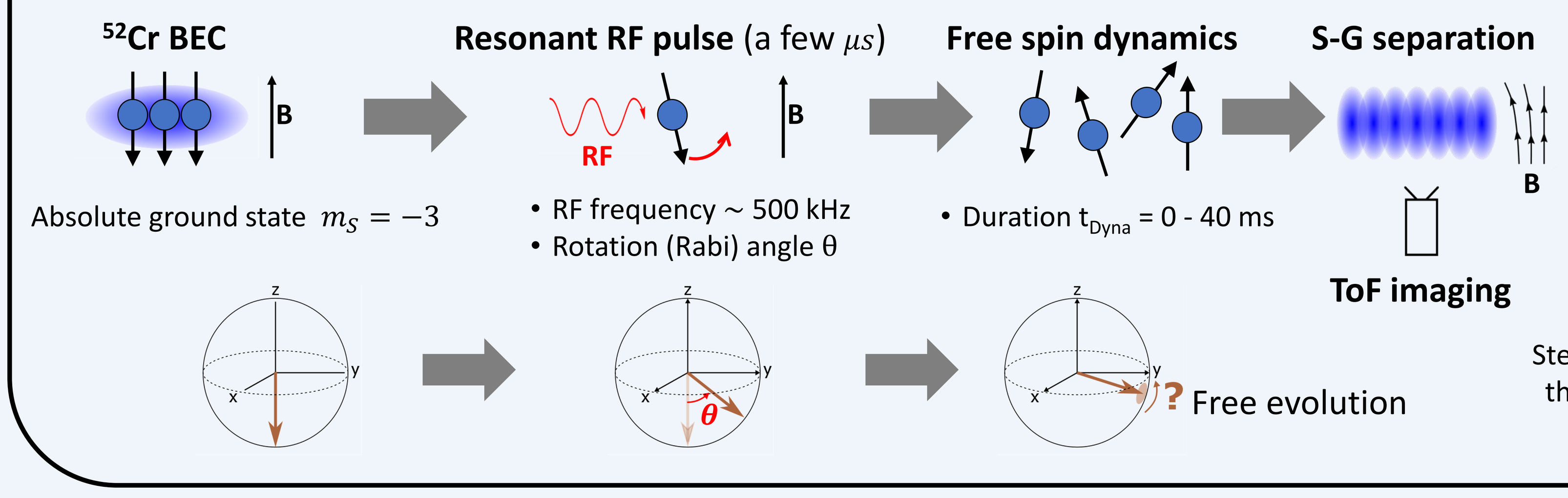
Dipolar quantum gases (Stuttgart, Innsbruck, Stanford, Boulder)

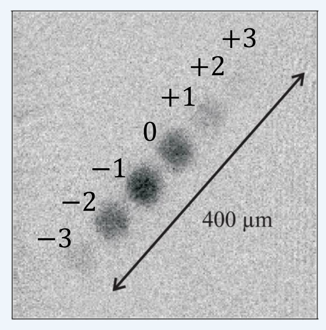
$S = 3$:

- 7 Zeeman states
- Large permanent magnetic moment of 6 μ_B
- **"Large spin" contact interactions**
- **Strong dipole-dipole interactions (DDI)**

Layout of the experiments

Observation of spin dynamics triggered by a radio-frequency pulse



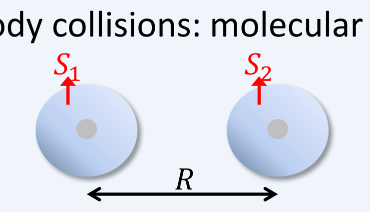


Stern-Gerlach measurement of the number of atoms in each Zeeman state

Spin dynamics after rotation: three main players

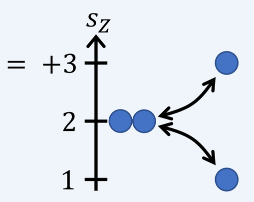
1. Spin dependent contact interactions

2-body collisions: molecular basis



$\vec{S}_{tot} = \vec{S}_1 + \vec{S}_2$

S = 3 → S_{tot} = 0, 2, 4 or 6

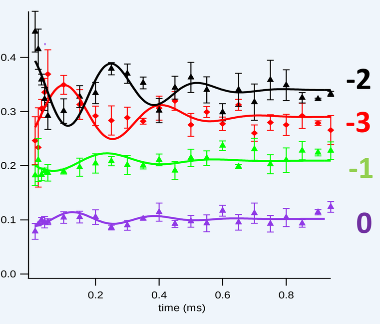


$V_{VdW}(R) \propto 1/R^6$

Isotropic and **short-range**

S_{tot} is conserved

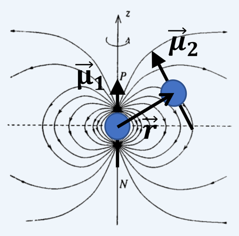
Pseudo-potential: $V(R) = \frac{4\pi\hbar^2}{m} a_{S_{tot}} \delta(R)$



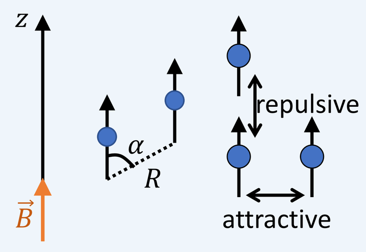
$\Gamma = \frac{4\pi\hbar^2}{m} n(a_6 - a_4)$

Pairs of atoms in a lattice [1]

2. dipole-dipole interactions



$\hat{V}_{DDI} = -\hat{\vec{\mu}}_2 \cdot \hat{\vec{B}}_{\vec{\mu}_1}(\vec{r}) \Rightarrow$ $\boxed{\hat{V}_{DDI} = \frac{\mu_0}{4\pi}(g_S\mu_B)^2 \left[\frac{\hat{S}_1\cdot\hat{S}_2}{R^3} - \frac{3(\hat{S}_1\cdot\hat{r})(\hat{S}_2\cdot\hat{r})}{R^5}\right]}$ **Anisotropic** and **long-range**



Magnetization conserving terms:

$$\hat{H}_{Ising} = \frac{\mu_0 {\mu_B}^2}{\pi R^3}\hat{S}_{1z}\hat{S}_{2z}\left(1 - 3\frac{\hat{z}^2}{R^2}\right)$$

$$\hat{H}_{exchange} = -\frac{\mu_0 {\mu_B}^2}{4\pi R^3}(\hat{S}_{1+}\hat{S}_{2-} + \hat{S}_{1-}\hat{S}_{2+})\left(1 - 3\frac{\hat{z}^2}{R^2}\right)$$

$m_s = -2 \;\; -2 \longrightarrow -3 \;\; -1$

Non magnetization conserving terms:

$$\hat{H}_{NMC} = \frac{\mu_0 {\mu_B}^2}{2\pi R^3}\left[-\frac{3}{2}\frac{\hat{z}\hat{r}_-}{R^2}(\hat{S}_{1z}\hat{S}_{2+} + \hat{S}_{1+}\hat{S}_{2z}) - \frac{3}{2}\frac{\hat{z}\hat{r}_+}{R^2}(\hat{S}_{1z}\hat{S}_{2-} + \hat{S}_{1-}\hat{S}_{2z}) - \frac{3}{4}\frac{\hat{r}_-^2}{R^2}\hat{S}_{1+}\hat{S}_{2+} - \frac{3}{4}\frac{\hat{r}_+^2}{R^2}\hat{S}_{1-}\hat{S}_{2-}\right]$$

$m_s = -2 \;\; -2 \longrightarrow -2 \;\; -3 \;\; + g_S\mu_B B$

$m_s = -2 \;\; -2 \longrightarrow -3 \;\; -3 \;\; + 2g_S\mu_B B$

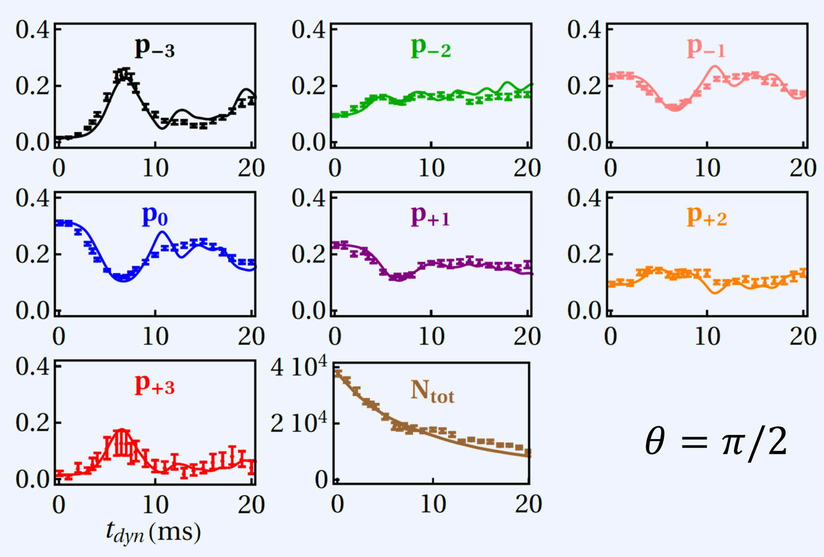
Atom losses

3. magnetic field gradient: creates inhomogeneity ⇒ spin dynamics in BEC (even for $\theta = \pi/2$).

Results in Bose-Einstein condensate [2]

Predictions for a dipolar BEC: dynamics expected with DDI except for the case $\theta = \pi/2$ → no dynamics predicted by mean-field (in absence of magnetic field gradient).

Dots: experimental data
Solid lines: results of our spinor BEC Gross-Pitaevskii numerical simulations (with no free parameter)



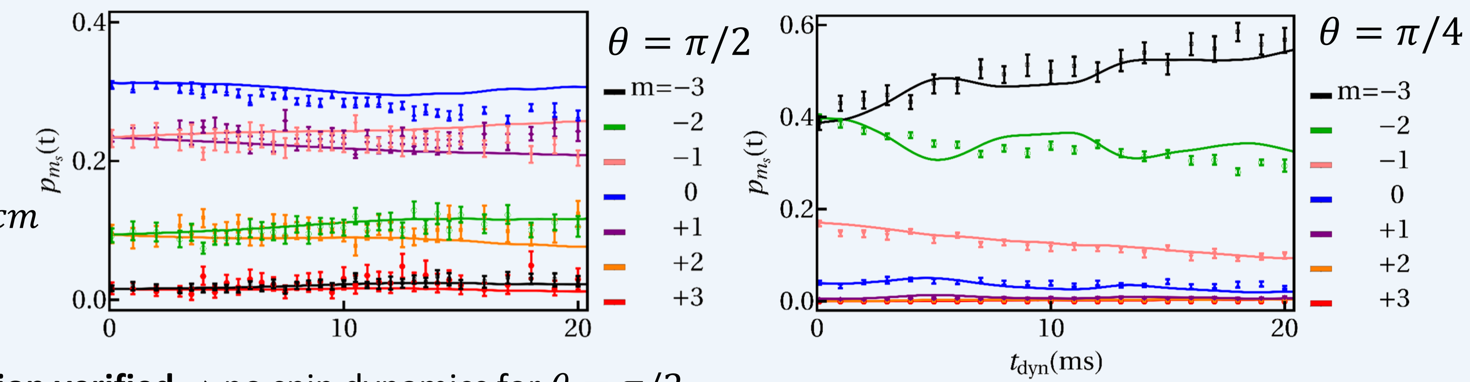
$B_0 = 165$ mG
$|\vec{\nabla}B| \approx 45 \pm 7$ mG/cm

→ **spin dynamics triggered by MG**

→ **locally ferromagnetic** (GP simulations from Paolo Pedri and Kaci Kechadi)

$\theta = \pi/2$

$B_0 = 190$ mG
$|\vec{\nabla}B| \approx 4 \pm 18$ mG/cm

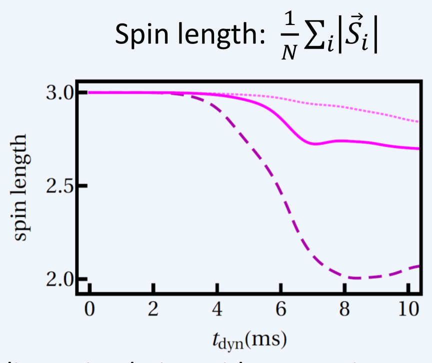


Mean-field prediction verified → no spin dynamics for $\theta = \pi/2$
No spin dynamics → not out of mean-field effects observed

Spin dynamics without MG → **DDI witness!**

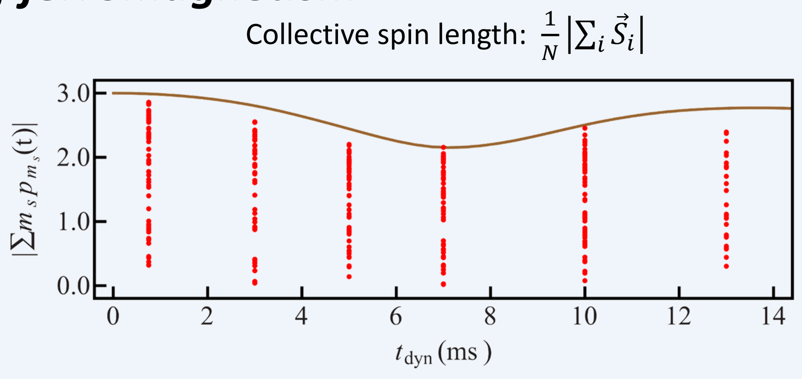
Protection of ferromagnetism

Spin length: $\frac{1}{N}\sum_i |\vec{S}_i|$



Solid lines: simulation with contact interactions and DDI
Dashed lines: simulation without contact interactions
Dotted lines: simulation without DDI

Collective spin length: $\frac{1}{N}|\sum_i \vec{S}_i|$



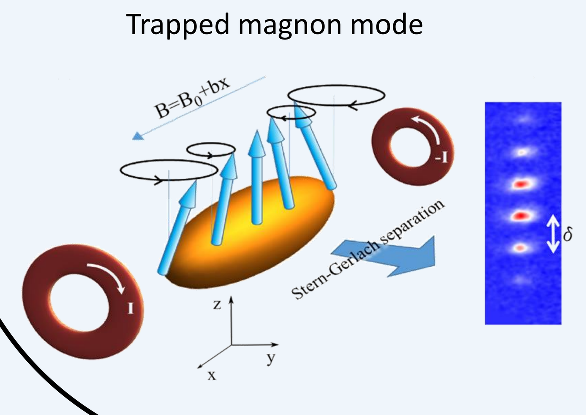
Dots: measurement of the value of $|\sum m_S p_{m_S}|$ after a $\frac{\pi}{2} - t_{dyn} - \frac{\pi}{2}$ sequence
Solid line: value of the collective spin length obtained from our GP simulations

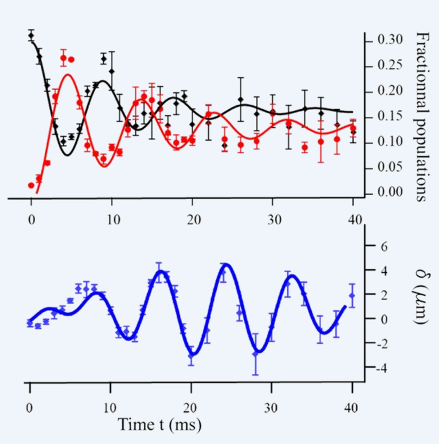
Simulations → **local ferromagnetic character** maintained during the dynamics.

This comes as a surprise since $a_6 - a_4 > 0$ energetically favors depolarization in the ^{52}Cr BEC. [3]

Spin modes of a ferrofluid [4]

Trapped magnon mode





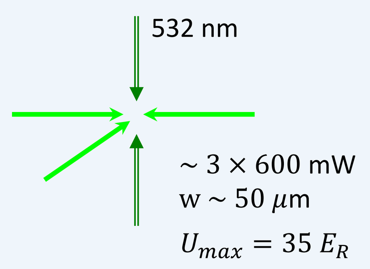
Spin populations and centres of mass of spin components oscillate at the same frequency which depends on the magnetic field gradient

Results are well captured by (classical) **hydrodynamic theory**

Characteristic frequencies $\sim \frac{\hbar^2}{mR^2} \ll f_{trap}$

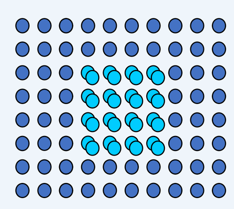
Results in Mott insulator state [5]

Predictions in a deep lattice [6]:
- Small θ: inhomogeneous classical precession (mean-field)
- $\theta \to \pi/2$: entanglement appears (beyond mean-field effects)

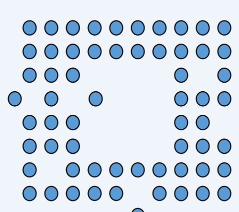


Rectangular lattice of anisotropic sites

$a_x \approx 288$ nm $f_x \approx 170$ kHz
$a_y \approx 695$ nm $f_y \approx 50$ kHz
$a_z \approx 266$ nm $f_z \approx 100$ kHz

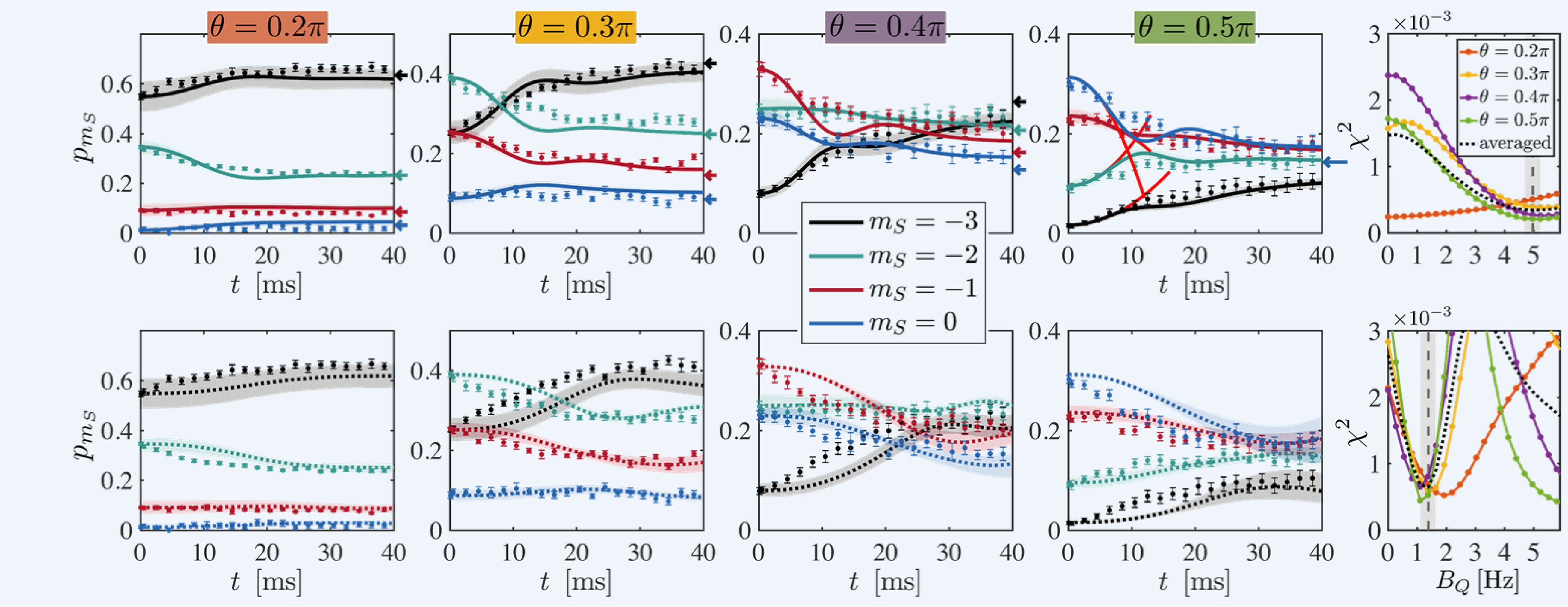


We first get rid of doublons with the help of dipolar relaxation at large B field ($g_S\mu_B B > U_{max}$) to simplify the system



Intersite spin dynamics of ~10000 atoms in singly occupied sites mediated only by DDI

Comparison between experimental spin dynamics and simulations



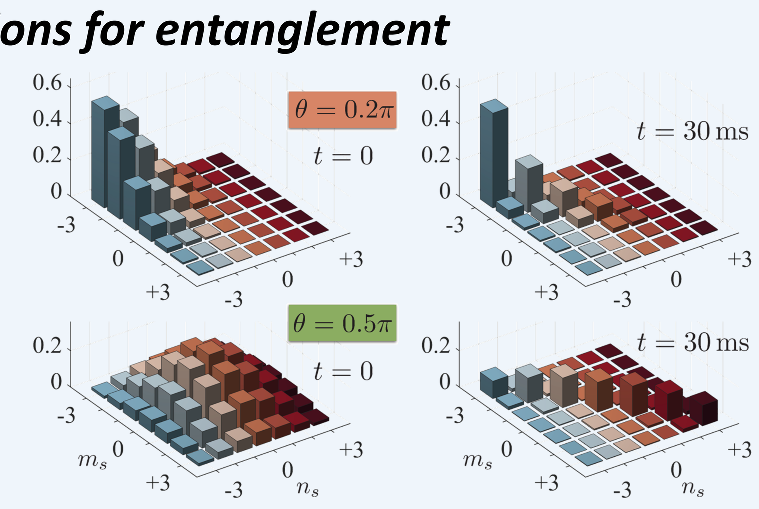
Top: Good agreement with **beyond mean-field** (GDTWA) simulations (160 spins, no adjustable parameter except the quadratic light shift)
Bottom: Agreement with **classical** (mean-field) simulations gets worse with large tipping angles θ
Red solid red line: Results of quantum perturbative calculations $p_{m_S}(t) = p_{m_S}(0) + \sin(\theta)^4 \alpha_{m_S}(\theta) t^2 V_{eff}^2 + O(t^4 V_{ij}^4)$ with $V_{eff}^2 = \frac{1}{N}\sum_{i,j\neq i} V_{ij}^2$

Results of GDTWA simulations for entanglement

Results for the **reduced density matrix ρ_0** of one spin:

In the measurement basis (along the B field) → evolution from a highly correlated state towards an almost totally **mixed** state for $\theta = \frac{\pi}{2}$

→ **Proof of close to maximal entanglement for a pure state**



Entanglement witnesses based on ρ_0: "quantum" entropies

Left: Second Renyi entropy $S_0^{(2)} = -\log_2[\mathrm{tr}(\hat{\rho}_0^2)]$

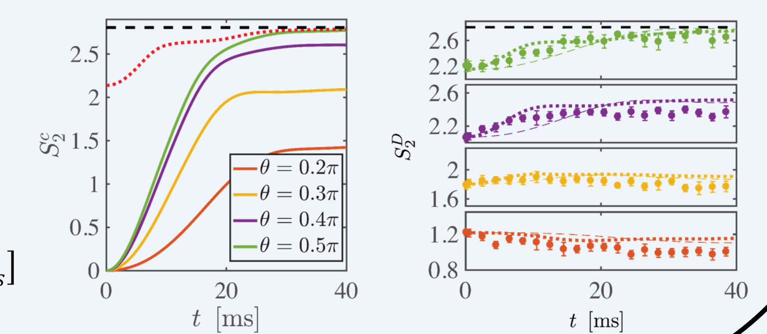
$S_0^{(2)} = 0$ for a mixed state and $S_0^{(2)} \to \log_2[7]$ for a maximally entangled state

Right: Diagonal entropy $S_2^D = -\log_2[\mathrm{tr}(\mathrm{diag}(\hat{\rho}_S)^2)]$

$\hat{\rho}_S$ is the averaged single particle density matrix

Assuming homogeneity, S_2^D can be evaluated from data: $S_2^D = -\log_2[\sum p_{m_S}^2]$

The diagonal entropy provides an upper bound for the entanglement entropy: $S_2^D \geq S_0^{(2)}$



References

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