Dynamical generation of spin squeezing in ultra-cold dipolar molecules

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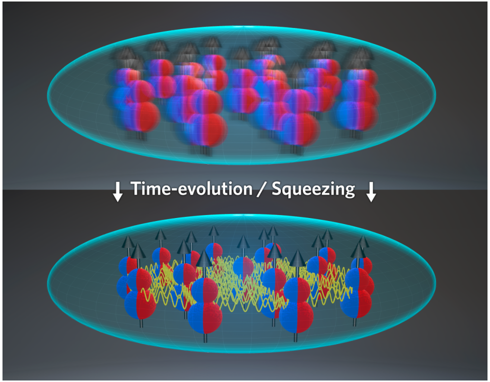


Summary

What

- Dipolar KRb molecules
- Confinement in 2D/single layer
- Spin model in mode space

Why

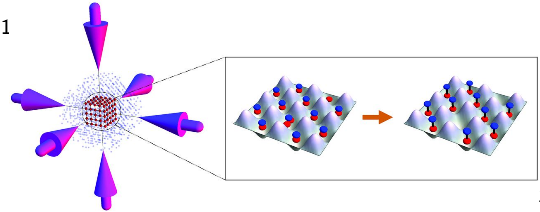
- Long-range interactions
- Enhanced interactions & suppressed losses
- Homogeneous couplings

Benefits

- Robust collective spin-dynamics
- Robust generation of entangled/spin-squeezed states ($\sim$ 19 dB)
- Time-Reversal & measurement noise robust enhanced sensing ($\Delta E \sim 188\,(\mathrm{nV/cm})/\sqrt{\mathrm{Hz}}$)

Milestones & Recent Advances in dipolar molecules

- Preparation at high phase-space density [1]
- Observation of dipolar exchange [2]
- Low entropy lattice preparation [3]



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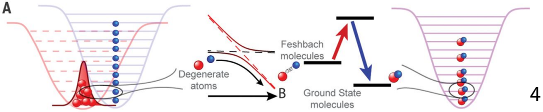
- Bulk quantum degenerate dipolar Fermi gas [4]
- 2D preparation & suppression of losses [5]
- Collisional shielding of collisions [6]
- Microwave shielding [7]
- State-control of reactions [8]



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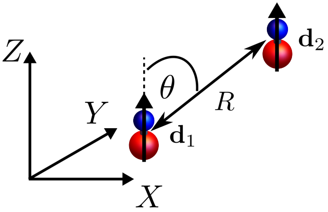
1 K.-K. Ni et al., Science 322 (2008)
2 J. Ye et al., Nature 501 (2013)
3 D.S. Jin et al., Science 350 (2015)
4 J. Ye et al., Science 363 (2019)
5 J. Ye et al., Nature 588 (2020)
6 J. Ye et al., Science 11 (2020)
7 Doyle et al., arXiv:2102.04365 (2021)
8 K.-K. Ni et al., Nat. Chem. 13 (2021)

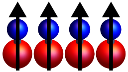
Key Advantages of 2D

Enhanced Interactions

$$\frac{1}{4\pi\epsilon_0 R^3}\left(1-3\cos^2(\theta)\right)\mathbf{d}_i\cdot\mathbf{d}_j$$

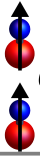


repulsive
Side-by-Side



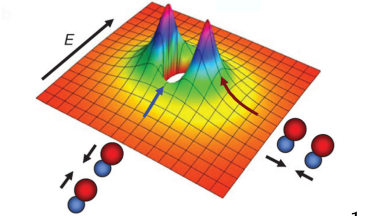
$\theta = 0$

attractive
Head-to-Tail



$\theta = \pi/2$

Suppression of Losses



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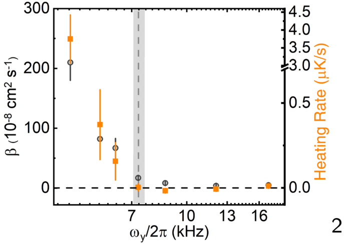

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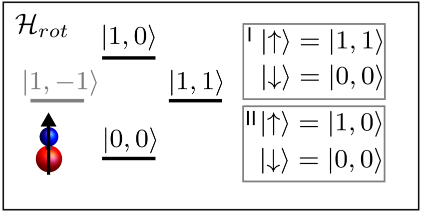
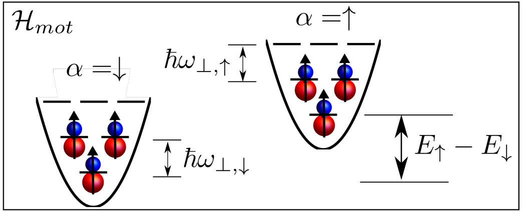
[1] K-K Ni et al., Nature 464 (2010)

[2] J. Ye et al., Science 11 (2020)

Full Many-Body Hamiltonian

$$\mathcal{H} = \mathcal{H}_{\text{rot}} + \mathcal{H}_{\text{motional}} + \mathcal{H}_{\text{dip}}$$





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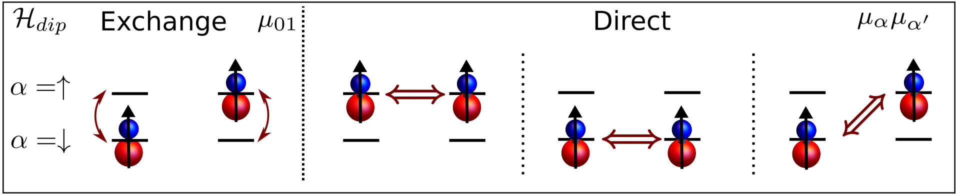


$$\mathcal{H}_{dip} = \sum_{i,j} \frac{1}{4\pi\epsilon_0 R^3} \left[\hat{\mathbf{d}}_i \cdot \hat{\mathbf{d}}_j - 3(\hat{R} \cdot \hat{\mathbf{d}}_i)(\hat{R} \cdot \hat{\mathbf{d}}_j)\right]$$

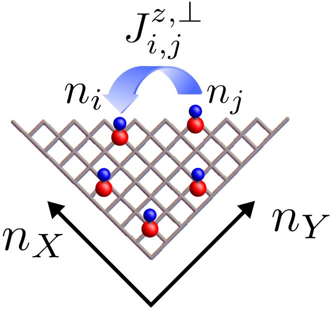
Spin Model in mode space

Long-range XXZ

$$\hat{H} = 1/2\left(\sum_{\mathbf{n}_1,\mathbf{n}_2} \hat{s}^z_{\mathbf{n}_1}\hat{s}^z_{\mathbf{n}_2} J^z_{\mathbf{n}_1\mathbf{n}_2} + 1/2\sum_{\mathbf{n}_1,\mathbf{n}_2}\left(\hat{s}^-_{\mathbf{n}_1}\hat{s}^+_{\mathbf{n}_2} + \hat{s}^+_{\mathbf{n}_1}\hat{s}^-_{\mathbf{n}_2}\right) J^\perp_{\mathbf{n}_1,\mathbf{n}_2}\right) + \sum_{\mathbf{n}_1} \hat{s}^z_{\mathbf{n}_1}\left(h^z_{\mathbf{n}_1} + \Delta E_{\mathbf{n}_1}\right)$$

Key approximations

- Expand in harmonic oscillator basis
- collisionless regime
- neglect mode-changing interaction terms



Spin Model in mode space

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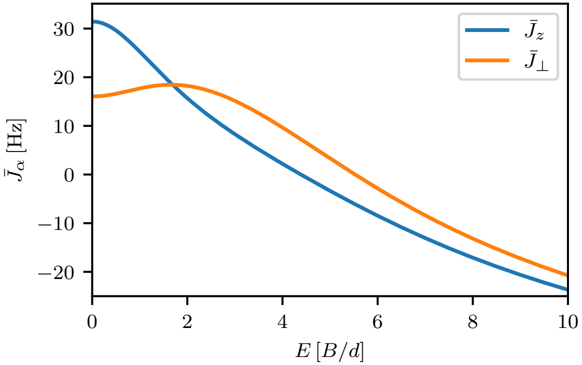
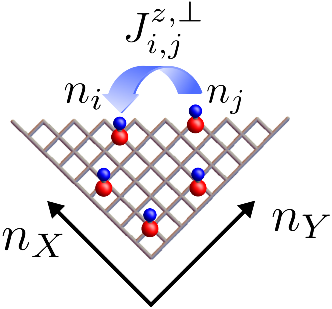
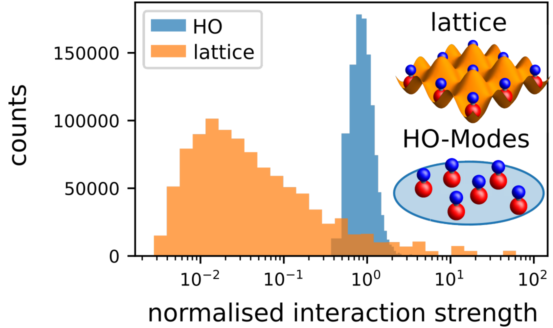




Key Advantages of Mode Space lattices

Collectiveness



Collective Limit/One-Axis Twisting [1]

One-axis twisting

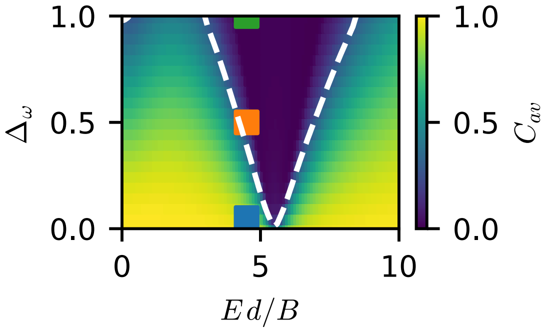
$$\mathcal{H} = \bar{J}_{\perp}\hat{S}^2 + (\bar{J}_z - \bar{J}_{\perp})\hat{S}_z^2 + \bar{h}_z\hat{S}_z$$

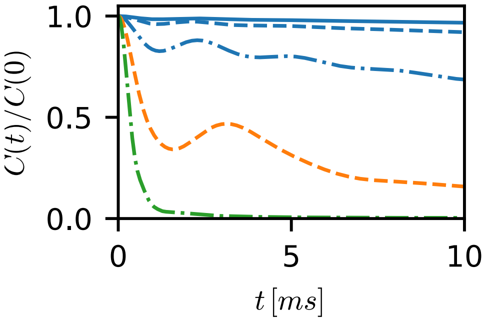
$$\hat{S} = \sum_i \hat{s}_i/N$$

$$\bar{J}_\alpha = \frac{1}{N^2}\sum_{i,j} J_{ij}^\alpha \quad \bar{h}_z = \frac{1}{N}\sum_i h_i^z$$

[1] Kitagawa & Ueda, PRA 47 (1993)

Dynamical phase transition/Robustness to dephasing





Contrast

$C(t) = |S(t)|/N$

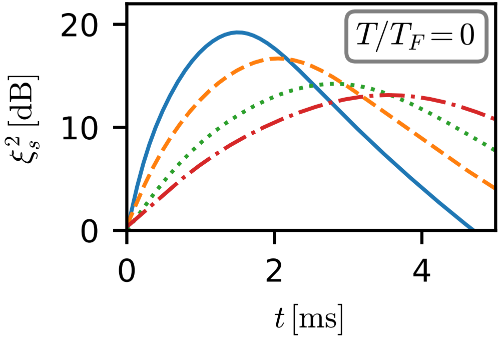
Gap Protection

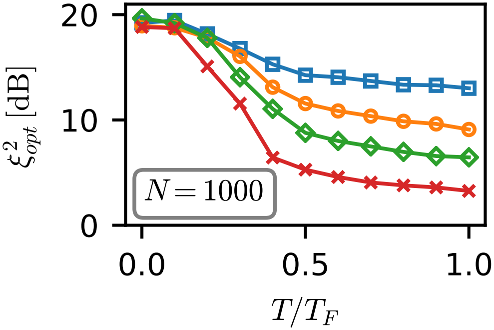
Many-body Gap $\sim N\bar{J}_\perp(E)$

Robust Squeezing

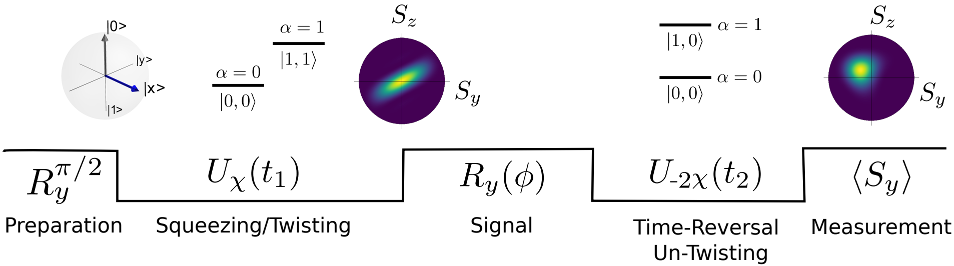
Ramsey Squeezing Parameter

$$\xi_s^2 = N \frac{\min_\phi \langle \mathrm{Var}[\hat{S}_\phi^\perp] \rangle}{|\langle \hat{\mathbf{S}} \rangle|^2}$$





Robust sensing protocol via time-reversal



- create a spin-squeezed state
- reduced state noise: $(\Delta S_z) \sim 1$
- apply rotation along y
- Sensitivity: $\Delta\phi = \frac{\Delta S_z}{\partial_\phi \langle S_z \rangle} \sim 1/N$

Requirements

Need to resolve at single-atom level

Time-Reversal

- Amplifies signal by factor G [a]
- Coherent state noise: $\Delta S_y \sim \sqrt{N}$

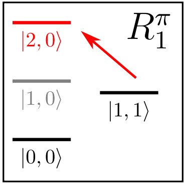
[a] M. Schleier-Smith et al, PRL (2016)

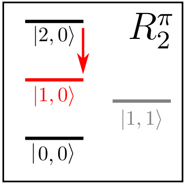
Requirements

Measurement Error $< \sqrt{N}$

Application: Sensing E-fields

$$R_z(\phi) = e^{it(\epsilon_{20}(E) - \epsilon_{00}(E))/\hbar}$$





Sensing capability

- $\Delta E \approx 188\,(\mathrm{nV/cm})/\sqrt{\mathrm{Hz}}$
- at $E = 1\,\mathrm{kV/cm}$
- for 10 ms phase accumulation
- sensitive to DC-fields

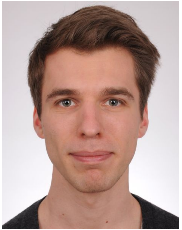
Summary & Outlook

- Robust collective spin-dynamics
- Robust generation of entangled/spin-squeezed states ($\sim$ 19 dB)
- Exploit Level-Structure for Time-Reversal
- Measurement noise robust enhanced sensing ($\Delta E \approx 188\,(\mathrm{nV/cm})/\sqrt{\mathrm{Hz}}$)

- Study of non-equilibrium dynamics?
- Non-trivial many-body phases/dynamics?

Thank you for your attention!

Thomas Bilitewski



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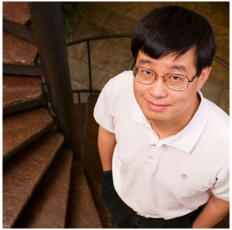

Contacts

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