Observation of Dynamical Quantum Phase Transitions in a Spinor Condensate

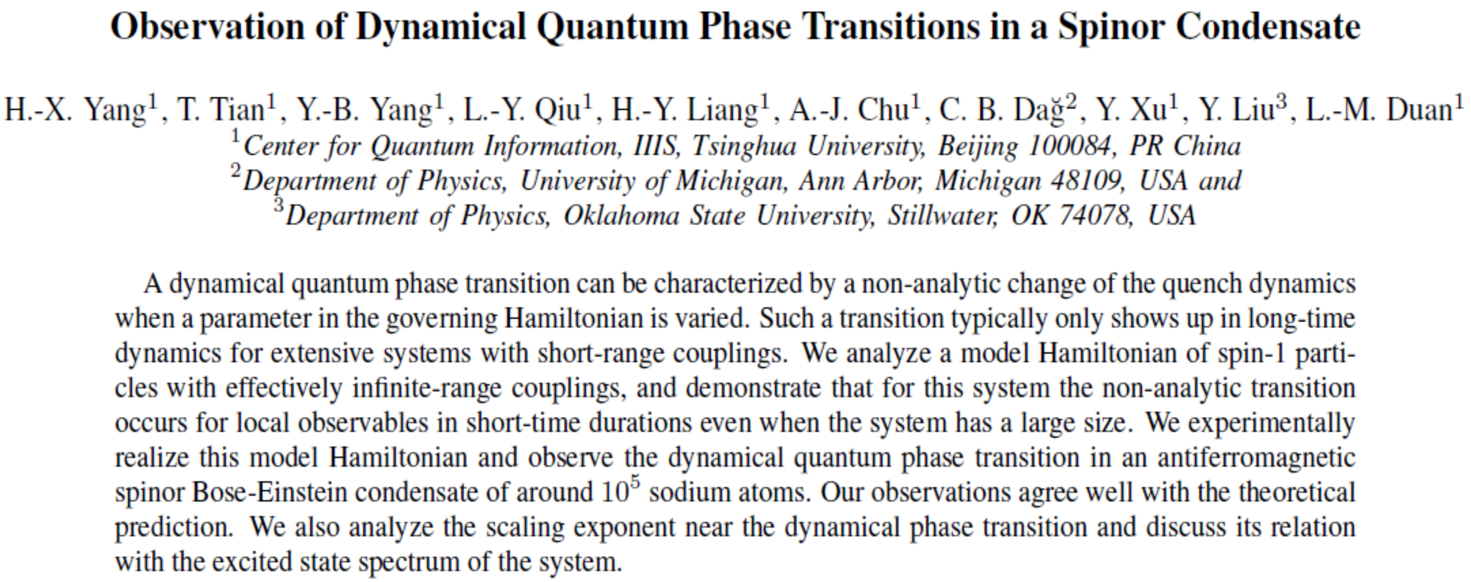
Atomtronics, Benasque, May 15

Tian Tian

CQI, IIIS, Tsinghua University, Beijing, China

Outline

- Introduction of dynamical quantum phase transition (DQPT)
- Theoretical model of spinor-1 BEC
- Experimental results and analysis
- conclusion



Observation of Dynamical Quantum Phase Transitions in a Spinor Condensate

H.-X. Yang[1], T. Tian[1], Y.-B. Yang[1], L.-Y. Qiu[1], H.-Y. Liang[1], A.-J. Chu[1], C. B. Dağ[2], Y. Xu[1], Y. Liu[3], L.-M. Duan[1]
[1]*Center for Quantum Information, IIIS, Tsinghua University, Beijing 100084, PR China*
[2]*Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA and*
[3]*Department of Physics, Oklahoma State University, Stillwater, OK 74078, USA*

A dynamical quantum phase transition can be characterized by a non-analytic change of the quench dynamics when a parameter in the governing Hamiltonian is varied. Such a transition typically only shows up in long-time dynamics for extensive systems with short-range couplings. We analyze a model Hamiltonian of spin-1 particles with effectively infinite-range couplings, and demonstrate that for this system the non-analytic transition occurs for local observables in short-time durations even when the system has a large size. We experimentally realize this model Hamiltonian and observe the dynamical quantum phase transition in an antiferromagnetic spinor Bose-Einstein condensate of around 10^5 sodium atoms. Our observations agree well with the theoretical prediction. We also analyze the scaling exponent near the dynamical phase transition and discuss its relation with the excited state spectrum of the system.

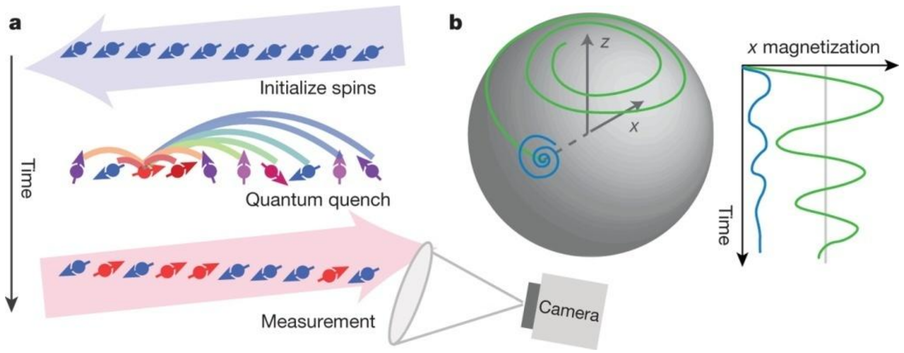
Dynamical quantum phase transition(DQPT)

- Type I DQPT arises when the quench dynamics undergoes a non-analytic change with respect to a **system parameter** in a **quenched Hamiltonian**.
- Type II DQPT appears when one global order parameter under the **quench Hamiltonian** has a non-analytic **singularity** in its **time evolutions** (such as the Loschmidt echo)

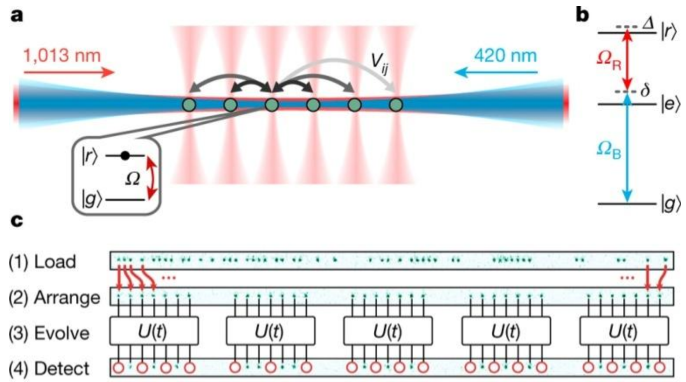
Difficulty: observing DQPTs in systems with short-range couplings requires measurements of **long-range** correlations (e.g., infinite-range in the thermodynamic limit for type-II DQPTs), or asymptotic **long-time** dynamics (e.g., infinite-time in the thermodynamic limit for type-I DQPTs)

[1] A. Polkovnikov, K. Sengupta, A. Silva, and M. Vengalattore, Rev. Mod. Phys. 83, 863 (2011).
[2] M. Heyl, Rep. Prog. Phys. 81, 054001 (2018).
[3] B. Sciolla and G. Biroli, Phys. Rev. Lett. 105, 220401 (2010).
[4] A. A. Zvyagin, Low Temperature Physics 42, 971 (2016).
[5] M. Heyl, A. Polkovnikov, and S. Kehrein, Phys. Rev. Lett. 110, 135704 (2013).
[6] B. Žunkovič, M. Heyl, M. Knap, and A. Silva, Phys. Rev. Lett. 120, 130601 (2018).
[7] P. Jurcevic, H. Shen, P. Hauke, C. Maier, T. Brydges, C. Hempel, B. P. Lanyon, M. Heyl, R. Blatt, and C. F. Roos, Phys. Rev. Lett. 119, 080501 (2017).
[8] V. Gurarie, arXiv:1806.08876 (2018).
[9] N. Fla¨schner, D. Vogel, M. Tarnowski, B. S. Rem, D.-S. Lu¨hmann, M. Heyl, J. C. Budich, L. Mathey, K. Sengstock, and C. Weitenberg, Nature Physics 14, 265-268 (2018).
[10] P. Titum, J. T. Iosue, J. R. Garrison, A. V. Gorshkov, and Z.-X. Gong, arXiv:1809.06377 (2018).

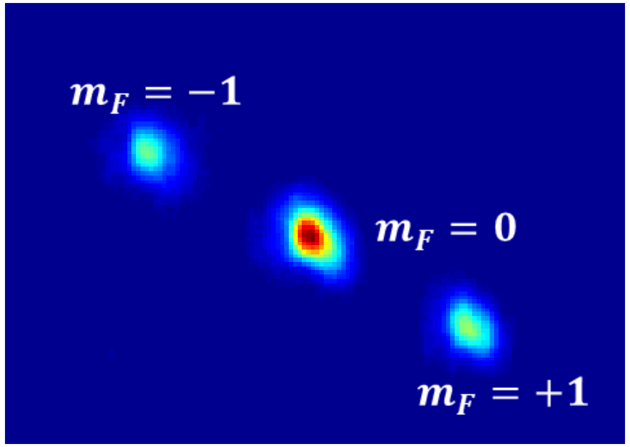
Type I DQPT observed in short time



trapped ion-53 qubits



Rydberg atom-51 qubits



Spinor BEC-10^5 atoms

Due to limited size

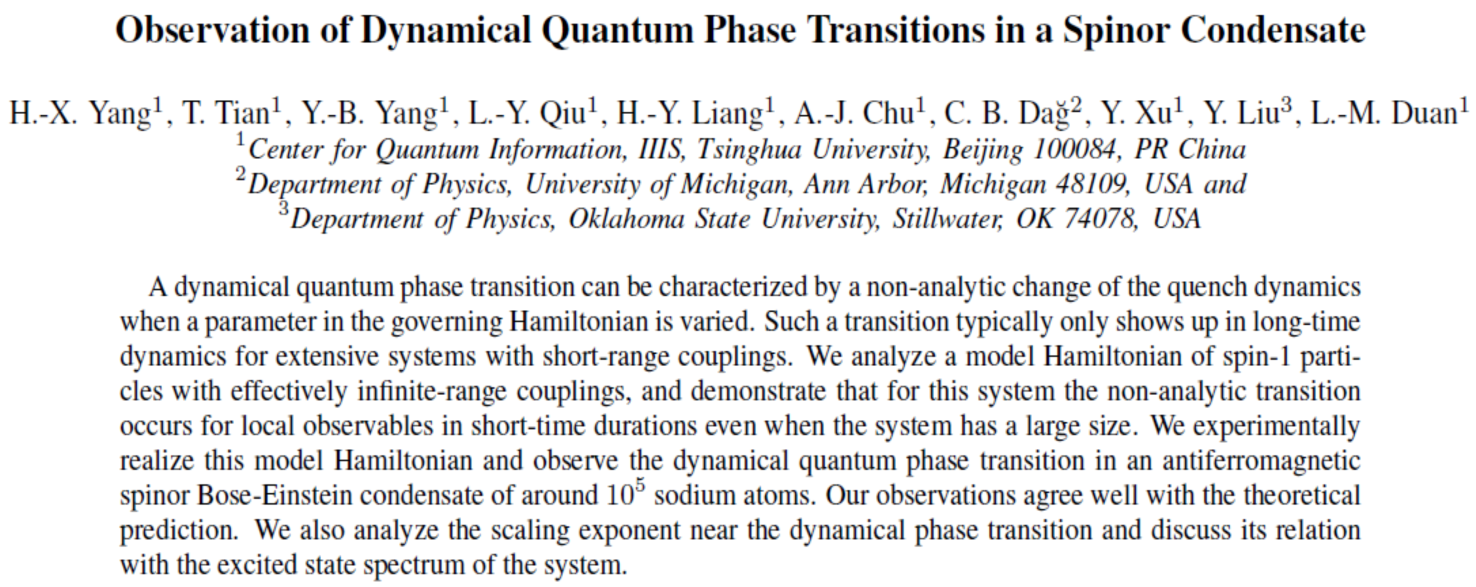
Due to effectively infinite-range couplings

[11] J. Zhang, G. Pagano, P. W. Hess, A. Kyprianidis, P. Becker, H.Kaplan, A. V. Gorshkov, Z.-X. Gong, and C. Monroe, Nature 551, 601 (2017).

[12] H. Bernien, S. Schwartz, A. Keesling, H. Levine, A. Omran, H. Pichler, S. Choi, A. S. Zibrov, M. Endres, M. Greiner, V. Vuleti´c & M. D. Lukin Nature 551, 579 (2017).

Outline

- Introduction of dynamical quantum phase transition (DQPT)
- Theoretical model of spinor-1 BEC
- Experimental results and analysis
- conclusion



Observation of Dynamical Quantum Phase Transitions in a Spinor Condensate

H.-X. Yang[1], T. Tian[1], Y.-B. Yang[1], L.-Y. Qiu[1], H.-Y. Liang[1], A.-J. Chu[1], C. B. Dağ[2], Y. Xu[1], Y. Liu[3], L.-M. Duan[1]
[1]*Center for Quantum Information, IIIS, Tsinghua University, Beijing 100084, PR China*
[2]*Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA and*
[3]*Department of Physics, Oklahoma State University, Stillwater, OK 74078, USA*

A dynamical quantum phase transition can be characterized by a non-analytic change of the quench dynamics when a parameter in the governing Hamiltonian is varied. Such a transition typically only shows up in long-time dynamics for extensive systems with short-range couplings. We analyze a model Hamiltonian of spin-1 particles with effectively infinite-range couplings, and demonstrate that for this system the non-analytic transition occurs for local observables in short-time durations even when the system has a large size. We experimentally realize this model Hamiltonian and observe the dynamical quantum phase transition in an antiferromagnetic spinor Bose-Einstein condensate of around 10^5 sodium atoms. Our observations agree well with the theoretical prediction. We also analyze the scaling exponent near the dynamical phase transition and discuss its relation with the excited state spectrum of the system.

Theoretical model of N spin-1 atoms

Hamitonian (infinite range coupling)

$$\hat{H} = \underbrace{\frac{c_2}{2N}\sum_{1\le i,j\le N}\mathbf{S}_i\cdot\mathbf{S}_j}_{\boxed{\text{Interaction}}} + \underbrace{\sum_{1\le i\le N}(qS_{iz}^2 - pS_{iz})}_{\boxed{\text{Zeeman energy}}}$$

SMA(single mode aproximation) $\hat{H} = c_2\frac{\hat{L}^2}{2N} + \sum_{m=-1}^{1}(qm^2 - pm)\hat{a}_m^\dagger\hat{a}_m$

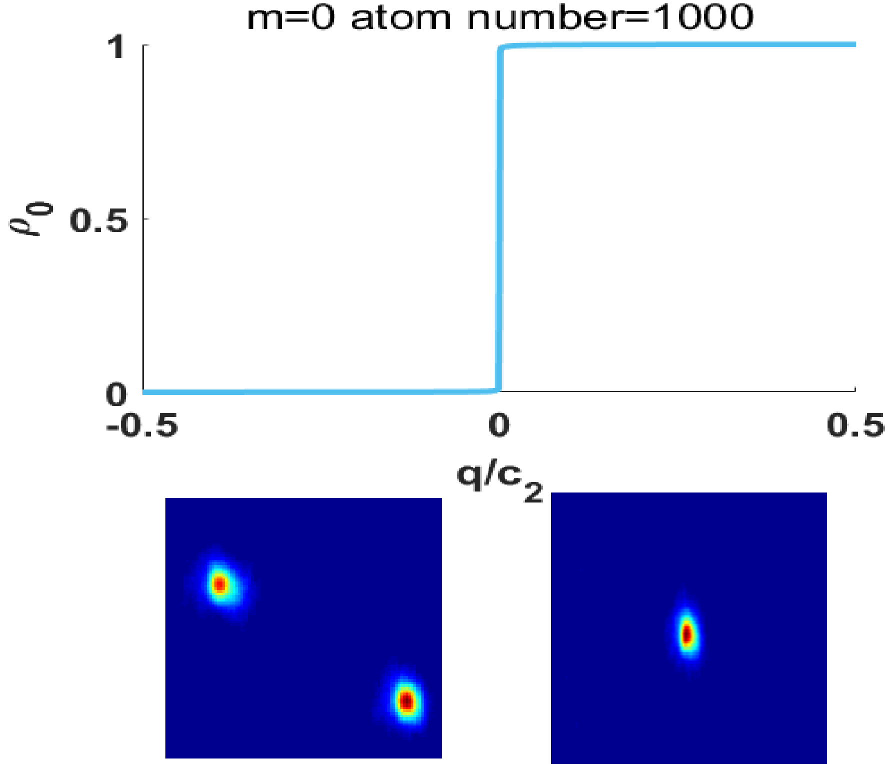
where $\hat{L}_\mu = \sum_{m,n}\hat{a}_m^\dagger(f_\mu)_{mn}\hat{a}_n$ is the BEC's total spin operator (f_μ is the spin-1 angular momentum matrix).

Fraction of spin-m_F component $\rho_{m_F} = \hat{a}_{m_F}^\dagger\hat{a}_{m_F}/N$.

Conservation of the longitudinal magnetization

m= $\rho_1 - \rho_{-1} = 0$ in experiment.

$$(\rho_{-1}, \rho_0, \rho_{+1}) = (0.5 - \rho_0/2, \rho_0, 0.5 - \rho_0/2)$$

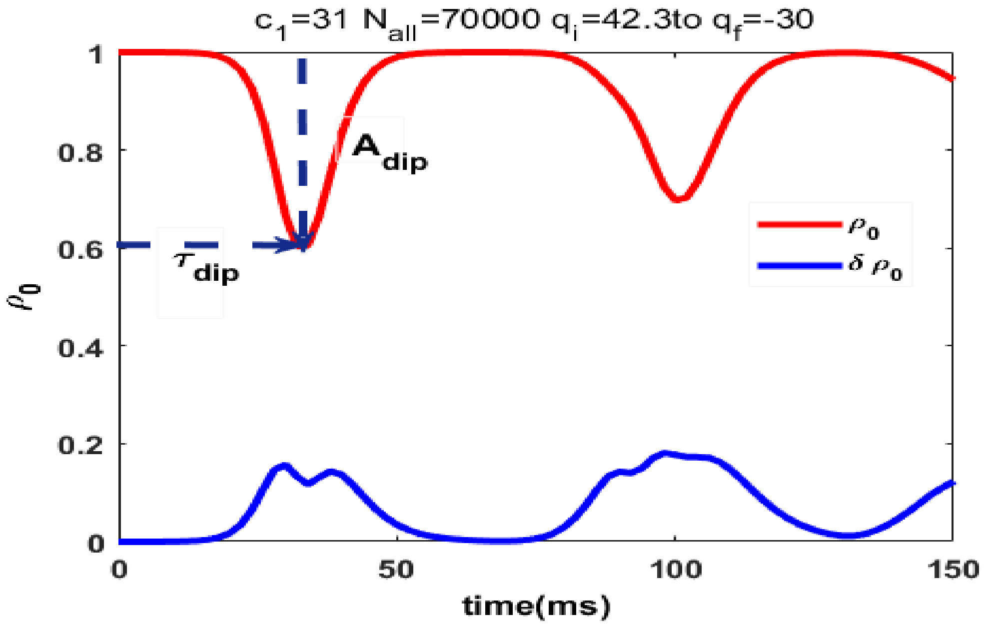


Observables

To simulate the quench dynamics, we numerically diagonalize the model Hamiltonian in the Fock basis |N1, N0, N−1⟩ = |n, N − 2n, n⟩

long-time property $\langle\overline{\rho_0}\rangle_\infty = lim_{T\to\infty}\frac{1}{T}\int_0^T\overline{\rho_0}(t)$

short-time property $A_{dip} \equiv 1 - \overline{\rho_0}(t = \tau_{dip})$



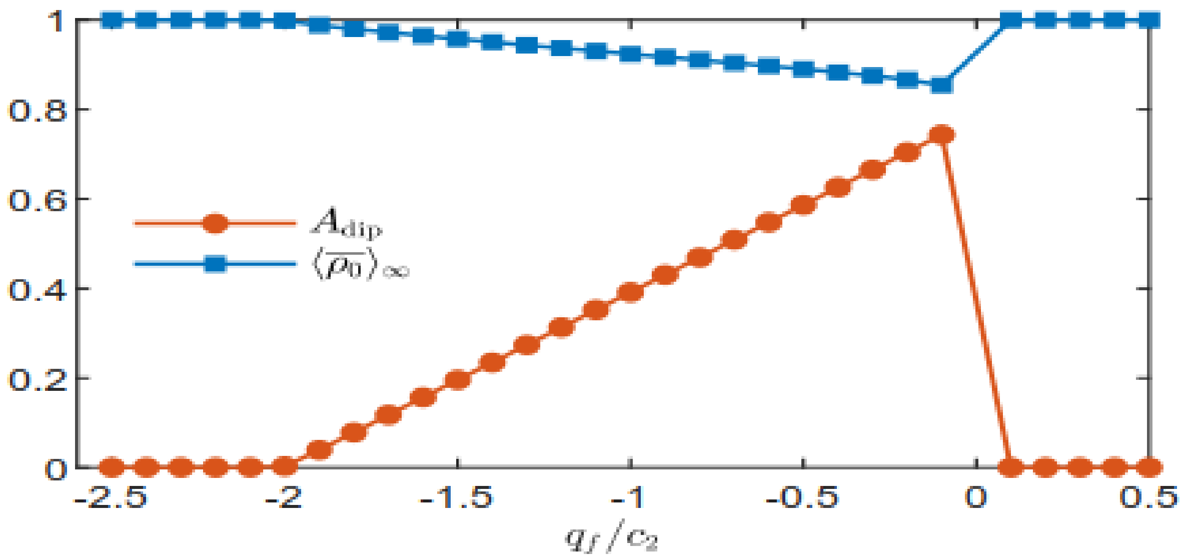
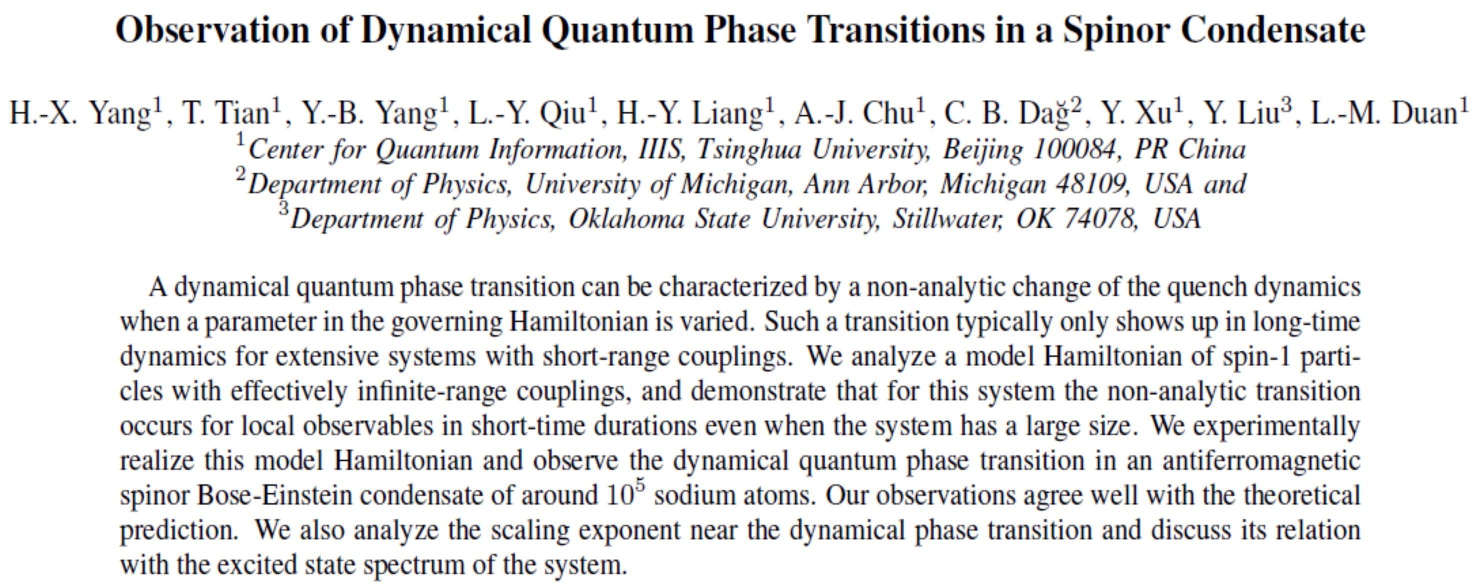


FIG. 1. The predicted $A_{\rm dip}$ (depth of the first dip in spin oscillations) and the long-time average $\langle\overline{\rho_0}\rangle_\infty$ as functions of q_f/c_2 for $N = 1\times10^5$ and $q_i = 0.5c_2$ (see text). It appears that the short-time property $A_{\rm dip}$ and the long-time property $\langle\overline{\rho_0}\rangle_\infty$ both signal DQPTs at the same q_f.

[17] C. B. Dağ, S.-T. Wang, and L.-M. Duan, Phys. Rev. A 97, 023603 (2018).

Outline

- Introduction of dynamical quantum phase transition (DQPT)
- Theoretical model of spinor-1 BEC
- Experimental results and analysis
- conclusion



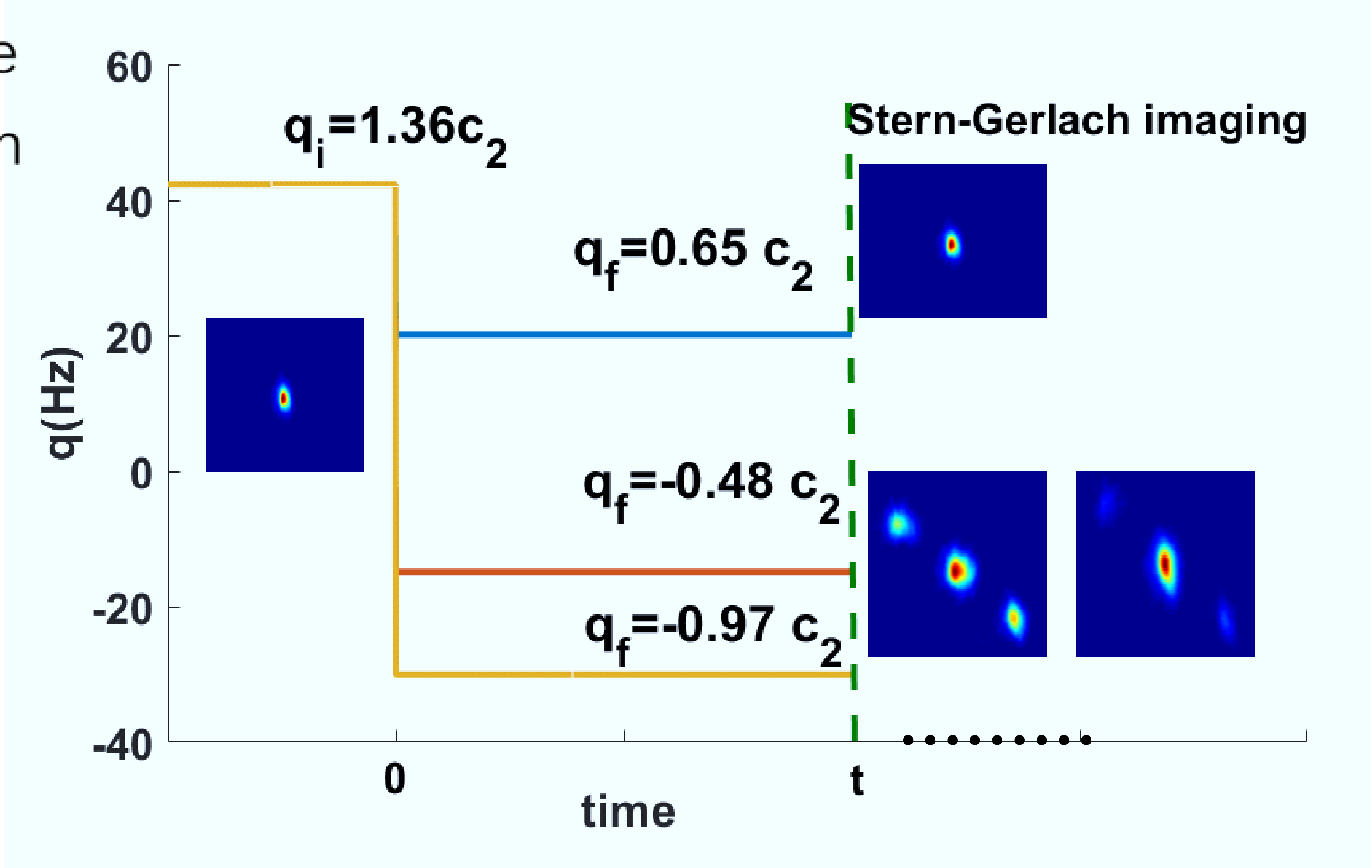
Observation of Dynamical Quantum Phase Transitions in a Spinor Condensate

H.-X. Yang[1], T. Tian[1], Y.-B. Yang[1], L.-Y. Qiu[1], H.-Y. Liang[1], A.-J. Chu[1], C. B. Dağ[2], Y. Xu[1], Y. Liu[3], L.-M. Duan[1]
[1]*Center for Quantum Information, IIIS, Tsinghua University, Beijing 100084, PR China*
[2]*Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA and*
[3]*Department of Physics, Oklahoma State University, Stillwater, OK 74078, USA*

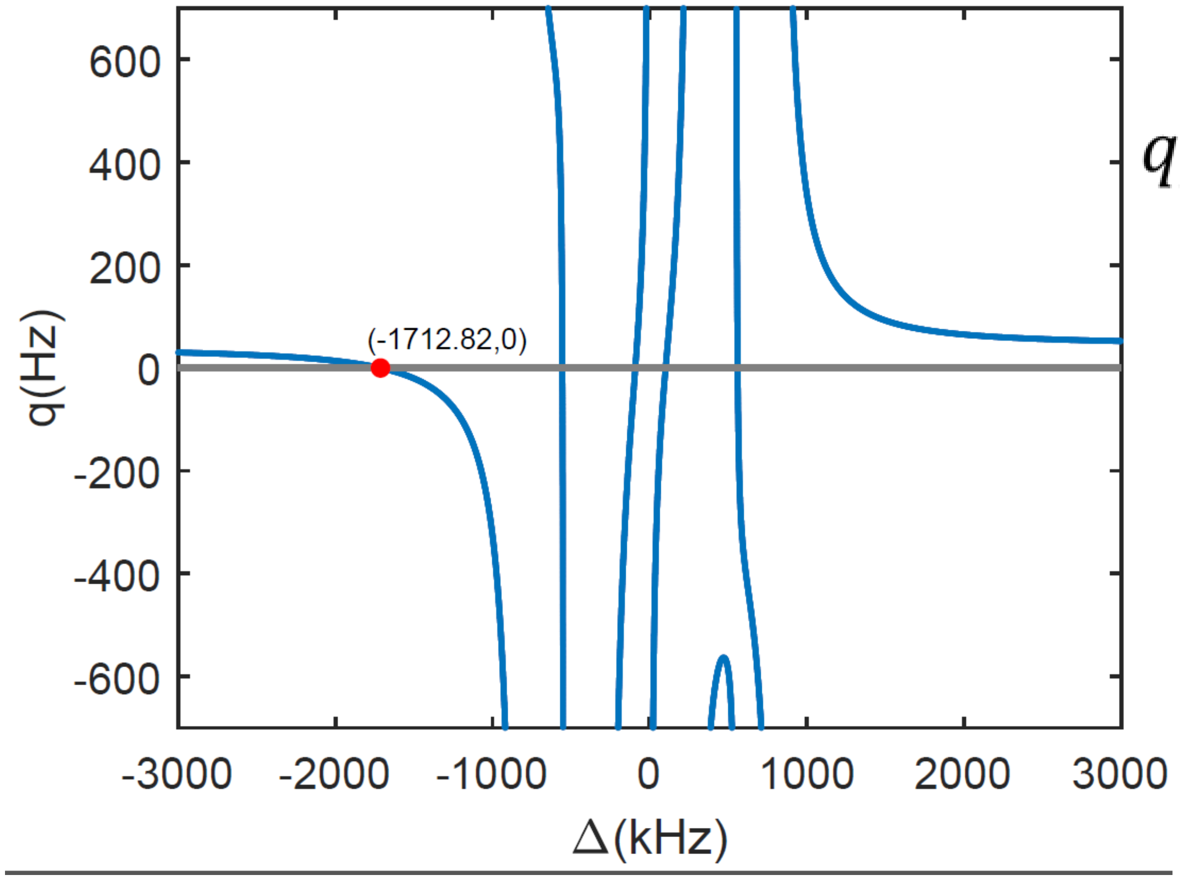
A dynamical quantum phase transition can be characterized by a non-analytic change of the quench dynamics when a parameter in the governing Hamiltonian is varied. Such a transition typically only shows up in long-time dynamics for extensive systems with short-range couplings. We analyze a model Hamiltonian of spin-1 particles with effectively infinite-range couplings, and demonstrate that for this system the non-analytic transition occurs for local observables in short-time durations even when the system has a large size. We experimentally realize this model Hamiltonian and observe the dynamical quantum phase transition in an antiferromagnetic spinor Bose-Einstein condensate of around 10^5 sodium atoms. Our observations agree well with the theoretical prediction. We also analyze the scaling exponent near the dynamical phase transition and discuss its relation with the excited state spectrum of the system.

DQPT experiment procedure

1. Initialize the BEC to ground state
2. At $0ms$, suddenly quench q from q_i to q_f .
3. At t, apply Stern-Gerlach absorption imaging
4. Repeat 80 times to get $\overline{\rho_0} = \langle \hat{a}_0^\dagger \hat{a}_0 \rangle / N$ and $\delta\rho_0$.



Quadratic Zeeman coefficient



quadratic Zeeman coefficient $q = q_B + q_M$

$$q_M = \frac{\delta E|_{m_F=1} + \delta E|_{m_F=-1} - 2\delta E|_{m_F=0}}{2} \qquad (1)$$

$$\begin{aligned}\delta E|_{m_F} &= \frac{h}{4}\sum_{k=0,\pm1}\frac{\Omega^2_{m_F,m_F+k}}{\Delta_{m_F,m_F+k}}\\ &= \frac{h}{4}\sum_{k=0,\pm1}\frac{\Omega^2_{m_F,m_F+k}}{\Delta - [(m_F+k)/2 - (-m_F/2)]\mu_B B}\end{aligned} \qquad (2)$$

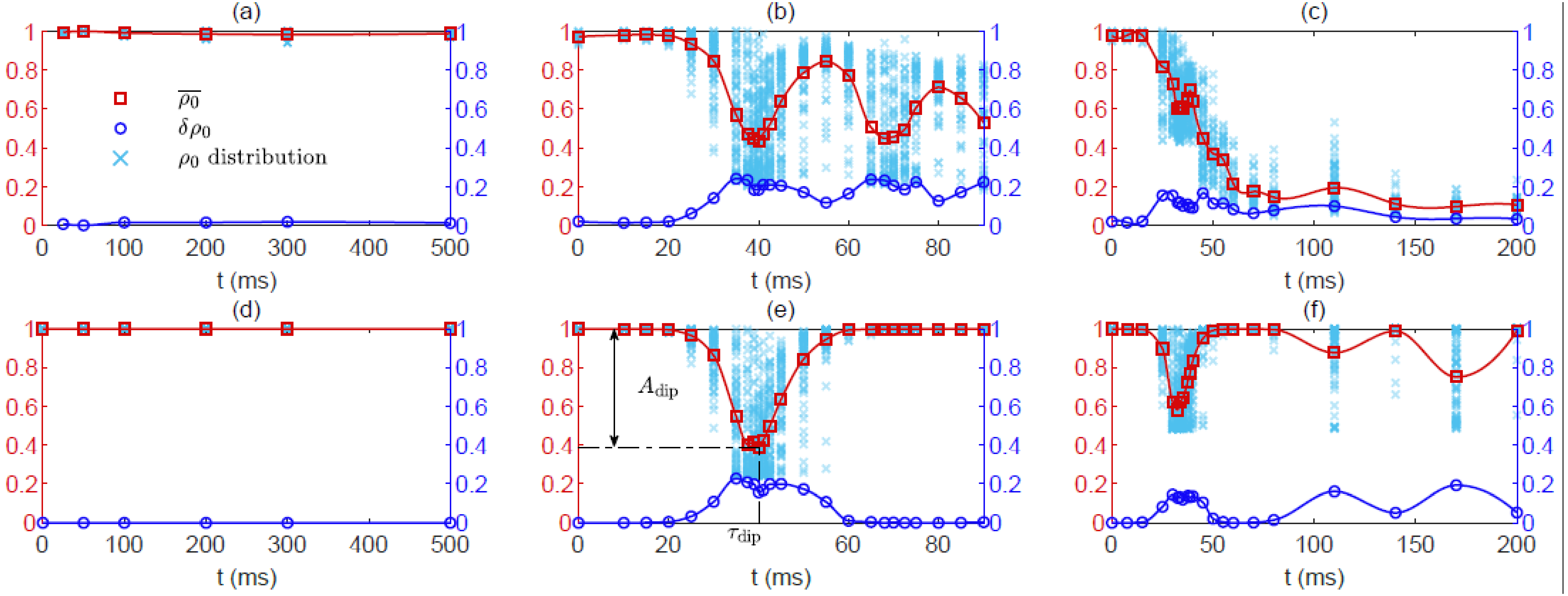
$$\Omega_{-1,-1} = \Omega_{1,1} = \frac{\sqrt{3}}{2}\Omega_{0,0}$$

$$\Omega_{0,1} = \sqrt{3}\Omega_{-1,0} = \frac{1}{\sqrt{2}}\Omega_{1,2}$$

$$\Omega_{0,-1} = \frac{1}{\sqrt{2}}\Omega_{-1,-2} = \sqrt{3}\Omega_{1,0}$$

Experiment & simulation result

$q_f/c_2 = 0.65$ $q_f/c_2 = -0.48$ $q_f/c_2 = -0.97$



A_{dip} versus q_f/c_2.

$\delta\rho_0$ versus q_f/c_2.

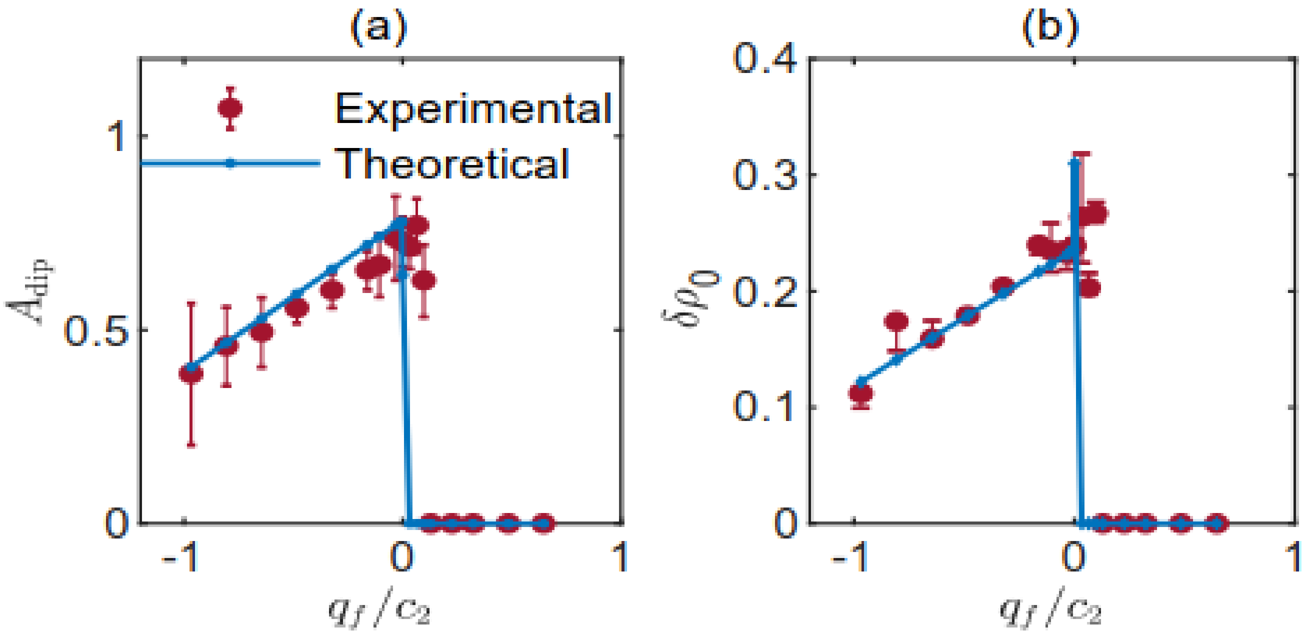


FIG. 3. Observed signatures of DQPTs. (a) The measured A_{dip} versus q_f/c_2. (b) The standard deviation $\delta\rho_0$ at $t=\tau_{\mathrm{dip}}$ versus q_f/c_2. Circles with error bars denote the experimental data and the solid lines represent the theoretical results from numerical simulations of the model Hamiltonian (see text).

τ_{dip} verse q_f/c_2

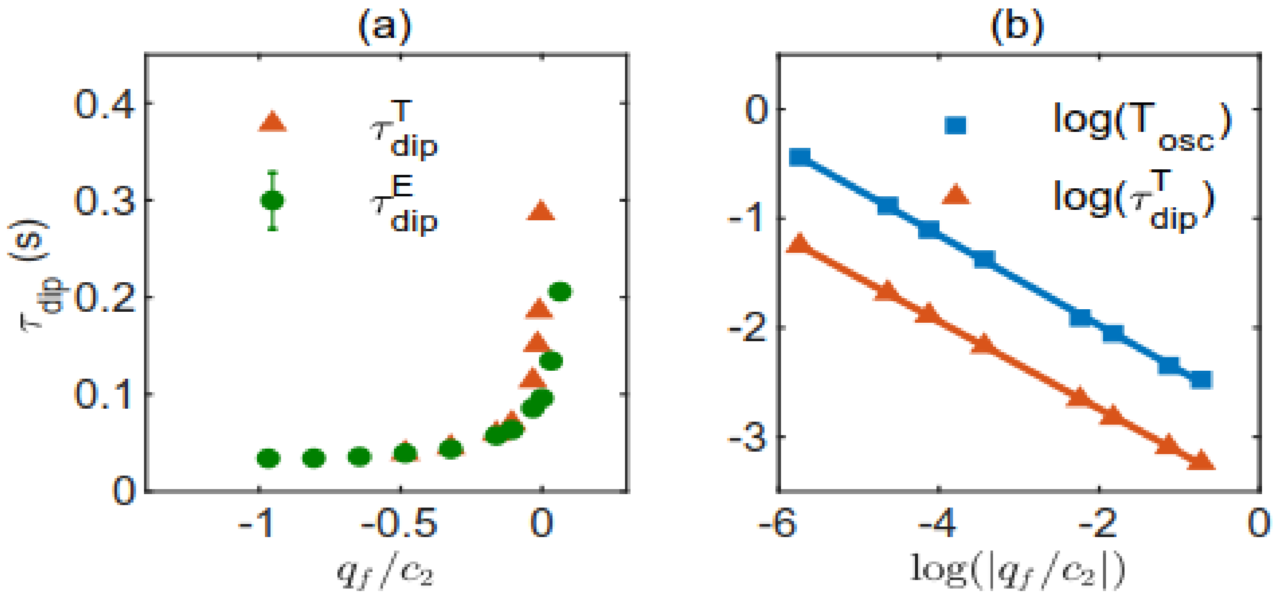


FIG. 4. (a) Circles (triangles) represent the observed occurrence time of the first dip (the corresponding theoretical results derived from numerical simulations) as a function of q_f/c_2. (b) The power law scaling of the theoretical dip time $\tau^T_{\rm dip}$ and $T_{\rm osc}$ (the inverse of the relevant energy gap) in a log-log diagram. The extracted critical exponents for $T_{\rm osc}$ and $\tau^T_{\rm dip}$ are respectively -0.41 and -0.40, based on linear fits (denoted by the solid lines) to the log-log curves.

Microwave induced relaxation and (negligible) atom loss

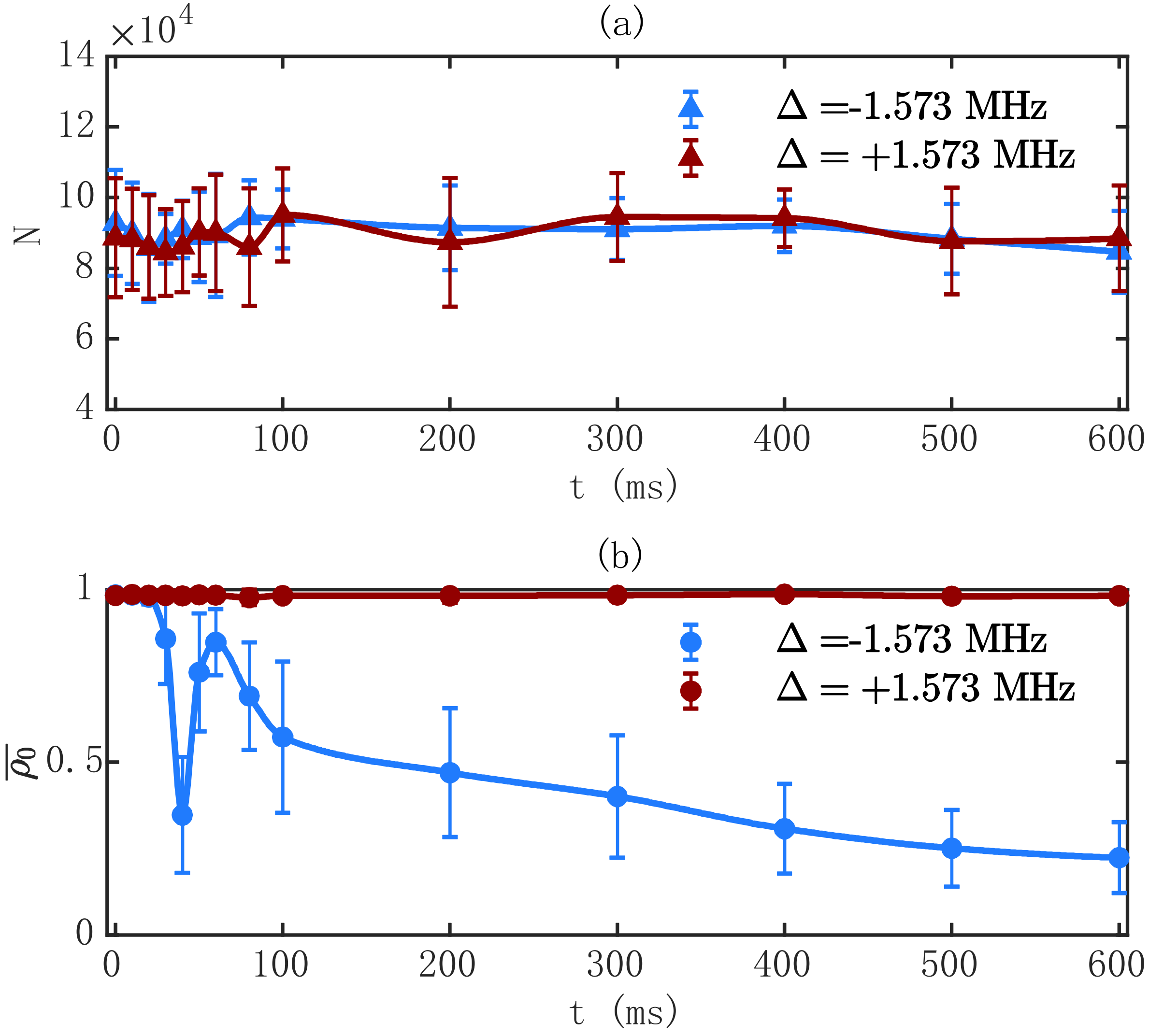
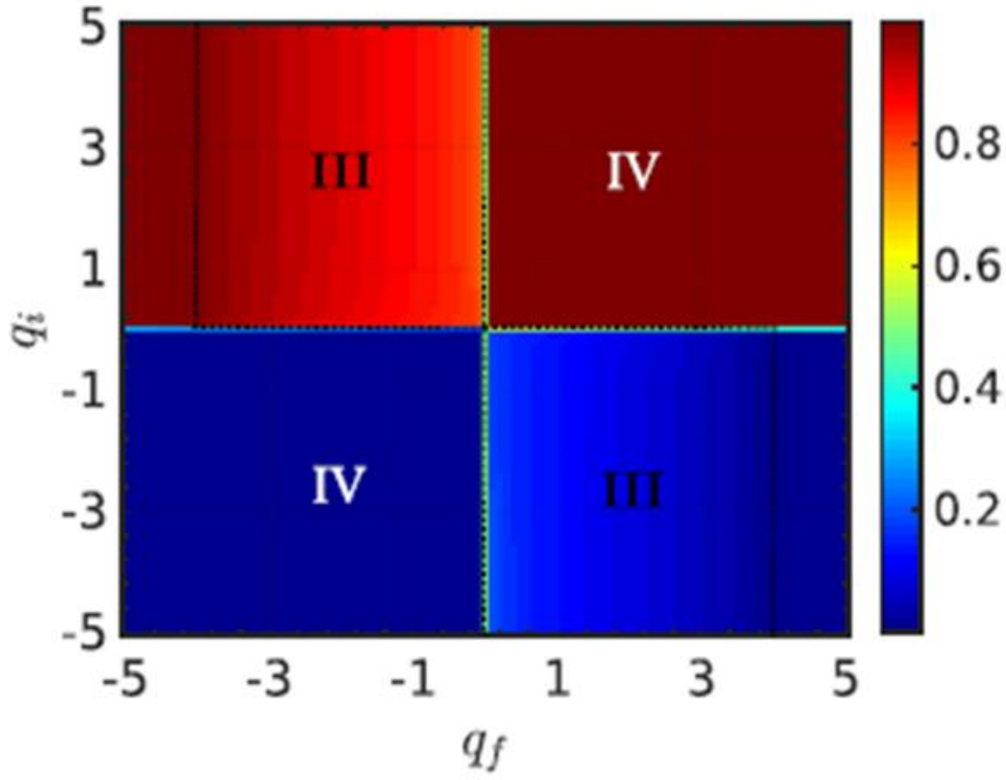


FIG. 5. Time evolutions of N (a) and $\overline{\rho_0}$ (b) observed in contrast experiments with two carefully-chosen microwave pulses at $c_2/h = 34\,\mathrm{Hz}$. The two pulses have the same intensity but opposite frequency detunings of $\Delta = \pm 1.573$ MHz, which induce different microwave dressing fields of $q_f/c_2 = -0.36$ for $\Delta = -1.573$ MHz and $q_f/c_2 = 2.53$ for $\Delta = +1.573$ MHz.

We attribute this to the breakdown of the SMA for the atomic motional state: the atoms in this case are in significantly excited states of the spin Hamiltonian and their energy can relax to the motional state through the spin-dependent collisions and thus invalidate the prediction from the single-mode Hamiltonian (2) in the long-time dynamics.

Conclusion

- observed a DQPT associated with an interacting model Hamiltonian of spin-1 particles with effectively infinite-range couplings.
- the DQPTs can be identified by short-time dynamical properties of local observables, which enables its detection in a large spinor condensate, saving it from the complication of long-time relaxation dynamics inevitable in open quantum many-body systems.



DQPT diagram for anti-ferromagnetic spinor-1 BEC

Thanks for your attention