Condensed matter physics with synthetic matter

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Happy birthday Shoucheng !
New directions

**Ultracold atoms**

Hubbard models in optical lattice
Challenge: cooling to reach magnetism/pairing

Measurements of nonlocal correlations
String order parameters, entanglement entropy

Systems with long range interactions
Polar molecules, Rydberg atoms, ion chains
Challenge: new states, quantum phase transitions

Systems with artificial gauge fields
Challenge: how to probe topological states

Nonequilibrium dynamics
Quenches, ramps in many-body systems, system-bath dynamics
New directions

Strongly nonlinear optical systems

1d systems. Nonlinearities at two photon level
Challenge: nonequilibrium dynamics of many-body systems with dissipation

Arrays of optical and/or microwave cavities
Challenge: nonequilibrium dynamics of open many-body systems
New directions

Atom like systems

Electron spins in quantum dots

NV centers in diamond

Superconducting Qbits and Two Level Systems

Challenge: dynamics of central spin models.

Anomalous spin diffusion. Many-body localization
Ultracold atoms. Nonequilibrium dynamics
Ultracold atoms. Dynamics of mobile impurity
Ultracold atoms. Dynamics of mobile impurity

\[ H_{\text{imp}} = \frac{p^2}{2M} + V_{\text{conf}}(x) + \omega_0 \sigma_z \]

\[ H_{\text{drive}} = \Omega_0 e^{i \omega t} \sigma_+ + \text{c.c.} \]

\[ H_{\text{int}} = \left( g_{\uparrow} \rho_{\uparrow} + g_{\downarrow} \rho_{\downarrow} \right) \sum_q e^{-i q \cdot x} \rho_q \]

Fermion bath

\[ H_R = \sum \epsilon_k c_k^+ c_k \]

\[ \rho_q = \sum c_{k+q}^+ c_k \]

Boson bath

\[ H_k = \sum \omega_k \gamma_k^+ \gamma_k \]

\[ \rho_q = f_q (\gamma_q^+ + \gamma_q^-) \]

Challenge: understand dynamics

Connection to orthogonality catastrophe, polarons, quasiparticles in strongly correlated electron systems
Ultracold atoms. Dynamics of mobile impurity

Metastability and Coherence of Repulsive Polarons in a Strongly Interacting Fermi Mixture


RF spectroscopy

Rabi oscillations

![Diagram of RF spectroscopy](image)

![Diagram of Rabi oscillations](image)
Atom-like systems.
Nonequilibrium quantum dynamics.
Many-body localization
Atom like systems. NV centers in diamond

Fluorescence of an array of single impurities in diamond

Nitrogen + Vacancy impurity in diamond
NV centers in diamond. Central spin problem

\[ H_2 = g_e \mathbf{S} \cdot \mathbf{h}(R_e) + g_n \sum_i \mathbf{\sigma}_i \cdot \mathbf{h}(r_i) \]

\[ H_{\text{int}} = \sum_i \mathbf{S}_i \cdot \mathbf{\sigma}_i \cdot V_d (R_e - r_i) + \sum_{ij} \mathbf{\sigma}_i \cdot \mathbf{\sigma}_j \cdot V_d (r_i - r_j) \]
NV centers in diamond. Random spin systems

Use electron spin to manipulate and measure individual nuclear spins

Use RF pulses to manipulate spin interactions

\[ \hat{H} = \sum \frac{A}{r_{ij}^3} \mathbf{\hat{z}}_i \mathbf{\hat{z}}_j + \sum \frac{B}{r_{ij}^6} \left( \mathbf{\hat{x}}_i \mathbf{\hat{x}}_j + \mathbf{\hat{y}}_i \mathbf{\hat{y}}_j \right) + \sum h_i \mathbf{\hat{z}}_i \]

Open questions:
- Anomalous spin diffusion at high T
- Many-body localization
How to probe correlation functions

\[ \hat{H} = \sum \frac{A}{r_{ij}^3} \sigma_i^z \sigma_j^z + \sum \frac{B}{r_{ij}^6} (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) + \sum h_i \sigma_i^z \]

Model with conserved Sz

\[
\begin{align*}
\langle \psi_0 | (1 + i \sigma_i^y) e^{iHT} e^{-iHT} (1 - i \sigma_i^y) | \psi_0 \rangle & \\
\langle \psi_0 | \sigma_i^y e^{iHT} \sigma_i^y e^{-iHT} | \psi_0 \rangle - \langle \psi_0 | e^{iHT} \sigma_i^y e^{-iHT} \sigma_i^y | \psi_0 \rangle & \\
\langle \psi_0 | \delta_i^y (0) \delta_i^y (t) - \delta_i^y (t) \delta_i^y (0) | \psi_0 \rangle & 
\end{align*}
\]

Retarded Green’s function
How to probe nature of excitations

\[ \tilde{\mathcal{H}} = \sum \frac{A}{r_{ij}^3} \sigma_i^z \sigma_j^z + \sum \frac{B}{r_{ij}^2} (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) + \sum h_i \sigma_i^z \]

Retarded Green’s function

\[ \langle \Psi_0 \mid \sigma_i^y(0) \sigma_i^y(t) - \sigma_i^y(t) \sigma_i^y(0) \mid \Psi_0 \rangle \]

T=0 delocalized phase

\[ \langle \sigma_i^y(t) \sigma_i^y(0) \rangle \]

T=0 localized phase

Does not work at finite T. Dephasing gives decay
How to detect many-body localization

\[ \tilde{\mathcal{H}} = \sum \frac{A}{r_{ij}^3} \sigma_i^z \sigma_j^z + \sum \frac{B}{r_{ij}} \left( \sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y \right) + \sum h_i \sigma_i^z \]

\[ \tilde{\mathcal{H}}_{\text{eff}} = \sum J_{ij} \tilde{\sigma}_i^z \tilde{\sigma}_j^z \]

Spin echo

\[ \langle \psi_0 | (1 + i \delta_i^y) e^{i H \frac{t}{2}} \delta_i^y e^{i H \frac{t}{2}} \delta_i^y e^{-i H \frac{t}{2}} \delta_i^y e^{-i H \frac{t}{2}} (1 - i \delta_i^y) | \psi_0 \rangle \]

Observe revival
Ultracold atoms.
How to probe topological order
Order parameters

Magnetization - order parameter in ferromagnets

How to measure topological order parameter?

Berry/Zak phase in 1d

\[ P = \frac{e}{\pi} \int A(k) \, dk \]

\[ A(k) = \sum_n \langle u_n(k) | \partial_k | u_n(k) \rangle \]

Measure the Berry/Zak phase itself, not its consequence

\[ P = \frac{\text{dipole moment}}{\text{length}} \]

Vanderbilt, King-Smith
PRB 1993
SSH model in bichromatic lattices

Su, Schrieffer, Heeger, 1979

\[ H = \sum_{i} (t + \delta t)c_{Ai}^\dagger c_{Bi} + (t - \delta t)c_{Ai+1}^\dagger c_{Bi} + h.c. \]

Analogous to bichromatic optical lattice potential

I. Bloch et al., LMU/MPQ
Tools of atomic physics: Bloch oscillations

\[ \frac{dk}{dt} = F \]

C. Salomon et al., PRL (1996)

FIG. 2. Bloch oscillations of atoms: momentum distributions in the accelerated frame for equidistant values of the acceleration time \( t_a \) between \( t_a = 0 \) and \( t_a = \tau_B = 8.2 \) ms. The light potential depth is \( U_0 = 2.3 E_R \) and the acceleration is \( a = -0.85 \) m/s\(^2\). The small peak in the right wing of the first five spectra is an artifact.
Tools of atomic physics: Ramsey interference

\[ \frac{\pi}{2} \text{ pulse} \]

\[ | \downarrow \rangle \rightarrow \frac{1}{\sqrt{2}} | \downarrow \rangle + \frac{1}{\sqrt{2}} | \uparrow \rangle \]

\[ \Psi(t) \rangle = \frac{1}{\sqrt{2}} e^{-i\mathcal{H}_\downarrow t} | \downarrow \rangle + \frac{1}{\sqrt{2}} e^{-i\mathcal{H}_\uparrow t} | \uparrow \rangle \]

\[ \frac{\pi}{2} \text{ pulse} + \text{ measurement of } S_z \text{ gives relative phase accumulated by the two spin components} \]

Used for atomic clocks, gravitometers, accelerometers, magnetic field measurements
Characterizing SSH model using Zak phase

Two hyperfine spin states experience the same optical potential

\[ \varphi_{\text{tot}} = \varphi_{\text{Zak}} + \varphi_{\text{dyn}} + \varphi_{\text{Zeeman}} \]

Problem: experimentally difficult to control Zeeman phase shift
Spin echo protocol for measuring Zak phase

Dynamic phases due to dispersion and magnetic field fluctuations cancel. Interference measures the difference of Zak phases of the two bands in two dimerizations.

Expect phase $p$
Bloch oscillations measurements

With p-pulse but no swapping of dimerization
Bloch oscillations measurements
With p-pulse and with swapping of dimerization
Zak/Berry phase measurements

\[ \delta \varphi = 0.97(2) \pi \]
How to measure Berry/Zak phases in 2D
Relation to Chern number

Measure Zak phase for different initial points in the primitive cell

\[ z(\alpha_2) = e^{-i\varphi_B(\alpha_2)} \]

This gives topological flux density in momentum space

Full winding of \( z \) gives Chern number of BZ

\[ c = -\frac{i}{2\pi} \int_0^1 d\alpha_2 \tilde{z}(\alpha_2) \partial_{\alpha_2} z(\alpha_2) \]
Outlook: measuring topological properties of many-body states
Outlook: measuring topological properties of many-body states
Summary:
Condensed matter physics with synthetic matter

New exotic many-body states

New ways of characterizing correlations

Understanding nonequilibrium dynamics of quantum many-body states

Nonequilibrium dynamics of open quantum many-body systems