Tunable Wigner states with dipolar atoms and molecules

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Wigner localization
- *Particle localization induced by long-range repulsive interactions*

Quantum mechanical particles prefer to spread out as much as possible to minimize kinetic energy.

But sufficiently strong long-range repulsive interactions may cause particles to localize at individual positions.

Electrostatic Coulomb interaction between ions:

\[
V(r_1, r_2) = \frac{e^2}{4\pi \varepsilon_0 \varepsilon_r} \frac{1}{|r_1 - r_2|}
\]

*Trapped ultra-cold ions*

ultra-cold atomic (or molecular) gas

interaction:
- short-range van der Waals
- long-range dipole-dipole for some particles

Bose-Einstein condensate

periodic potentials (lattices), few particles in each well
Ultra-cold few-body systems

periodic potentials (lattices), few particles in each well

recently developed "micro-trap", handles few particles
The dipole-dipole interaction depends both on the distance between the particles, but also their relative orientation:

Attraction may give collapse, but quasi-2D confinement + external aligning field could stabilize system

Realized with dysprosium atoms, see Lu et al., arXiv:1108.5993v2

Figures from Lahaye, Menotti, Santos, Lewenstein, Pfau, Rep. Prog. Phys. 72, 126401 (2009)
Ultra-cold dipolar atoms or molecules

- particles in quasi-2D confinement
- dipole-dipole interaction
- dipoles aligned to external field (forms angle $\Theta$ with plane)

$\Theta = 55^\circ$, $\Theta = 90^\circ$

-> tunable anisotropic interaction

contours of interaction potential
19 classical point-particle dipoles

\[ D = \text{interaction strength} \]

19 classical point particles, with dipole-dipole interaction, in 2D harmonic trap
Interaction for quantum particles

- assume tight trap in $z$-direction, with no $z$-nodes in wavefunction
- integration along $z$ gives effective in-plane interaction
- we ignore any short-range interactions
Results with 3 quantum mechanical particles

- trapped atoms or molecules with dipolar interactions
- dipole moments aligned to external field
- quasi-2D trap gives anisotropic interaction

Schematic setup:

\[ D = \text{interaction strength (dipole moment)} \]

Tunable Wigner states, due to tunable anisotropic interaction.
Results with 3 quantum mechanical particles

Crossing for fermions, anti-crossing for bosons.

$D = \text{interaction strength}$
Wigner localized dipoles: Parities

\[ P_x : (x,y) \rightarrow (-x,y) \]
\[ P_y : (x,y) \rightarrow (x,-y) \]

The Hamiltonian, and its eigenstates, have conserved mirror-parities. Here, a parity flip may correspond to exchanging two particles, so parity gets connected to the many-body (anti-)symmetry.

Crossing for fermions, anti-crossing for bosons.

\[ D = \text{interaction strength} \]
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