Superfluidity and Emergent Structure in Scalar and Binary Dipolar Bose Gases

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Abstract
Recent experimental advances in cooling dipolar atoms and molecules have generated considerable interest in such systems, which present an ideal platform for the study of strong interactions in quantum degenerate matter. Here, we consider the role of dipolar interactions in single (scalar) and binary patterned Bose condensates. When polarized, the dipolar interactions can drive such systems to energetic collapse, so we treat a reduced geometry where a tight trapping potential exists parallel (or near parallel) to the polarization direction, restricting the system to a zero-point motion in this direction. For gases with sufficiently strong interactions, such "quasi" two-dimensional geometries introduce roton-maxon character in the quasiparticle dispersion relation. Interestingly, the roton emerges in both the density- and spin-dimensional geometries introduce roton-maxon character in the quasiparticle dispersion relation. We demonstrate how such rotons play a critical role in the ground state and dynamic superfluid properties of these systems. Whereas the superfluid critical velocity and vortex-antivortex pair production mechanism show strong dependence on the roton in the scalar condensate, the spin-wave roton introduces novel instabilities and emergent patterned immiscible phases of the binary condensate. Additionally, we show how rotons can be made strongly anisotropic by tilting the dipole polarization field, resulting in anisotropic superfluidity and striped phases in the scalar and binary systems, respectively.

Dipole-dipole interaction
Two-body interaction potential: $V_{dd}(\vec{r}_1, \vec{r}_2) = g_{dd}(\vec{r}_1, \vec{r}_2) + d_1 d_2 \frac{1 - 3 \cos^2(\theta)}{\vec{r}_1 \cdot \vec{r}_2}$

Candidate species
- $^{23}$Na: $g_{dd} = 1 \times 10^{-6}$
- $^{87}$Rb: $g_{dd} = 1 \times 10^{-6}$
- $^{85}$Rb: $g_{dd} = 2 \times 10^{-7}$
- $^{39}$K: $g_{dd} = 5 \times 10^{-7}$

Dipole length
- $d_1 = 2.6 \, \text{nm}$
- $d_2 = 4.2 \, \text{nm}$

Hamiltonian
$\hat{H} = \sum \int d^3 \phi (\vec{r}) \left( \frac{1}{2} \nabla^2 \phi + \frac{4}{\hbar^2} m \phi^2 \right) + \sum \int d^3 \phi (\vec{r}) \left( V_{dd}(\vec{r}) \phi^2(\vec{r}) \right) + \sum \int d^3 \phi (\vec{r}) \left( V_{ex}(\vec{r}) \phi(\vec{r}) \right)$

Bose field operator
- Bogoliubov decomposition (T=0):

Scalar condensate
3D geometry (large trap)
Quasiparticle dispersion
- $\omega = \sqrt{\frac{k^2}{2 \mu} + \frac{\hbar^2 k^2}{2m}}$
- $\Delta = \sum_{\alpha} \frac{\hbar^2 k^2}{2m} \phi_\alpha(0)$

Quasi-2D geometry (tight axial trap)
Quasiparticle dispersion
- $\omega = \sqrt{\frac{k^2}{2 \mu} + \frac{\hbar^2 k^2}{2m} + \frac{4k^4}{M}}$
- $\Delta = \sum_{\alpha} \frac{\hbar^2 k^2}{2m} \phi_\alpha(0)$

Binary condensate
- $\alpha, \beta = 1, 2$

Anisotropic Superfluidity
2D energy
- Anisotropic quasiparticle dispersion [1]
- $\nu = \sqrt{\frac{\hbar^2 k^2}{2m} + \frac{\hbar^2 k^2}{2m} + \frac{4k^4}{M}}$
- $\Delta = \sum_{\alpha} \frac{\hbar^2 k^2}{2m} \phi_\alpha(0)$

Anisotropic vortex pair production
- $U_{\alpha} > \mu$ slower
- $U_{\alpha} < \mu$ faster
- $A_1^\alpha$ single-particle Hamiltonian
- $B_{22}^\alpha = \frac{\hbar^2}{2M} \alpha^2 - \frac{\hbar^2 k^2}{2m}$
- $\phi_\alpha(\vec{r}) = \phi(\vec{r}) + \phi(\vec{r})$
- $\phi(\vec{r})$ condensate field (c-number)
- $\phi(\vec{r})$ quantum fluctuation (diagonalize for quasiparticle spectrum)

Bogoliubov decomposition
- $\hat{V}(\vec{r}, \vec{r}') = \int d^3 \phi (\vec{r}) \int d^3 \phi (\vec{r}') \hat{\phi} (\vec{r}) \hat{\phi} (\vec{r}')$