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 dipolar 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-wave dispersions of the binary condensate. 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 bistabilities 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: $V_{\alpha\beta}(\vec{r}_1-\vec{r}_2)=g_{\alpha\beta}\delta(\vec{r}_1-\vec{r}_2)+d_\alpha d_\beta\frac{1-3\cos(\theta)^2}{|\vec{r}_1-\vec{r}_2|^3}$

Candidate species

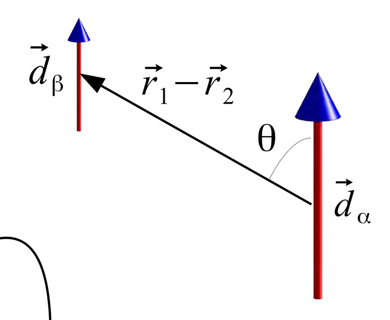
Species	Dipole Moment	a_{dd} (a_0)
^{87}Rb	1 μ_B	0.71
^{52}Cr	6 μ_B	15.36
^{164}Dy	10 μ_B	134.57
^{41}K^{87}Rb	0.57 Debye	3.940×10^3
^{87}Rb^{133}Cs	1.25 Debye	3.257×10^4
^{232}Th^{16}O	3.89 Debye	3.556×10^5

Dipole length

$b_{\alpha\beta}=\frac{M\,d_\alpha d_\beta}{3\hbar^2}$

$g_{\alpha\beta}=\frac{2\pi\hbar^2 a_{\alpha\beta}}{M_{\alpha\beta}}$

s-wave scattering length



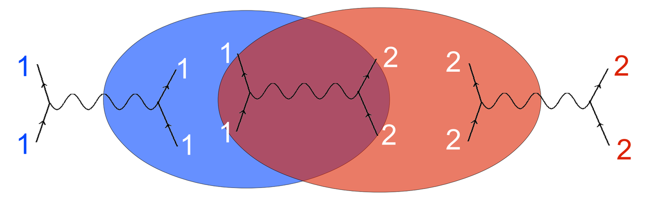
Hamiltonian

$$\hat{H}=\sum_\alpha\int d\vec{r}\,\hat{\psi}^\dagger_\alpha(\vec{r})\hat{H}^{(1)}_\alpha(\vec{r})\hat{\psi}_\alpha(\vec{r})+\frac{1}{2}\sum_{\alpha\beta}\int d\vec{r}\int d\vec{r}\,'\hat{\psi}^\dagger_\alpha(\vec{r})\hat{\psi}^\dagger_\beta(\vec{r}\,')V_{\alpha\beta}(\vec{r}-\vec{r}\,')\hat{\psi}_\beta(\vec{r}\,')\hat{\psi}_\alpha(\vec{r})$$

Bose field operator

Single-particle Hamiltonian

$$\hat{H}^{(1)}_\alpha(\vec{r})=-\frac{\hbar^2}{2M_\alpha}\nabla^2+\frac{1}{2}M_\alpha(\omega_z^2 z^2+\omega_\rho^2\rho^2)$$



No exchange interaction! (two Goldstone modes)

Condensate field (c-number)

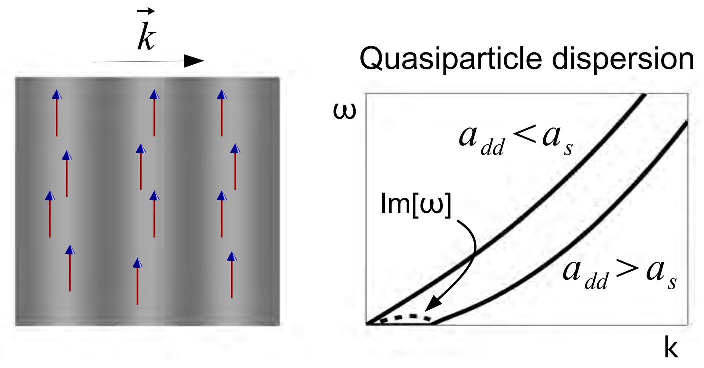
Bogoliubov decomposition (T=0): $\hat{\psi}_\alpha(\vec{r})\rightarrow\phi_\alpha(\vec{r})+\hat{\varphi}_\alpha(\vec{r})$

Quantum fluctuations (diagonalize for quasiparticle spectrum)

Scalar condensate

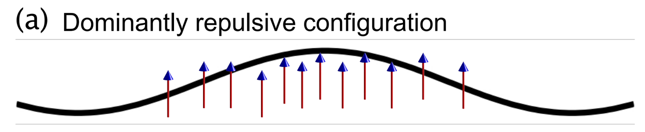
$(\alpha=\beta)$

3D geometry (large trap)

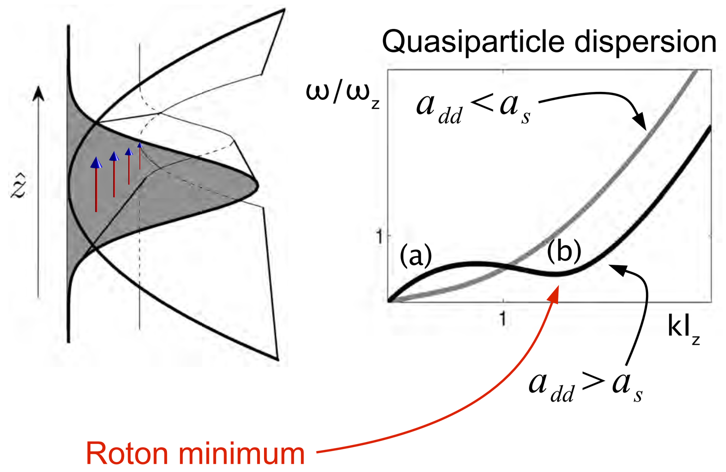


- Anisotropic sound propagation
- Phonon instability when $a_{dd}>a_s$
- *No* dominantly dipolar condensates

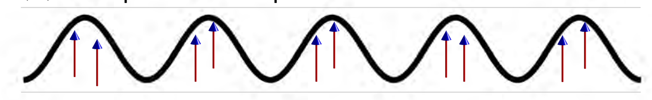
(a) Dominantly repulsive configuration



Quasi-2D geometry (tight axial trap)

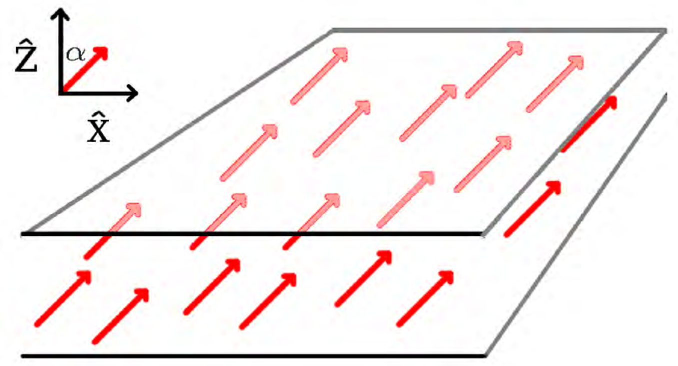


(b) Sample attractive part of interaction

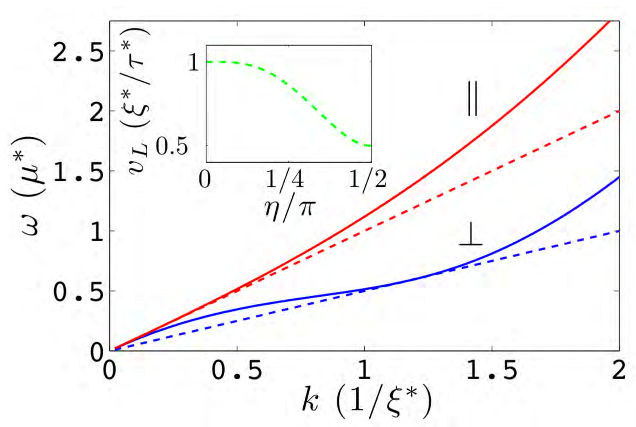


Anisotropic Superfluidity

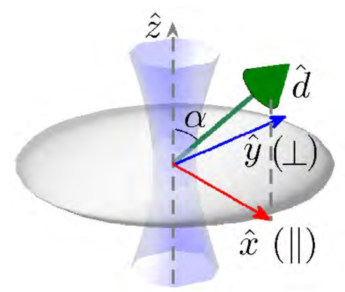
Dipoles tilted off of trap axis



Anisotropic quasiparticle dispersion [1]



Use blue-detuned laser as probe of superfluidity

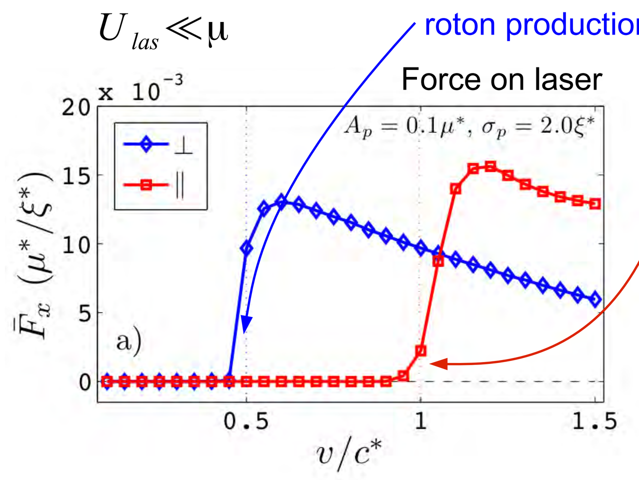


Landau criterion for superfluidity

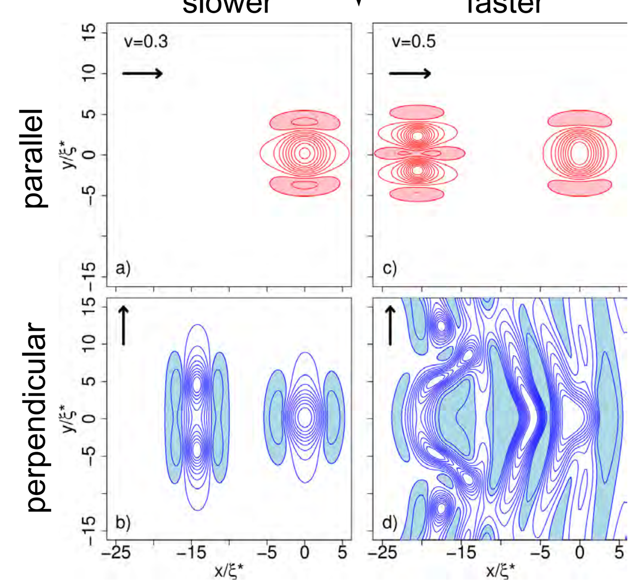
$v_L=min\left(\frac{\omega(k)}{k}\right)$

Anisotropic vortex pair production

$U_{las}\ll\mu$



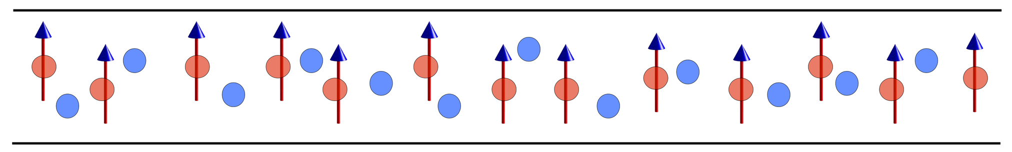
$U_{las}>\mu$



$\vec{F}(\vec{\rho},t)=-\int d\vec{\rho}\,|\phi(\vec{\rho},t)|^2\vec{\nabla}U_{las}(\vec{\rho},t)$

Binary condensate

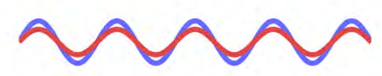
$(\alpha,\beta=1,2)$



$$\omega^2_\pm(\vec{k})=\frac{1}{2}\left(\omega_1^2(\vec{k})+\omega_2^2(\vec{k})\pm\sqrt{(\omega_1^2(\vec{k})-\omega_2^2(\vec{k}))^2+\frac{4k^2}{M_1M_2}n_1n_2\tilde{V}^2_{12}(\vec{k})}\right)$$

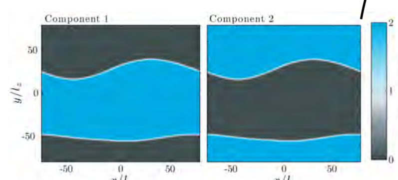
Density waves

"Spin" waves

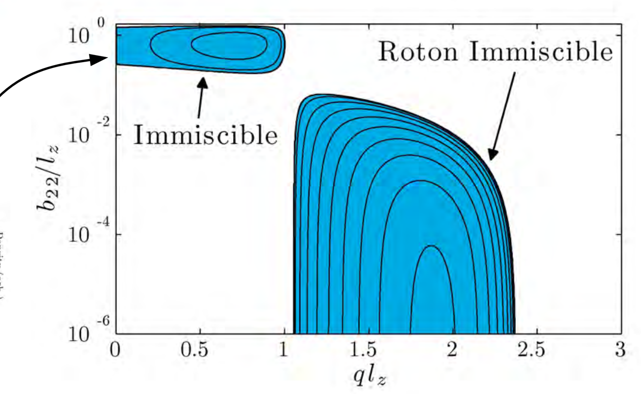


$a_{11}=a_{22}<a_{12}$

$b_{11}=b_{22}=\frac{2}{3}a_{11}$

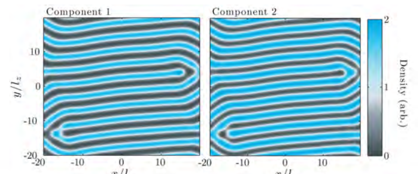


Imaginary part of Bogoliubov spin wave



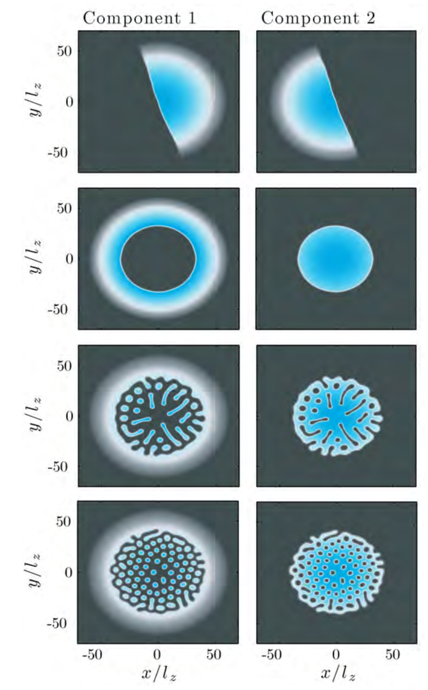
$a_{11}=a_{22}<a_{12}$

$b_{22}=0\quad b_{11}=\frac{2}{3}a_{11}$



Radial trap $(b_{22}=0)$

$(b_{22}=0)$



$b_{11}=0$

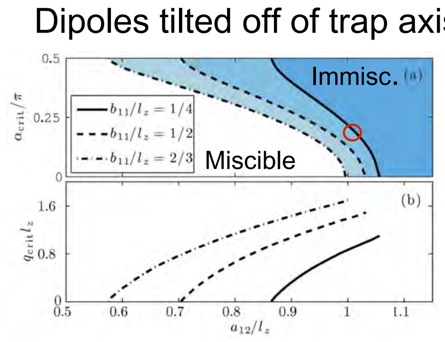
$b_{11}=\frac{1}{4}a_{11}$

$b_{11}=\frac{1}{2}a_{11}$

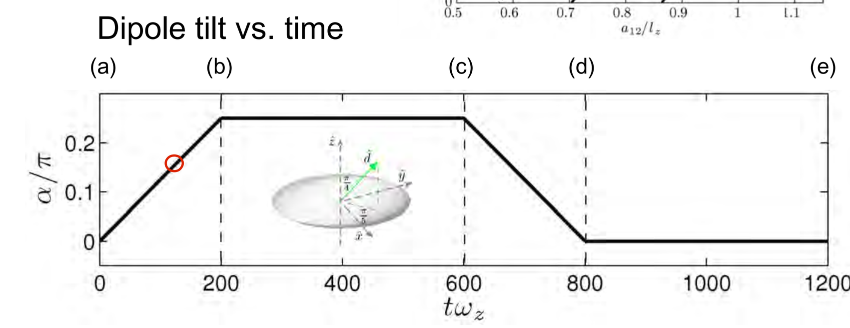
$b_{11}=\frac{2}{3}a_{11}$

- Equal dipole moments - behaves like purely contact interactions
- Unequal dipole moments introduces roton immiscibility
- Anisotropic spin-wave roton drives immiscible stripe phase

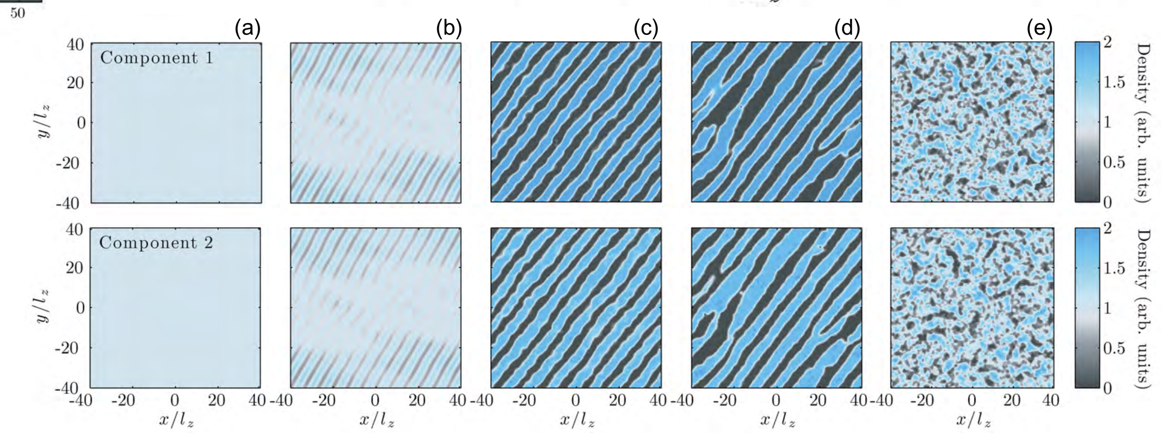
Dipoles tilted off of trap axis



Dipole tilt vs. time



- Tilting dipole polarization off of axis introduces anisotropic spin roton
- System driven to striped immiscible phase (c)
- Long-time thermalization upon return to miscible parameter space, like prethermalization (e)



Acknowledgments and Funding

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[1] C. Ticknor, R. M. Wilson and J. L. Bohn, PRL 106 65301 (2011).

[2] R. M. Wilson, C. Ticknor, J. L. Bohn and E. Timmermans, PRA 86 033606 (2011).