$p-$wave Superfluid Phases of Fermi Molecules in a Bilayer Lattice Array

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Abstract

We investigate the emergence of superfluid $p = p_x + ip_y$ phases in an ultracold gas of dipolar Fermi molecules lying in two parallel square lattices in 2D with the dipole moments of the molecules oriented in opposite directions in each layer. The T = 0 phase diagram summarizes our findings: Stable and metastable superfluid phases appear as a function of the filling factor and the dipole-dipole interaction parameter. Our model predicts that these superfluid phases can be observed experimentally at 0.6 nK in molecules of NaK. Such temperature can be raised up to few nK by using the subwavelength confinement technique.

Model

In the presence of an electric field perpendicular to the layers, the dipoles align in opposite directions. In this scenario, the interaction potential between two molecules situated in different layers is:

$$V_{dip}(\vec{r}) = -d^2 \frac{r^2 - 2L^2}{(r^2 + L^2)^{5/2}}, \tag{1}$$

where r is the interplanar distance, d the intensity of the dipoles, and L the separation of the layers.

$$\chi = \frac{a_d}{a}, \qquad \Lambda = \frac{L}{a}$$
$$m_{ef} = \frac{\hbar^2}{2ta^2}, \quad a_d = \frac{m_{ef} d^2}{\hbar^2} \tag{2}$$

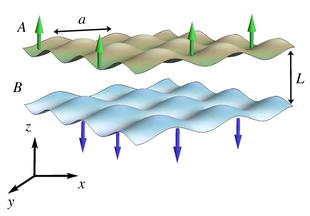

Figure 1: Schematic representation of the dipolar Fermi gas.

Conclusions

We conclude that the bilayer dipolar system studied represents a genuine candidate to simulate the physics of unconventional superfluids, in particular, $p-$wave superfluids. Which can have potential applications in quantum information.

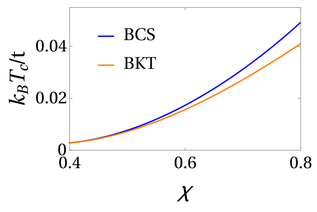

Figure 2: BCS and BKT critical temperature as a function of the dipolar interaction χ.

References

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[3] A. Camacho-Guardian and R. Paredes, Annalen der Physik **528**, 778 (2016).

Acknoledgements

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Two body problem

To get insight of the appropriate values for which the interaction parameter χ tends to form either scattered pairs and true bound pairs, we find the solutions of the binding equation as a function of the interaction parameter χ

$$1 = \frac{1}{\Omega} \sum_{\vec{q}} \frac{V(\vec{q})}{E_B - E_{\vec{K},\vec{q}}}, \tag{3}$$

where $E_{\vec{K},\vec{q}} = -4t \left(\cos\left(\frac{K_x a}{2}\right) \cos(q_x a) + \cos\left(\frac{K_y a}{2}\right) \cos(q_y a) \right)$ and $\Omega = 121\text{x}121$ the number of lattice sites.

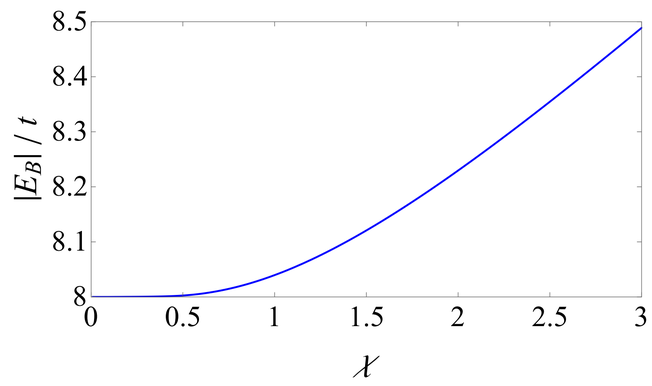

Figure 3: Absolute value of the binding energy of a dimer composed of two dipolar Fermi molecules.

We find, that for values $\chi \lesssim 0.5$ molecules are weakly bound, and thus for lower values of χ we are dealing with purely fermionic physics.

Bardeen-Cooper-Schrieffer superfluidity

For equal filling factors in each layer $n = n_A = n_B$, we solve the effective self-consistent BCS equations:

$$\Delta_{\mathbf{k}} = -\frac{1}{\Omega} \sum_{\mathbf{k}'} V_{dip}(\mathbf{k} - \mathbf{k}') \frac{\Delta_{\mathbf{k}'}}{2E_{\mathbf{k}'}} \tanh\left(\frac{\beta E_{\mathbf{k}'}}{2}\right) \tag{4}$$

$$n = \frac{1}{2}\left[1 - \frac{1}{\Omega} \sum_{\mathbf{k}} \frac{\xi_{\mathbf{k}}}{E_{\mathbf{k}}} \tanh\left(\frac{\beta E_{\mathbf{k}}}{2}\right)\right], \tag{5}$$

being $\beta = 1/k_B T$, μ the chemical potential, $\xi_{\mathbf{k}} = \epsilon_{\mathbf{k}} - \mu + nV_{dip}(\mathbf{k} = \mathbf{0})$ and $E_{\mathbf{k}} = \sqrt{\xi_{\mathbf{k}}^2 + |\Delta_{\mathbf{k}}|^2}$ the quasiparticle energy.

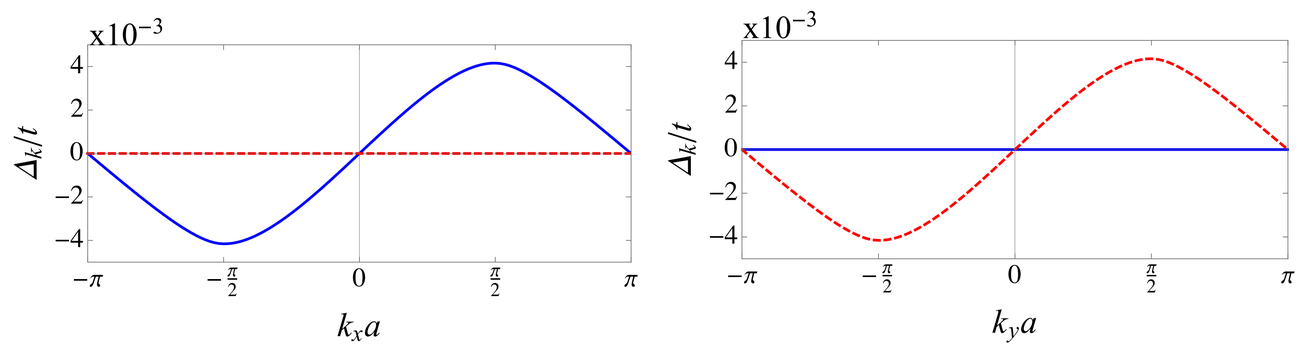

Figure 4: Energy gap parameter $\Delta_{\mathbf{k}}$ as a function of $\mathbf{k}$ for filling factor $n = 0.16$, coupling strength $\chi = 0.4$ and $T = 0$. Left and right panels corresponds to $k_y a = 0$ and $k_x a = 0$ respectively.

The $p_x + ip_y$ phase is unstable towards phase separation, in order to analyze its stability in the (n, χ) diagram at $T = 0$ we use the Maxwell construction of equal areas.

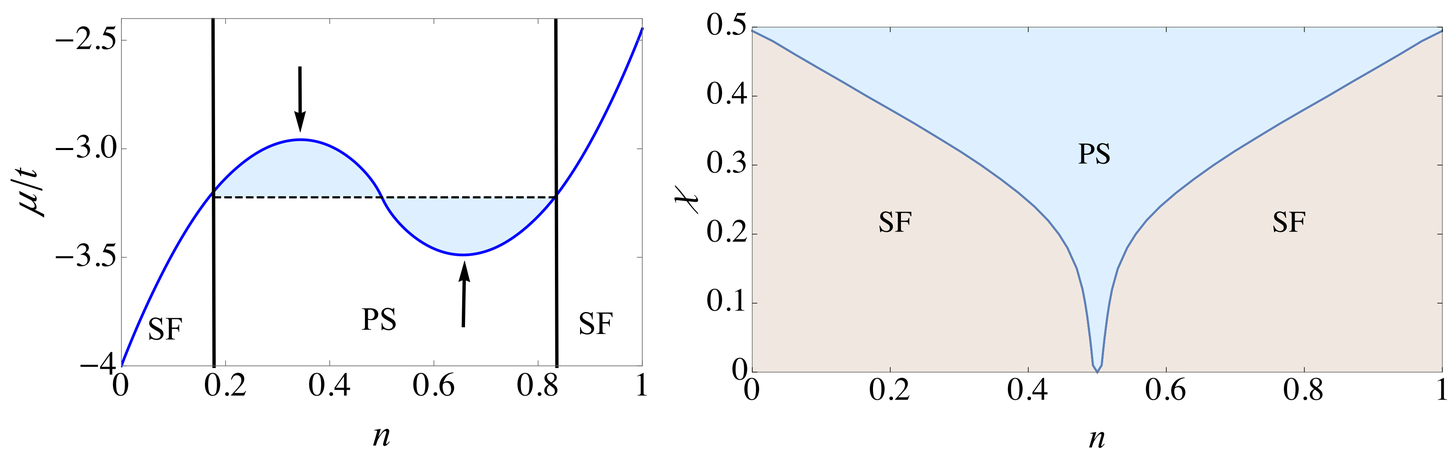

Figure 5: Left panel shows the chemical potential μ vs filling factor n. Right panel, Phase diagram at $T = 0$.

Using the Berezinkii-Kosterlitz-Thouless theory, we estimate the critical temperature of the p-wave superfluid phase for the parameters $\chi = 0.4$ and $n = 0.16$.

$$\rho(T_{BKT}) = \frac{8}{\pi} k_B T_{BKT}. \tag{6}$$

Using molecules of NaK confined in an optical lattice of size $a = 532$ nm, the critical temperature is $T_{BKT} = 0.6$ nK. This temperature can be raised by means of the use of the recently proposed subwavelength lattice technique which yield temperatures of around 8 nK.