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Topological superfluid phase of fermionic polar molecules

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New quantum phases in fermionic dipolar gases

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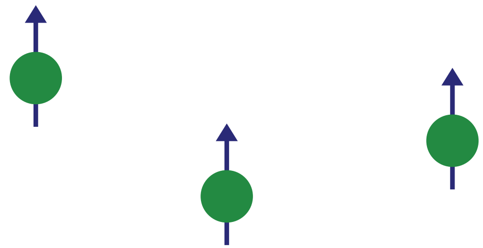
Outline I

- Introduction. Progress with polar molecules
- RF-dressed polar molecules. Effective intermolecular interaction
- Dipolar 2D Fermi gas of RFD particles. Superfluid transition
- Topological aspects of $p_x + ip_y$ state
- Collisional stability
- Conclusions

Collaborations: N.R. Cooper (Cambridge)

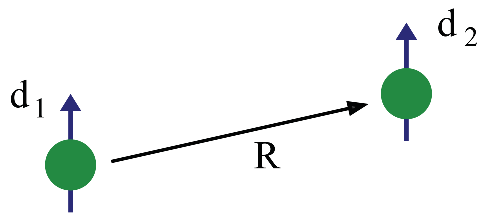
Dipolar gas



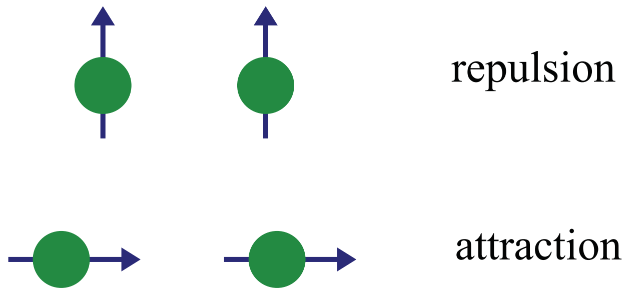
Polar molecules, atoms with a large magnetic moment

Dipole-dipole interaction

$$V_d = \frac{\vec{d}_1 \vec{d}_2 R^2 - 3(\vec{d}_1 \vec{R})(\vec{d}_2 \vec{R})}{R^5} \sim \frac{1}{R^3}$$



long-range, anisotropic



Different physics compared to ordinary atomic ultracold gases

Dipole moment

Polar Molecules

CO	$0.1\mathcal{D} \approx 0.05au$
CsCl	$10\mathcal{D} \approx 5au$
KRb	$0.5\mathcal{D} \approx 0.25au$

Atoms with a large magnetic moment

$\mathrm{Cr} \Rightarrow 6\mu_B$ equivalent to $d = 0.048\mathcal{D} = 0.022au$

Presently a quatum gas of Cr bosons is created and Bose-condensed (Stuttgart, Villetaneuse)

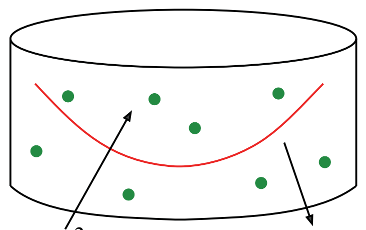
Radius of the dipole-dipole interaction $\Rightarrow \frac{\hbar^2}{mr_*^2} \approx \frac{d^2}{r_*^3}$

$r_* = \frac{md^2}{\hbar^2}$ ranges from tens of angstrems to tens of microns

Polar molecules

Cooling and trapping of preexisting molecules

Buffer-gas cooling (Doyle, Harvard)



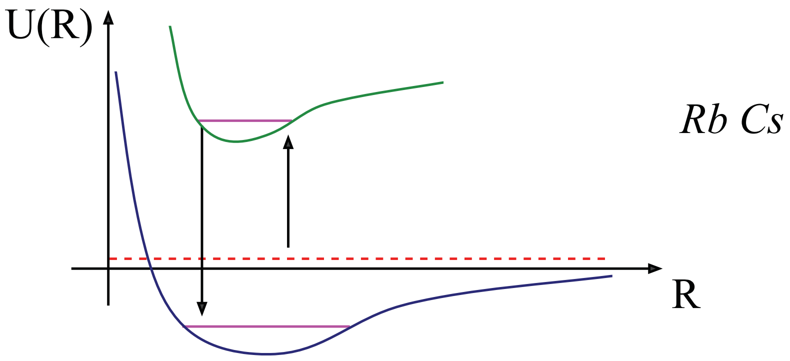
Stark deceleration (Meijer, Berlin)

H_3, ND_3, CO, etc. $\quad n \sim 10^8 cm^{-3}; \quad T \sim 10mK$

Polar molecules

Photoassociation

(many labs; first experiments De Mille, Yalle)

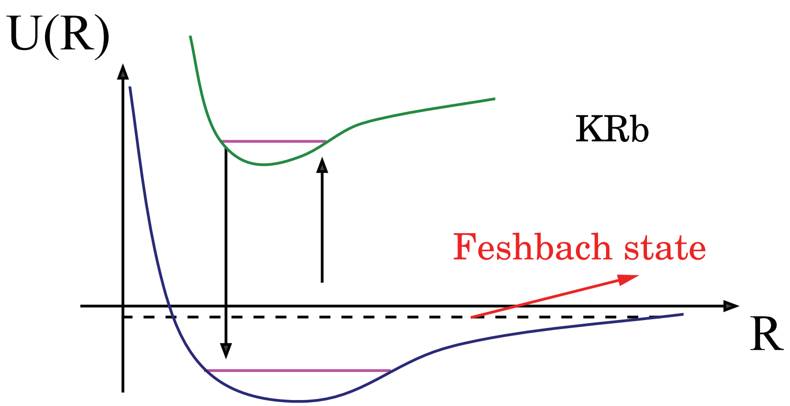


ground state CsLi molecules

Weidemuller group

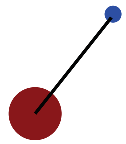
Transfer of weakly bound KRb molecules to the ground rovibrational state

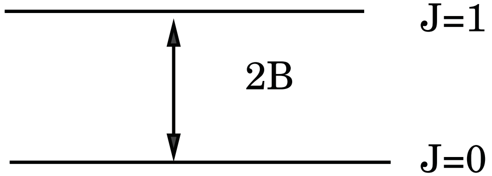
JILA, D. Jin, J. Ye groups

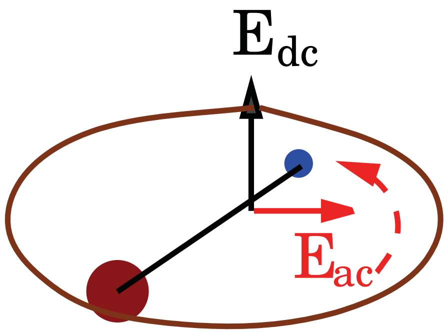


$$n \sim 10^{12} - 10^{13}\ \text{cm}^{-3}$$
$$T \approx 400nK \approx 3E_F$$

RF-dressed polar molecules (Innsbruck idea)





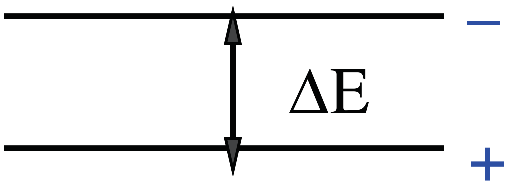


σ^+ polarized RF E_{ac}

+ constant $E_{dc} \rightarrow 0$

Dressed states $|+\rangle = \alpha|0,0\rangle + \beta|1,1\rangle; \quad , |-\rangle = \beta|0,0\rangle - \alpha|1,1\rangle$

$$\alpha = -\frac{A}{\sqrt{A^2+\Omega^2}}; \quad \beta = \frac{\Omega}{\sqrt{A^2+\Omega^2}}; \quad A = \frac{1}{2}(\Delta + \sqrt{\Delta^2 + 4\Omega^2})$$

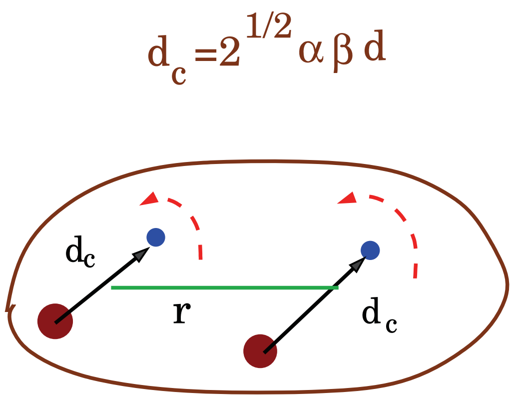


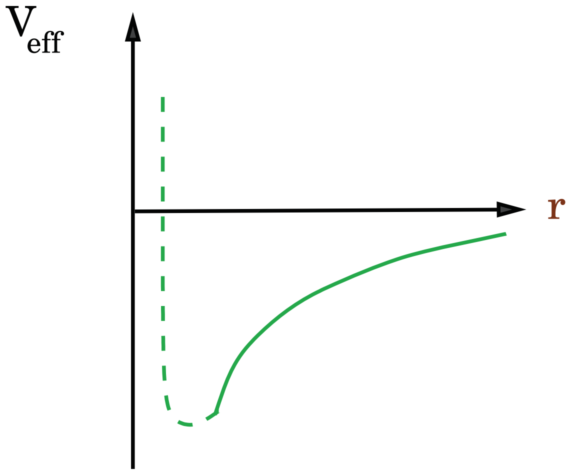
$|\alpha|>|\beta|$

$\Delta E=(\Delta^2+ \Omega^2)^{1/2}$

Effective interaction potential

Two RFD molecules in 2D. The dipole moment is rotating with RF frequency





Distance scale $\frac{d_c^2}{r_\Delta^3} = |\Delta| \Rightarrow \; r_\Delta$

$$r > r_\Delta \;\; \Rightarrow \quad V_{eff} = \langle (1 - 3\cos^2\phi) \rangle \frac{d_c^2}{r^3} = -\frac{d_c^2}{2r^3}$$

$$r_* = m d_c^2 / 2\hbar^2$$

Fermionic RFD molecules. Superfluid transition

Fermionic RFD molecules in a single quantum state in 2D

Attractive interaction for the p-wave scattering ($l = \pm 1$)

$$\hat{H} = \int d^2r\, \hat{\Psi}^\dagger(\mathbf{r})\{-(\hbar^2/2m)\Delta + \int d^2r' \hat{\Psi}^\dagger(\mathbf{r}')V_{eff}(\mathbf{r}-\mathbf{r}')\hat{\Psi}(\mathbf{r}') - \mu\}\hat{\Psi}(\mathbf{r})$$

$$\Rightarrow \hat{H} = \int d^2r\, \{-\Psi^\dagger(\mathbf{r})[(\hbar^2/2m)\Delta - \mu]\hat{\Psi}(\mathbf{r}) + \int d^2r\prime(\Delta(\mathbf{r}-\mathbf{r}')\hat{\Psi}^\dagger(\mathbf{r})\hat{\Psi}^\dagger(\mathbf{r}') + h.c.)\}$$

$$\Delta(\mathbf{r}-\mathbf{r}') = \langle V_{eff}(\mathbf{r}-\mathbf{r}')\hat{\Psi}(\mathbf{r})\hat{\Psi}(\mathbf{r}')\rangle$$

Gap equation $\Delta(\mathbf{k}) = -\int \frac{d^2k}{(2\pi)^2} V_{eff}(\mathbf{k}-\mathbf{k}')\Delta(\mathbf{k}')\frac{\tanh(\epsilon(k')/T)}{2\epsilon(k')}$

$$\epsilon(k) = \sqrt{(\hbar^2k^2/2m - \mu)^2 + |\Delta(k)|^2}; \quad \mu \approx E_F$$

$$T_c \approx E_F \exp(-3\pi/4k_F r_*)$$

$\Delta(\mathbf{k}) = \Delta \exp(i\phi_k)$ $\quad p_x + ip_y$ state ($l = \pm 1$)

Superfluid transition

Why the result is similar to the result of s-wave pairing in 3D?

For short-range potentials should be $V_{eff} \propto k^2$ and $T_c \propto \exp(-1/(k_F b)^2)$

Anomalous scattering in $1/r^3$ potential $\rightarrow$ Contribution from $r \sim 1/k$

$$V_{eff}(k) = -\frac{8\hbar^2}{3m}(kr_*); \qquad |k| = |k'|$$

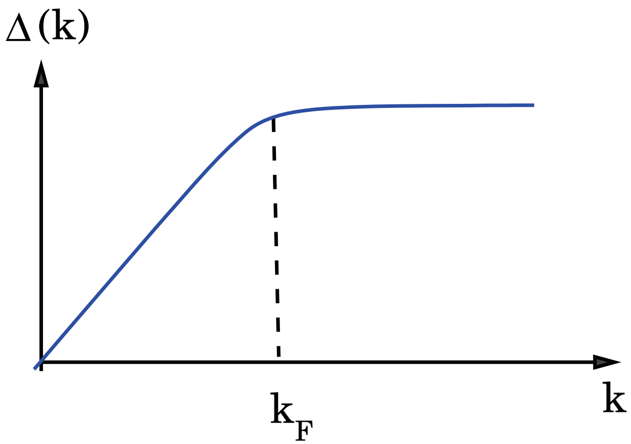
$$T_c \propto \exp\left(-\frac{1}{\nu(k_F)|V_{eff}(k_F)|}\right)$$

$$\nu = \frac{m}{2\pi\hbar^2}$$

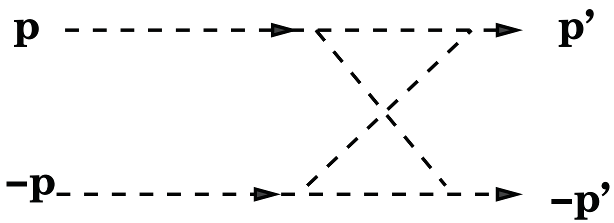
$$T_C \propto \exp\left(-\frac{3\pi}{4k_F r_*}\right)$$

Transition temperature

Do better than simple BCS. Find $\Delta(k)$



$$\Delta(\mathbf{k}) = -\int \frac{d^2k'}{(2\pi)^2}\Gamma_d(\mathbf{k},\mathbf{k}')\left\{\frac{\tanh(\epsilon(k')/T)}{2\epsilon(k')} - \frac{m}{\hbar^2 k'^2}\right\}\Delta(\mathbf{k}')$$
$$-\int \frac{d^2k'}{(2\pi)^2}\delta V(\mathbf{k},\mathbf{k}')\frac{\tanh(\epsilon(k')/T)}{2\epsilon(k')}\Delta(\mathbf{k}')$$

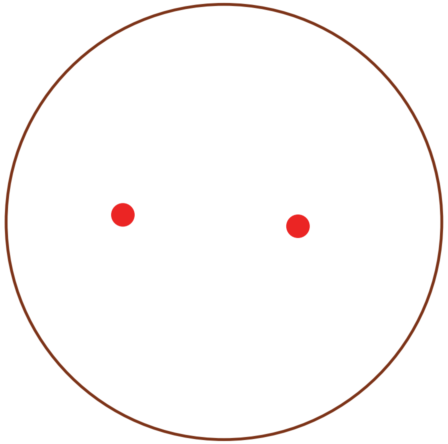


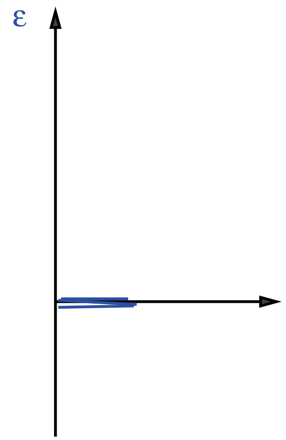
$\delta V \rightarrow$ 2nd order

$$T_c \Rightarrow E_F \exp\left(-\frac{3\pi}{4k_F r_*}\right)$$

Topological aspects of $p_x + ip_y$ state

Vortices. Zero-energy mode related to two vortices. (Read/Green, 2000)





The number of zero-energy states exponentially grows with the number of vortices $2^{(N_v/2-1)}$

Non-abelian statistics $\Rightarrow$ Exchanging vortices creates a different state!

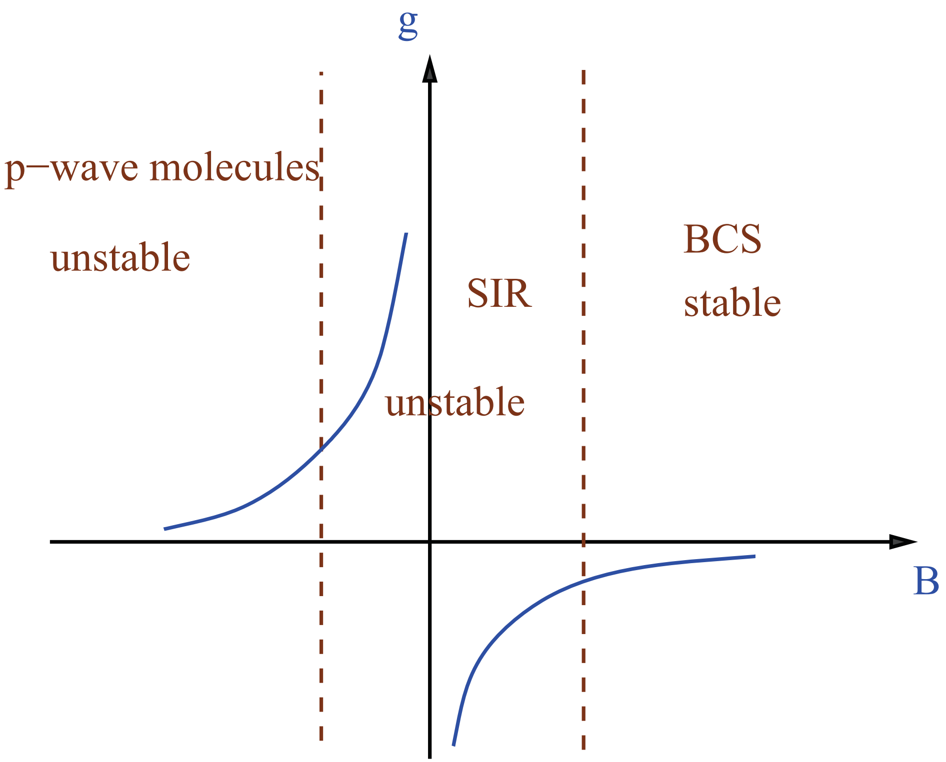
Non-local character of the state. Local perturbation does not cause decoherence

Topologically protected state for quantum information processing

p-wave pairing of fermionic atoms

Short-range interaction + p-wave resonance. Review Gurarie/Radzihovsky

Collisional stability. Transition temperature

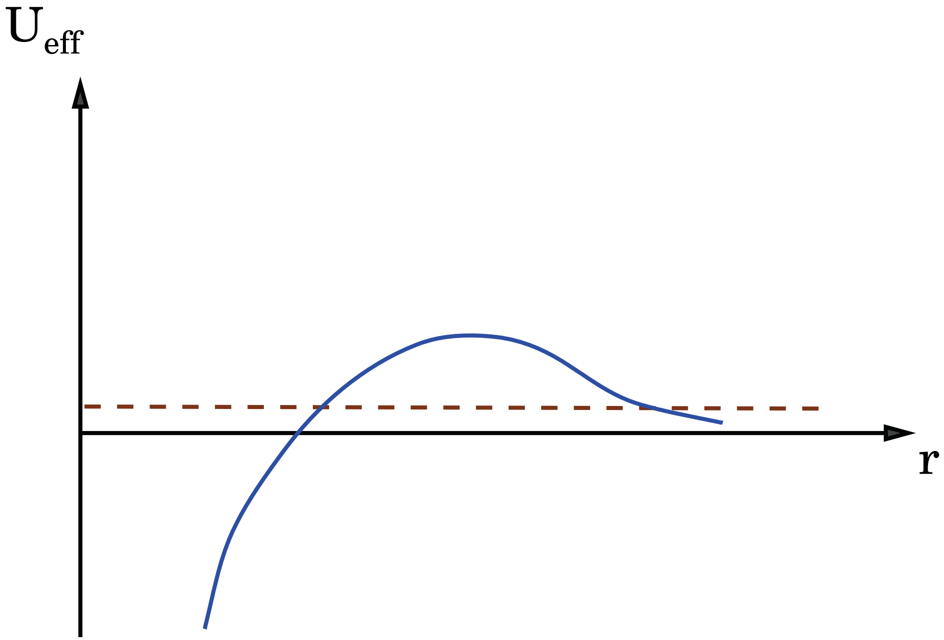


p-wave pairing of fermionic atoms

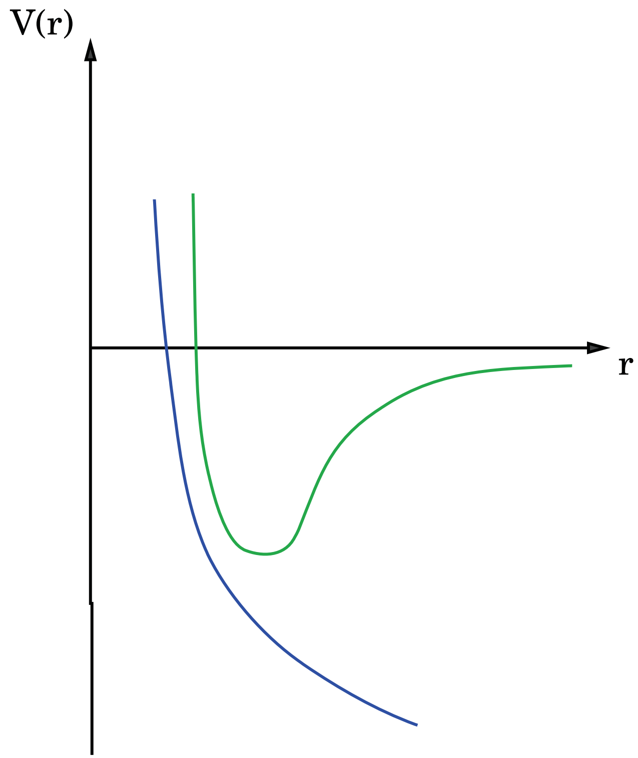
BCS $\Rightarrow \quad T_c \sim \exp\left(-\frac{1}{(k_F b)^2}\right)$

Strongly interacting regime $\Rightarrow$ collisional instability

Gurarie/Cooper; Castin/Jona-Lazinio



Collisional stability



$$\alpha_{in} = A\frac{\hbar}{m}(kr_*)^2; \qquad A \Rightarrow \; 10^{-2} - 10^{-3}$$

$$\alpha_{in} \rightarrow \; 0.5 \times (10^{-8} - 10^{-9}) \text{ cm}^3\text{/s}$$

Can this work ?

KRb molecules $\rightarrow$ $d_c \approx 0.2$ D $\approx 0.1 e a_0$ $\quad r_* \approx 1000 a_0$

$n = 2 \times 10^9$ cm^{-2} $\Rightarrow k_F = 1.5 \times 10^5$ cm; $E_F = 2\pi\hbar^2 n/m = 400$ nK

$T_c \approx 20$ nK

$\tau \sim 1$s

Conclusions

Creation of ultracold polar molecules opens wide avenues to make new quantum states

$p_x + ip_y$ state for spinless fermions is one of the examples