Novel macroscopic quantum states in dipolar systems

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Outline

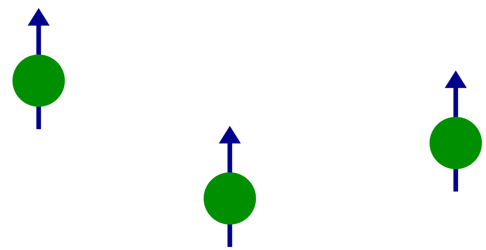
- Introduction
- RF-dressed fermionic polar molecules in 2D
- Topological $p_x + ip_y$ phase
- p-wave and d-wave pairing in bilayered systems
- Conclusions and outlook

Collaborations: N.R. Cooper and J. Levinsen (Cambridge), M. Efremov (Orsay)

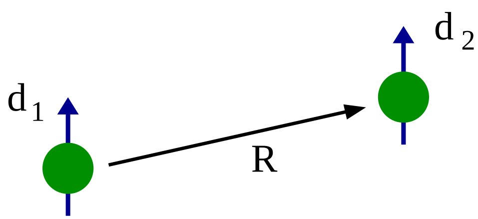
Evora, October 12, 2012

Dipolar gas

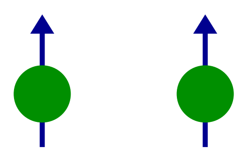
Polar molecules or atoms with a large magnetic moment



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



repulsion

attraction

Different physics compared to ordinary atomic ultracold gases

Alkali-atom molecules d from $0.6\,D$ for KRb to $5.5\,D$ for LiCs

Atoms with large μ

Remarkable experiments with Cr atoms ($\mu = 6\mu_B \Rightarrow d \approx 0.05$ D)

T. Pfau group (Stuttgart)

Effects of the dipole-dipole interaction in the dynamics

Stability diagram of trapped dipolar BEC

Spinor physics in chromium experiments at Villetaneuse, B. Laburthe-Tolra

Dysprosium BEC ($\mu = 10\mu_B$, (B. Lev, Stanford))

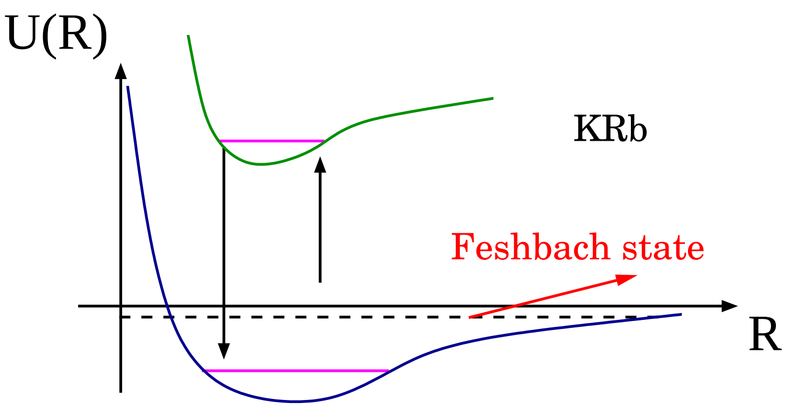
Erbium BEC ($\mu = 7\mu_B$, (F. Ferlaino, Inscbruck))

Polar molecules. Creation of ultracold clouds

Photoassociation

Transfer of weakly bound KRb fermionic molecules to the ground rovibrational state

JILA, D. Jin, J. Ye groups



$$n \sim 10^{12} - 10^{13}\ \text{cm}^{-3}$$
$$T \approx 200nK\ \sim E_F$$

Ground-state LiCs molecules at Heidelberg

Ground-state RbCs molecules in Innsbruck

Ground-state KRb bosonic molecules in Tokyo

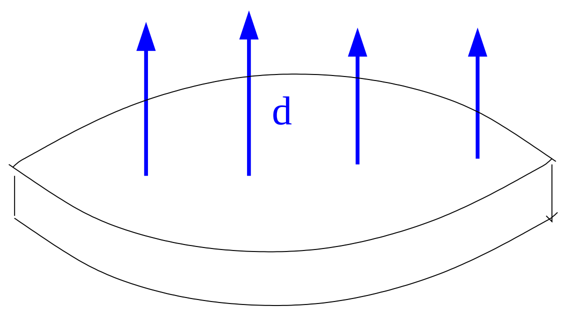
Experiments with NaK (MIT, Munich, Trento, Hannover) and KCs (Innsbruck) molecules

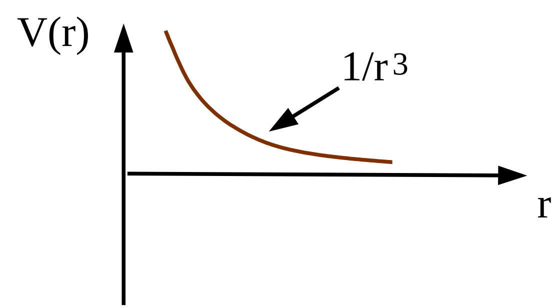
Ultracold chemistry

Ultracold chemical reactions $\mathrm{KRb} + \mathrm{KRb} \Rightarrow \mathrm{K}_2 + \mathrm{Rb}_2$

Suppress instability $\rightarrow$ induce intermolecular repulsion

For example, 2D geometry with dipoles perpendicular to the plane





Reduction of the decay rate by 2 orders of magnitude at JILA

Select non-reactive molecules, like NaK, KCs, RbCs

What are prospects for novel physics ?

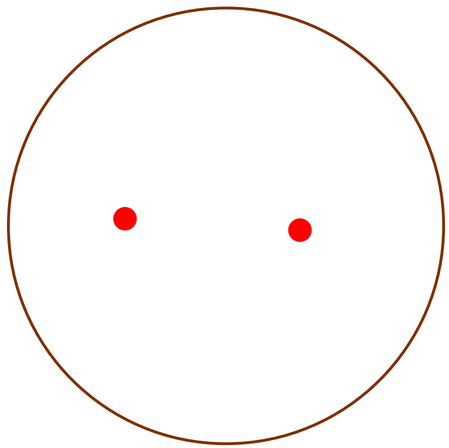
Theoretical studies

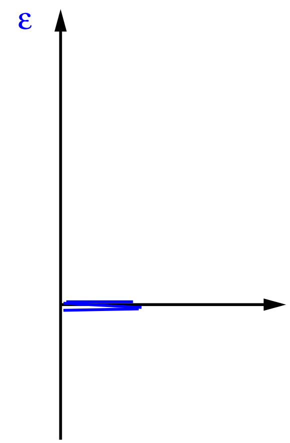
- Innsbruck group (P. Zoller, G. Pupillo, M.A. Baranov et al). Large variety of proposals including bilayer systems, Rydberg atoms etc.
- Trento group (S. Stringari et al). Excitation modes etc
- Harvard group (E. Demler, M. Lukin et al). Multilayer systems etc
- Hannover group (L. Santos et al). Spinor and dipolar systems
- Tokyo group (M. Ueda et al) Spinor and dipolar systems
- Cambridge group (N.R. Cooper, Jesper Levinsen). Novel states
- Rice group (H. Pu et al). Excitations and stability etc
- Maryland group (S. Das Sarma et al) Fermi liquid behavior etc
- Taipei group (D.-W. Wang et al)
- Barcelona group (M. Lewenstein et al)

Why single-component fermions are interesting?

Topological aspects of $p_x + ip_y$ state in 2D

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

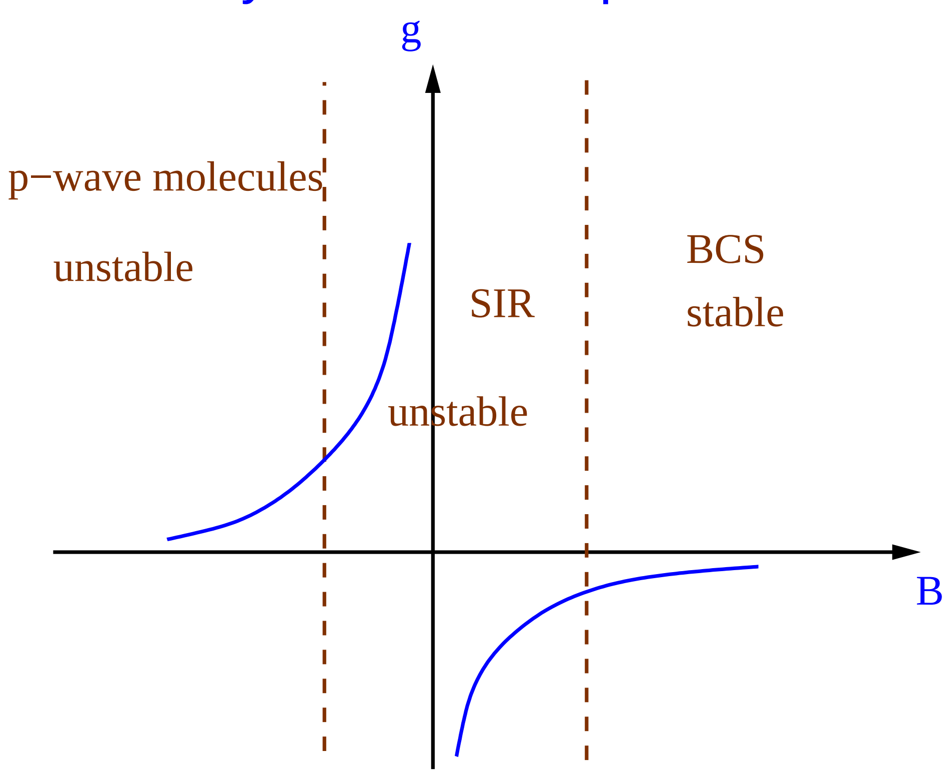
p-wave resonance for fermionic atoms

p-wave resonance   Experiments at JILA, ENS, Melbourne, Tokyo, elsewhere

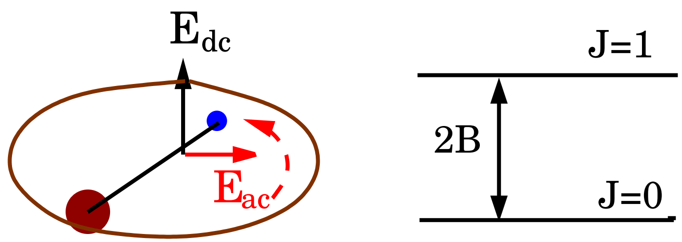
BCS $\Rightarrow$ $\quad T_c \sim \exp\left(-\frac{1}{(k_F b)^2}\right)$ practically zero

Molecular and strongly interacting regimes $\Rightarrow$ rather high T_c, but collisional instability

Gurarie/Radzihovsky; Gurarie/Cooper; Castin/Jona-Lazinio



RF-dressed polar molecules in 2D;Gorshkov et al (2008)



σ^+ polarized RF E_{ac}

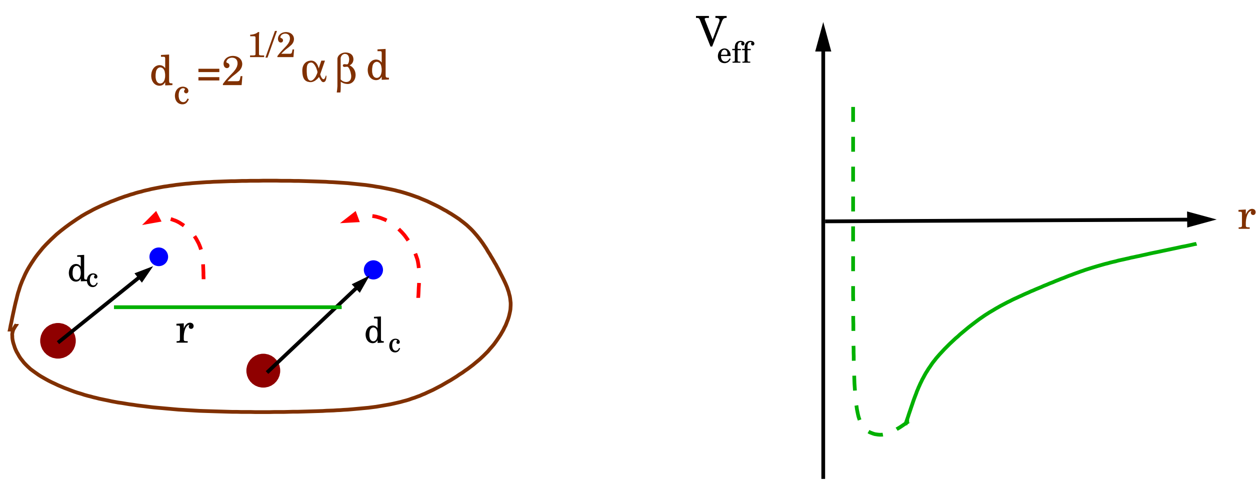
+ constant $E_{dc} \longrightarrow 0$

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

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

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

$d_c = 2^{1/2} \alpha \beta d$



Large $r \rightarrow \quad V_{eff} = \langle (1 - 3\cos^2\phi) \rangle \frac{d_c^2}{r^3} = -\frac{d_c^2}{2r^3}; \quad r_* = m d_c^2 / 2\hbar^2$

Fermionic RFD molecules. Superfluid transition; Cooper/G.S. (2009)

Fermionic RFD molecules in a single quantum state in 2D

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

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

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

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. Role of anomalous scattering

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

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

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

$$T_c \propto \exp\left(-\frac{1}{\nu(k_F)|V_{eff}(k_F)|}\right); \qquad \nu = \frac{m}{2\pi\hbar^2}$$

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

Second order diagrams $\Rightarrow$ Get a correct preexponential factor?

Transition temperature

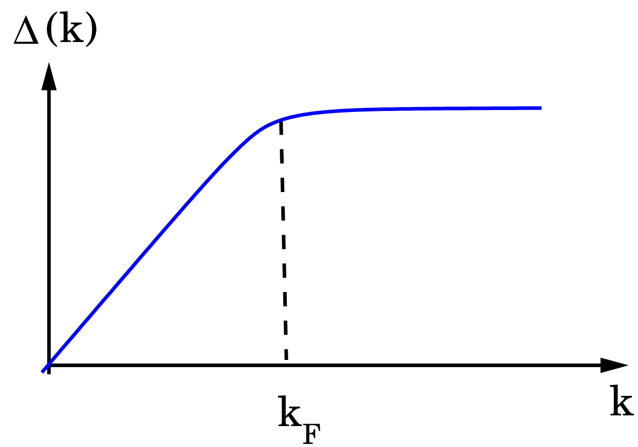
Do better than simple BCS. Reveal the role of short-range physics

Renormalized gap equation

$$\Delta(\mathbf{k}') = -\int f(\mathbf{k}', \mathbf{k})\Delta(\mathbf{k}) \left\{ \frac{\tanh[\epsilon(k)/2T]}{2\epsilon(k)} - \frac{1}{(E_k - E_{k'} - i0)} \right\} \frac{d^2k}{(2\pi)^2}$$

$\Delta(\mathbf{k}) = \Delta(k)\exp(i\phi_k)$; $f(\mathbf{k}', \mathbf{k}) = f(k', k)\exp[i(\phi_k - \phi_{k'})]$ scattering amplitude

$$\Delta(k) = \Delta(k_F) f(k, k_F)/f(k_F, k_F)$$



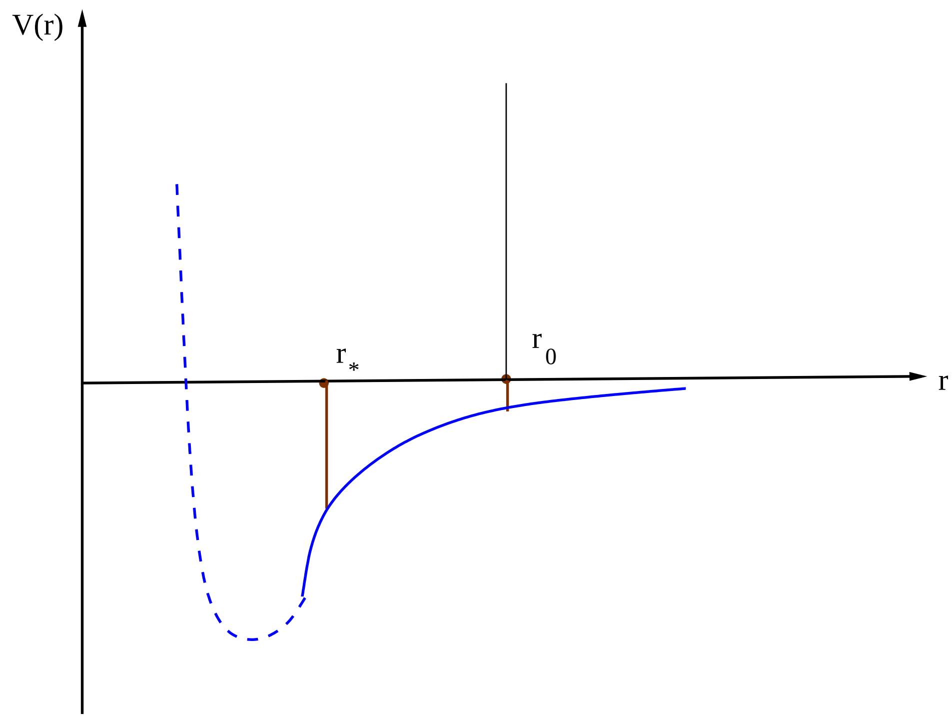
2D scattering in the potential with a $1/r^3$ tail

Scattering amplitude. No transparent exact solution for a finite k

Asymptotic method for slow scattering ($kr_* \ll 1$)

Divide the range of distances into two parts, $r < r_0$ and $r > r_0$

The distance r_0 is such that $r_0 \gg r_*$, but $kr_0 \ll 1$



$r < r_0$ Match exact zero-energy with free finite-k solution at $r = r_0$: $f \Rightarrow (\pi/2)d^2 r_* k^2 \ln k$

$r > r_0$ interaction as perturbation: $f = -(8\pi/3)d^2 k + (\pi/2)d^2 r_* k^2 \ln k$

Related results for the off-shell scattering amplitude

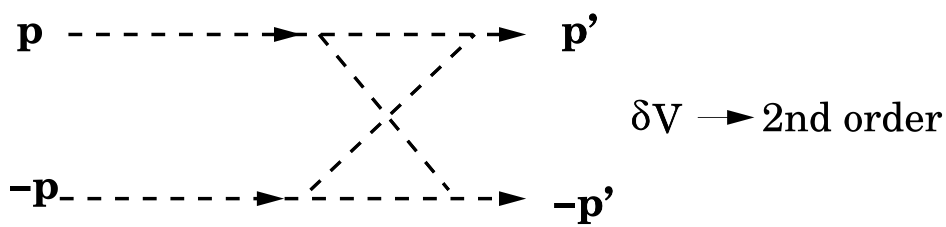
Manipulate T_c?

$$f(k',k) = -\pi d^2 k F\left(\frac{1}{2}, -\frac{1}{2}, 2, \frac{k^2}{k'^2}\right); \quad k \le k'; \; kr_* \ll 1$$

Include k^2-term $f = \frac{1}{2}\pi d^2 r_* k^2 \ln[kr_* u]$

$$T_c = \frac{2e^C}{\pi} E_F \exp\left\{-\frac{3\pi}{4k_F r_*} - \frac{9\pi^2}{64}\ln[k_F r_* u]\right\}$$

Take into account second-order Gor'kov-Melik-Barkhudarov processes



$$\Delta(\mathbf{k}) = -\int \frac{d^2k'}{(2\pi)^2} f(\mathbf{k},\mathbf{k}') \left\{\frac{\tanh(\epsilon(k')/T)}{2\epsilon(k')} - \frac{1}{2(E_{k'} - E_k)}\right\}\Delta(\mathbf{k}')$$
$$-\int \frac{d^2k'}{(2\pi)^2} \delta V(\mathbf{k},\mathbf{k}') \frac{\tanh(\epsilon(k')/T)}{2\epsilon(k')}\Delta(\mathbf{k}')$$

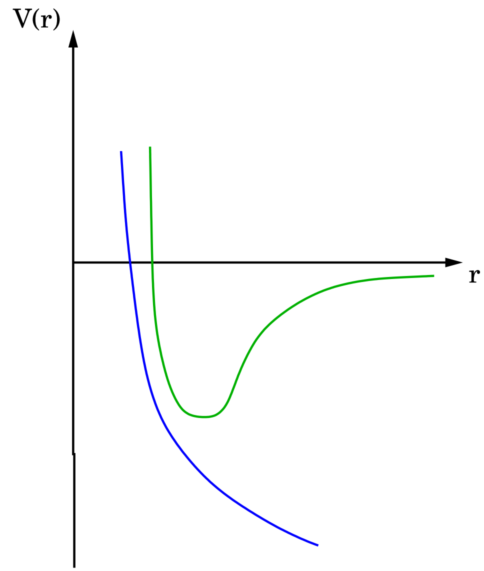
$$T_c = \kappa E_F^{0.3} E_*^{0.7} \exp\left\{-\frac{3\pi}{4k_F r_*}\right\}; \quad E_* = \frac{\hbar^2}{2mr_*^2} \gg E_F$$

κ depends on short-range physics and can be varied within 2 orders of magnitude

Collisional stability and T_c

p-wave atomic superfluids: $\mathrm{BCS} \Rightarrow T_c \to 0$ Resonance $\Rightarrow$ collisional instability

Polar molecules $\Rightarrow$ sufficiently large T_c and collisional stability



$\alpha_{in} = A\frac{\hbar}{m}(kr_*)^2;$ $A \Rightarrow 10^{-3} - 10^{-4}$ $\alpha_{in} \to (10^{-8} - 10^{-9})$ cm^2/s

LiK molecules $\to$ $d \simeq 3.5$ D $r_* \approx 4000 a_0$

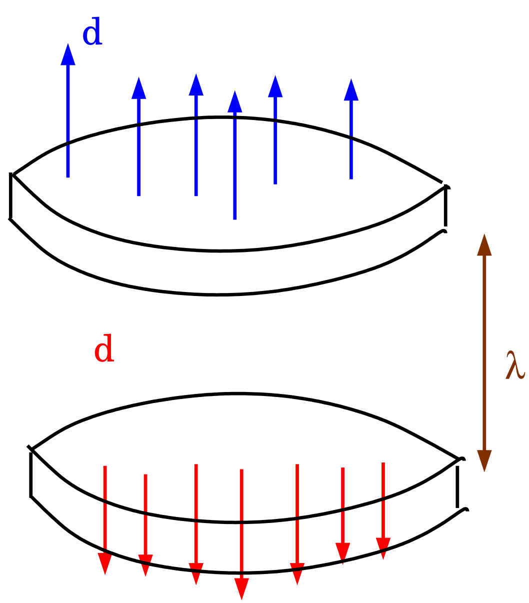
$n = 2 \times 10^8$ cm$^{-2} \Rightarrow$ $E_F = 2\pi\hbar^2 n/m = 120$ nK $T_c \approx 10$ nK; $\tau \sim 2$s

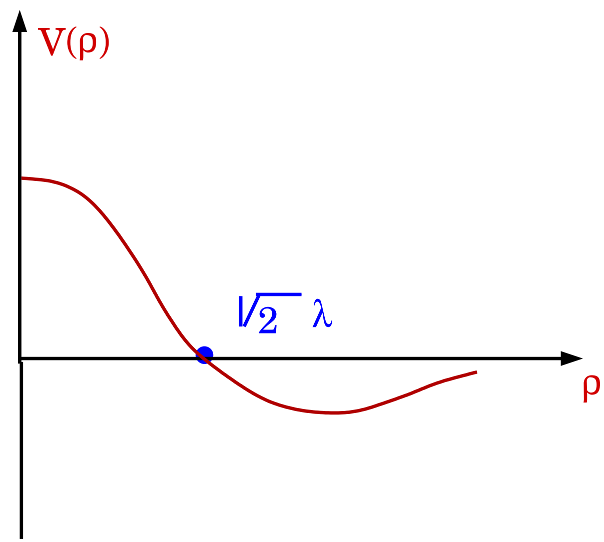
Bilayer system of ↑ and ↓ dipoles

Put $J = 0$ molecules in one layer and $J = 1$ in the other

Apply an electric field perpendicularly to the layers

Slightly non-uniform to prevent resonant dipolar flips leading to a rapid decay





Always a bound state of ↑ and ↓ dipoles

$$\beta \lesssim 1 \Rightarrow \quad \epsilon_b \simeq \frac{\hbar^2}{m\lambda^2} \exp[-8/\beta^2 - 8/\beta - (5 + 2C - 2\ln 2)]$$

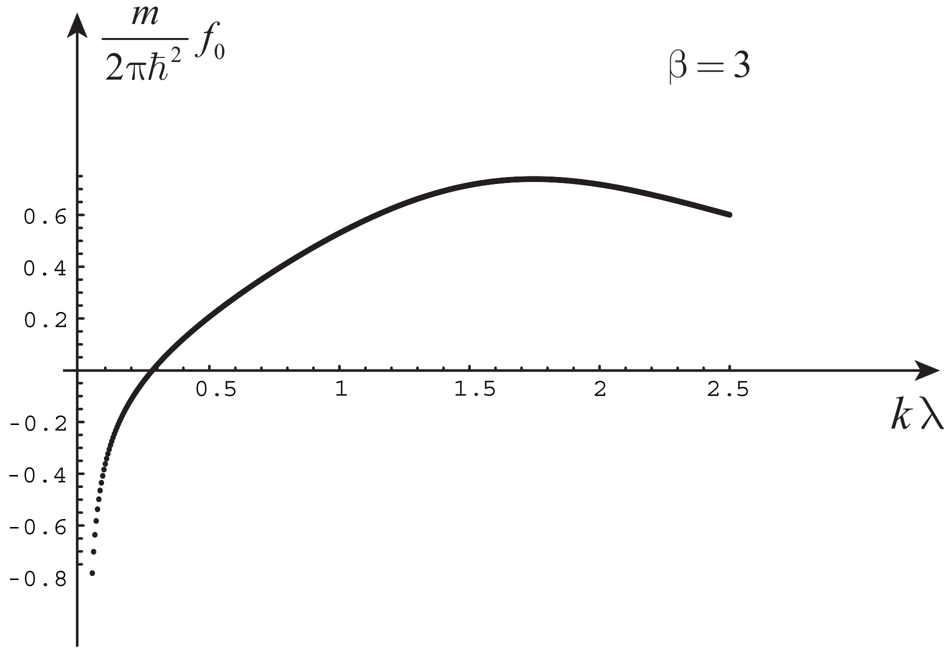
$$\beta = r_*/\lambda$$

Interlayer interaction. Scattering amplitudes

s-wave amplitude $k \to 0 \quad f_0(k) = \dfrac{4\pi\hbar^2}{m\ln(\epsilon_b/\epsilon)} + \dfrac{8\hbar^2}{m} k r_*$

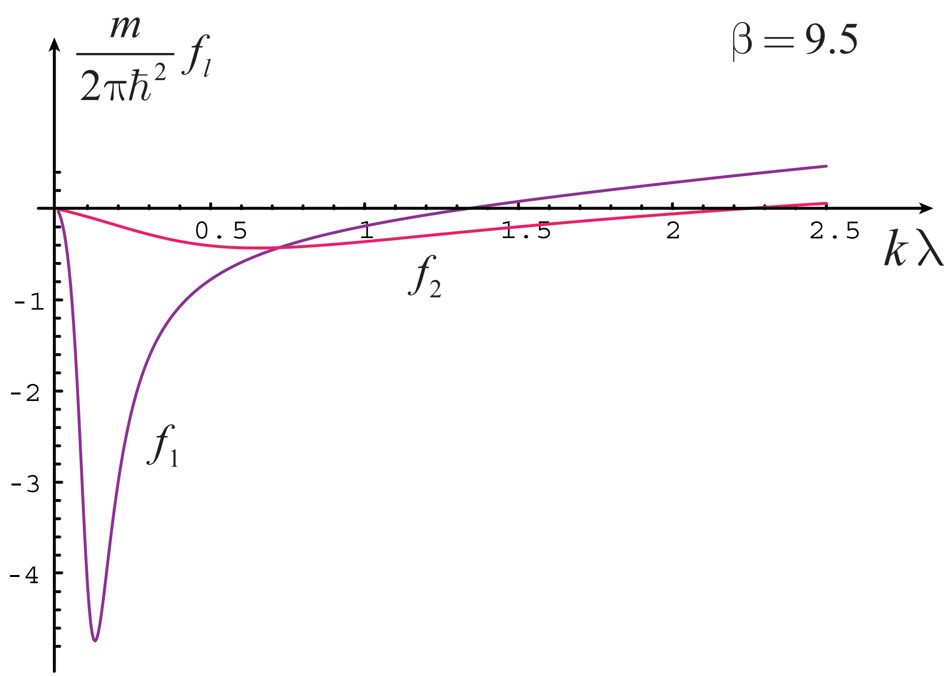
$$\epsilon = \hbar^2 k^2/m \quad r_* = md^2/\hbar^2$$

$f_0 > 0$ for reasonable k. No interlayer superfluid pairing



Interlayer interaction. Scatering amplitudes

p-wave and d-wave amplitudes are < 0



Interlayer p-wave and d-wave pairing

For $k_F r_* \gtrsim 1$ the effective mass significantly decreases

Transition temperature $T_c \sim E_F^* \exp\left(\frac{2\pi\hbar^2}{m_*|f(k_F)|}\right)$

The quasiparticle Fermi energy increases

Compensate the decrease of m_* in the exponent by increasing d^2 and, hence, f

p-wave interlayer superfluid with $T_c \sim$ tens of nK

d-wave superfluids with $T_c \sim$ nK. Analogy with high-temperature superconductors

LiCs with $n > 10^9$ cm^{-2}

Conclusions

Creation of ultracold polar molecules opens

wide avenues to make new quantum states

- $p_x + ip_y$ topological state for identical fermions
- p-wave and d-wave interlayer superfluids in bilayered fermionic dipolar systems