Clustered Wigner crystal phases of cold polar molecules in arrays of one-dimensional tubes

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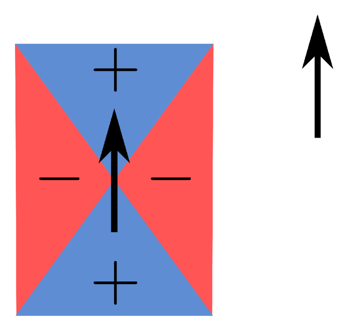
INTRODUCTION

- dipolar interactions
  A) long-ranged
  B) anisotropic



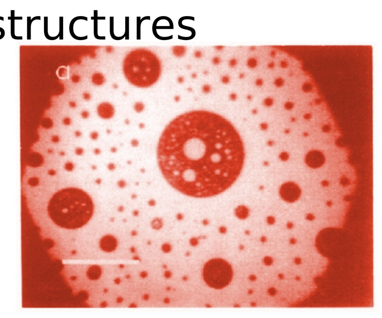
$$V(\mathbf{r}) = \frac{\mu^2 - 3(\mathbf{m}\mathbf{e}_r)^2}{r^3}$$

$\mathbf{m}$ ... dipolar moment
μ ... dipolar strength $|\mathbf{m}|$

- spontaneous translational symmetry breaking

Examples:

- **classical systems:** domain structures
  - Langmuir-Blodgett films
  - thin ferromagnetic layers

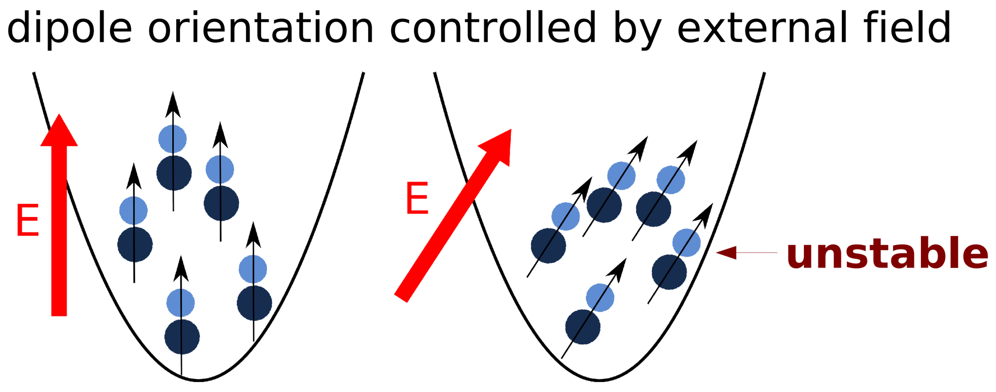


- **quantum systems:** Fermi liquid to Wigner crystal transition of electrons [1]
- transport measurements provide only very indirect insight

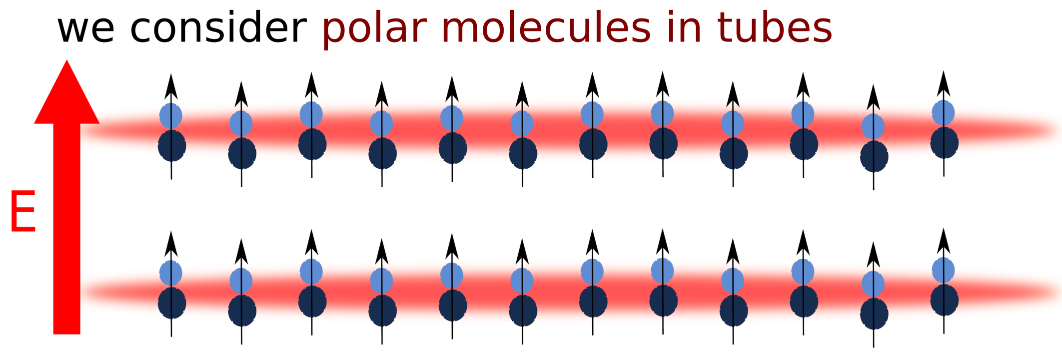
use powerful tools of atomic physics to explore possible emergent cluster and emulsion phases

EXPERIMENTAL SETUP

- cold polar molecules in trap
- dipole orientation controlled by external field

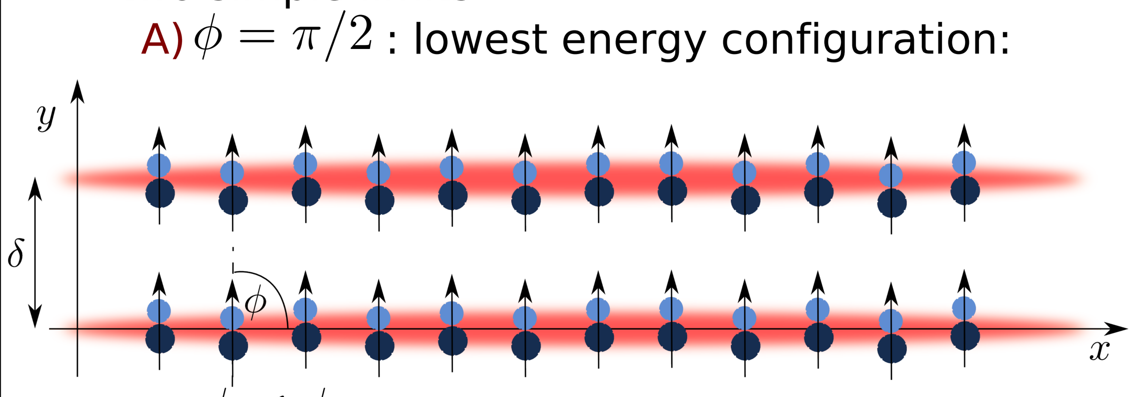


- stabilize through geometrical confinement: we consider polar molecules in tubes



CLASSICAL LIMIT

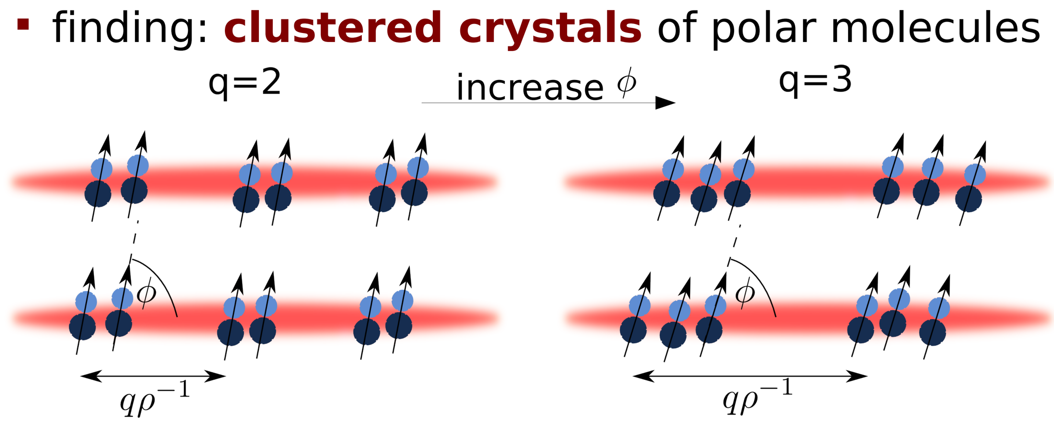
- Q: What happens for varying in-plane angle ϕ ?
- two simple limits
  A) $\phi = \pi/2$: lowest energy configuration:



B) $\phi < \phi_c$: unstable below critical angle

Q: **What happens for other values of ϕ ?**

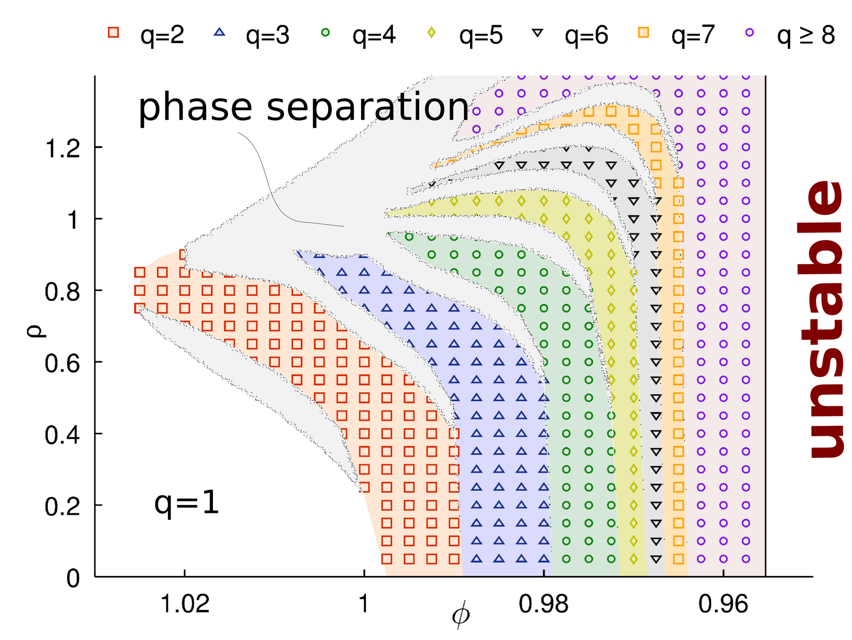
- we optimize potential energy
- finding: **clustered crystals** of polar molecules



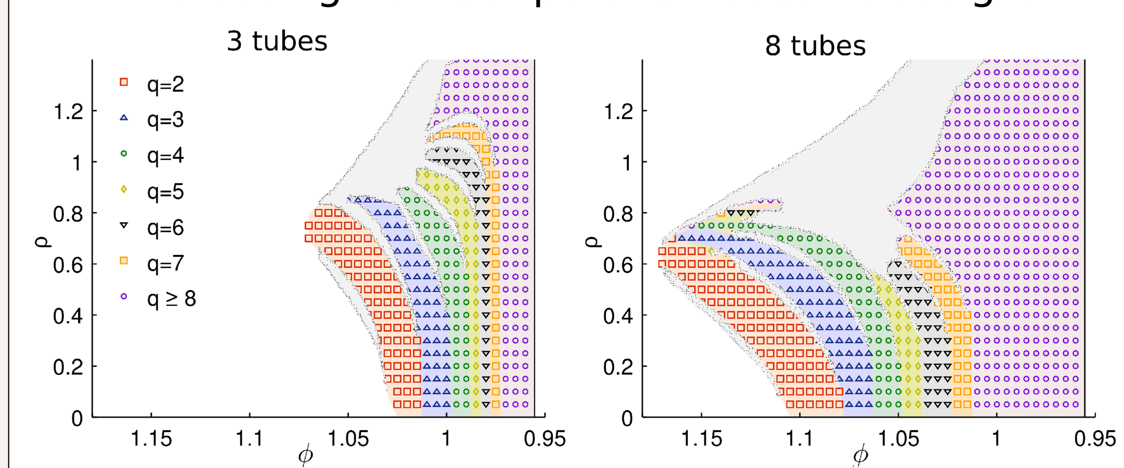
- cluster (unitcell) contains q molecules per tube
- **q can be tuned by orientation of external field and can take arbitrary values!**

CLASSICAL LIMIT

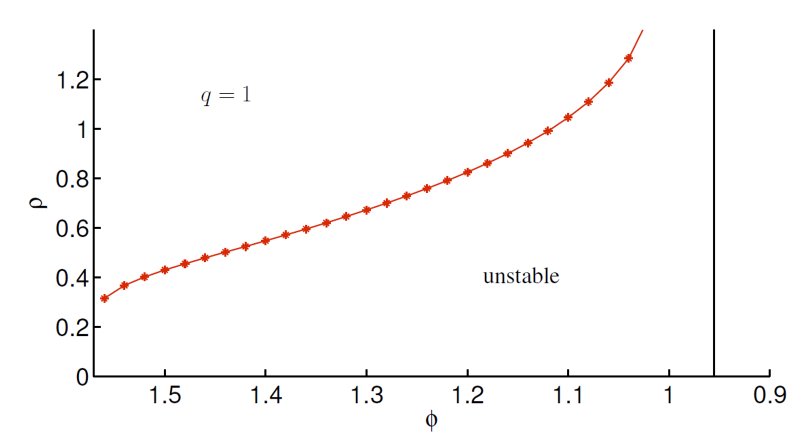
- classical phase diagram



- increasing number parallel tubes: lobes grow



- infinite number of tubes: q=1 Wigner crystal phase + macroscopic phase separation (surface energy is positive!)



QUANTUM MECHANICS

- Mermin-Wagner theorem: **no** true long-range order in 1D even at T=0
- density-density correlations decay as power low
- Q: What happens to clustered Wigner crystal phases in the presence of **quantum fluctuations**?
- **Luttinger-liquid** analysis
  - uniform system:

$$H \sim \int dx \rho_0 \frac{(\nabla\Theta)^2}{2m} + \frac{\mu^2\rho_0^2}{\pi^2}(\nabla\phi)^2 \rightarrow \int dx[uK(\nabla\Theta)^2 + \frac{u}{K}(\nabla\phi)^2]$$

  - clustered system

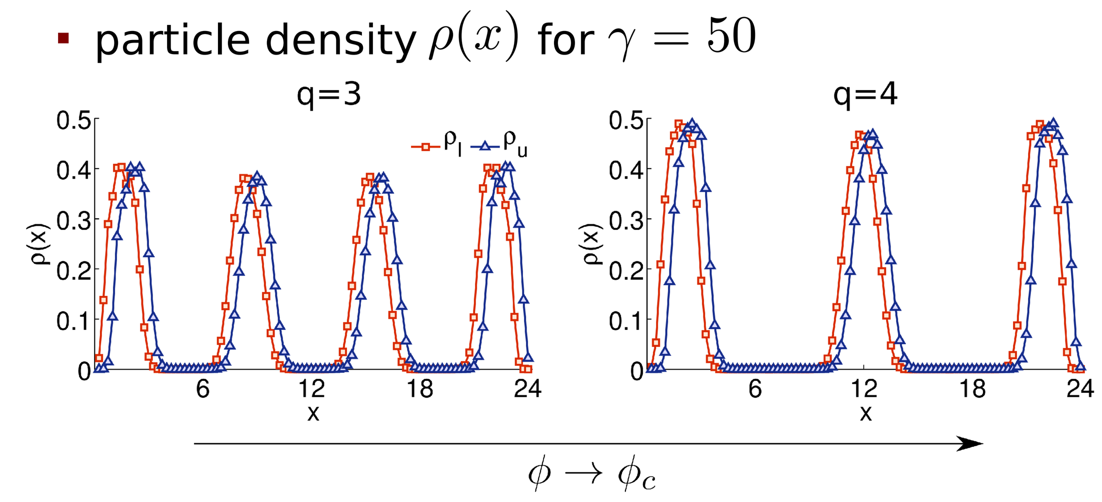
$$H_c \sim \int dx \frac{\rho_0}{q}\frac{(\nabla\Theta)^2}{2qm} + \frac{(q\mu)^2\rho_0^2}{q^2\pi^2}(\nabla\phi)^2 \rightarrow \int dx[u_c K_c(\nabla\Theta)^2 + \frac{u_c}{K_c}(\nabla\phi)^2]$$

$$\langle\rho(x)\rho(0)\rangle \sim \cos\frac{2\pi\rho x}{q}\left(\frac{1}{x}\right)^{2\frac{K}{q}}$$

  - phases with larger q are more classical
- A: phases melt into distinguishable **clustered Luttinger liquids**
- quantitative predictions from numerics (DMRG)
- interactions characterized by ratio γ between dipolar interactions and kinetic energy

$$E_{dip} \sim \mu^2\rho^3 \qquad E_{kin} \sim \frac{\rho^2}{m} \quad \rightarrow \quad \gamma \equiv \frac{E_{dip}}{E_{kin}} = \mu^2\rho m$$

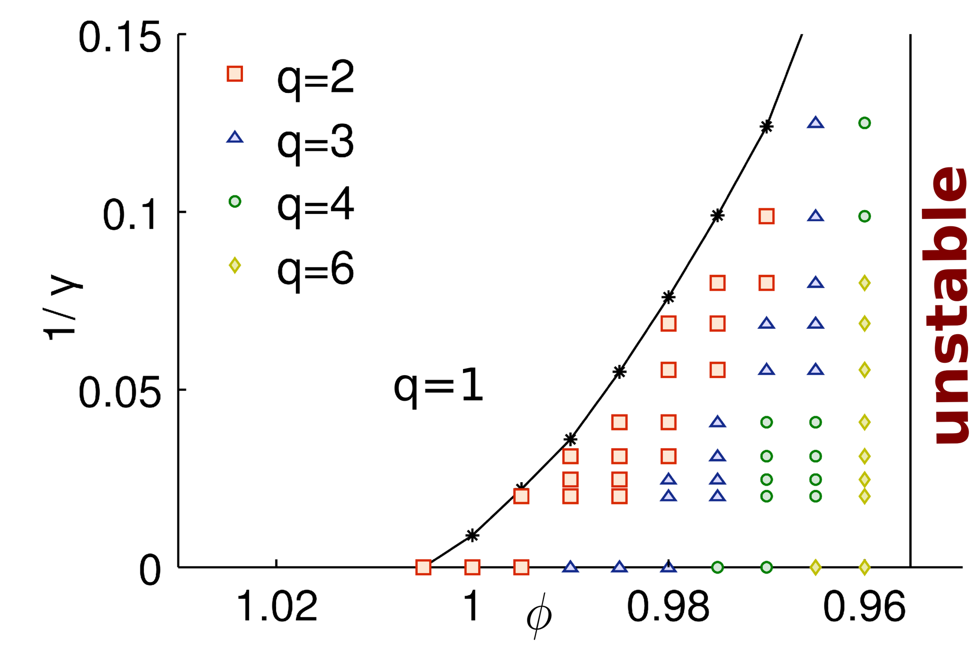
- particle density $\rho(x)$ for $\gamma = 50$



- left right symmetry broken
  → density of upper and lower tube shifted

QUANTUM MECHANICS

- complete **quantum** phase diagram



quantum melting of mesoscopic structures

EXPERIMENTAL IMPLICATIONS

- current experiments: (assumed density $\rho = 10^4\mathrm{cm}^{-1}$)

	μ/De	γ
KRb [2]	0.6	**0.7**
RbCs [3]	1.0	**3.3**
NaK [4]	2.7	**6.8**
NaCs [5]	4.6	**49.4**
LiCs [6]	5.5	**63.3**

- alternative: increase γ by optical lattice along tube
- further important effects:
  (a) incommensurability of the particle number with the cluster size
  (b) shallow trap potential along tube direction
  (c) the strong but finite transverse confinement
  (d) quantum fluctuations in the orientation of the dipoles
  (e) finite temperature effects
- we find in [7] that (a)-(e) are **no obstacles** for observation of clustered crystal phases!
- possible detection schemes
  - elastic light scattering
  - optical quantum non-demolition detection
  - noise correlations in time-of-flight images
  - spectroscopic measurement of binding energy

CONCLUSIONS

- clustered phases of polar molecules are a distinct consequence of long-ranged and anisotropic nature of interactions
- clustered phases can be explored under current experimental conditions

MK, E. Berg, M. Gahanl, E. Demler, PRB 86, 064501 (2012)

LITERATURE

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ACKNOWLEDGEMENTS

MK acknowledges financial support from the Austrian Science Fund (FWF) under Project No. J3361-N20.