Towards the Creation of Degenerate Fermionic/Bosonic NaK Molecular Gases with Long-range Dipolar Interactions

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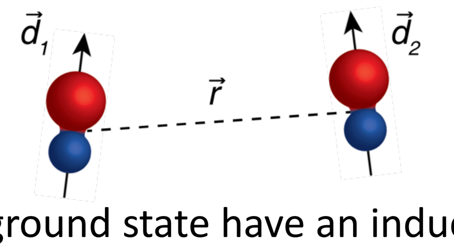
Motivation

Experiments with ultracold atoms probe quantum many-body physics with unprecedented precision. However, bare atoms interact with each other only through **contact interactions** and have limitations in realizing stable long-range anisotropic interactions that arise in nature.



Dipolar Molecules

Bialkali molecules in their absolute ground state have an induced dipole moment that gives them the ability to undergo **long-range anisotropic interactions.**

Thus, one can access :

➔ **Many-body physics**: exotic superfluidity, supersolidity, quantum crystals, long-range lattice spin models...

➔ **Quantum information processing**: processing of quantum information through dipolar interactions in molecular arrays

Why NaK?

Compared to other bialkali molecules, NaK molecules have:

1. **Large dipole moment of 2.72 Debye**
2. **Stability to chemical loss**: NaK + NaK ↛ Na_2 + K_2
3. **Fermionic (^{23}Na ^{40}K) and Bosonic (^{23}Na ^{41}K) molecules**

Fermionic and Bosonic NaK Molecules

Dipolar molecules feature strong, tunable dipole-dipole interactions and rich internal states. These interactions can be precisely controlled using external electric fields and optical trapping.

Dipolar Fermionic molecules are ideal particles to **emulate the behavior of electrons in complex condensed matter systems**. Especially, one may hope to realize exotic fermionic superfluid phases with topological nature. Also, in the presence of an optical lattice, one may realize the extended Fermi-Hubbard model with beyond onsite interactions.

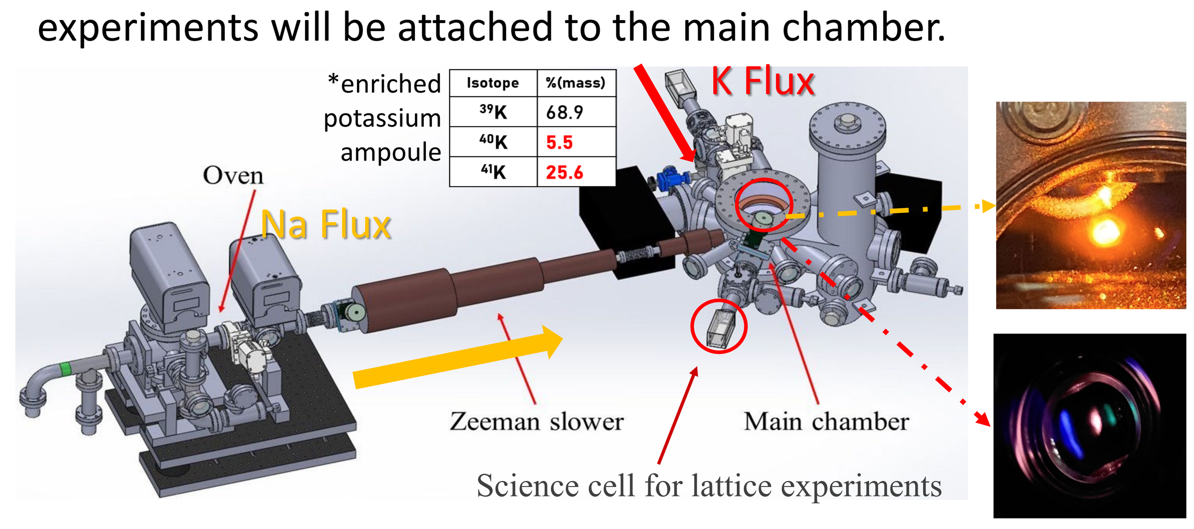
Dipolar Bosonic molecules can access exotic quantum phases such as self-bound quantum droplets, dipolar supersolid states, and Wigner crystals. Also, in the presence of a bilayer 2D trap, interlayer paired bosonic superfluidity may be observed.

How to make ultracold NaK gases?

Apparatus Design

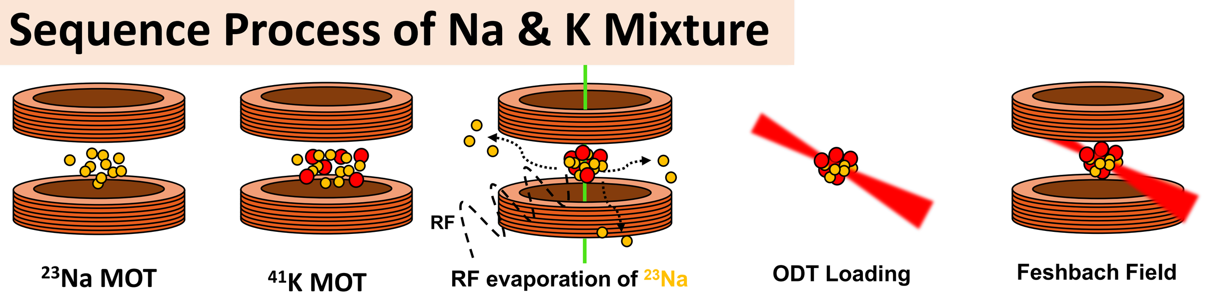
➢ Our NaK apparatus is designated to easily switch between cooling **^{40}K** and **^{41}K** by turning on/off several AOMs in the potassium laser system.

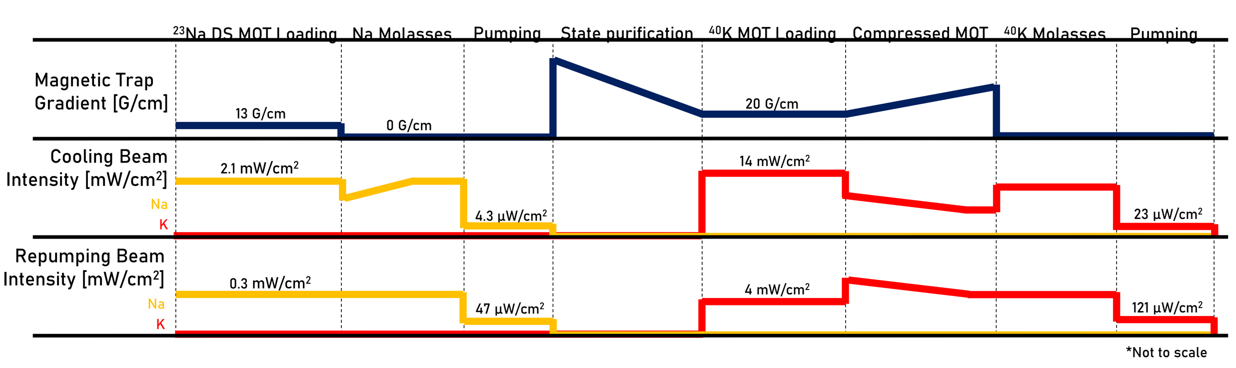
➢ A science cell for high-resolution imaging and lattice experiments will be attached to the main chamber.



Isotope	%(mass)
^{39}K	68.9
^{40}K	5.5
^{41}K	25.6

Sequence Process of Na & K Mixture





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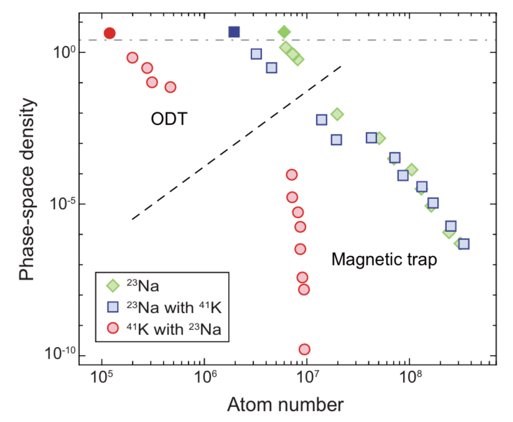
^{23}Na - ^{41}K Feshbach Molecules

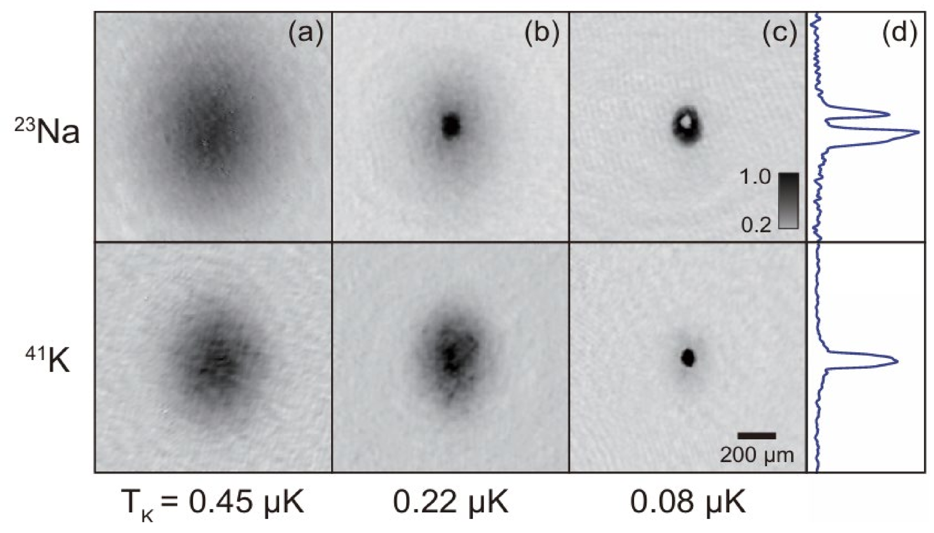
Evaporative Cooling to Dual BEC



[Phase space density curve]

➢ Na (~1x10^9) and ^{41}K (~1x10^8) in $|F=2, m_F=2\rangle$ stretched states are cooled by RF-evaporation of Na, then transferred to a single beam optical dipole trap(ODT) for the rest of evaporative cooling to **dual degeneracy**.

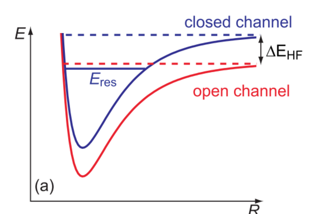
➢ **Dual F=2 BEC of Na & ^{41}K with ~ 10^5 atoms. Such quantum mixture has not been created before!**



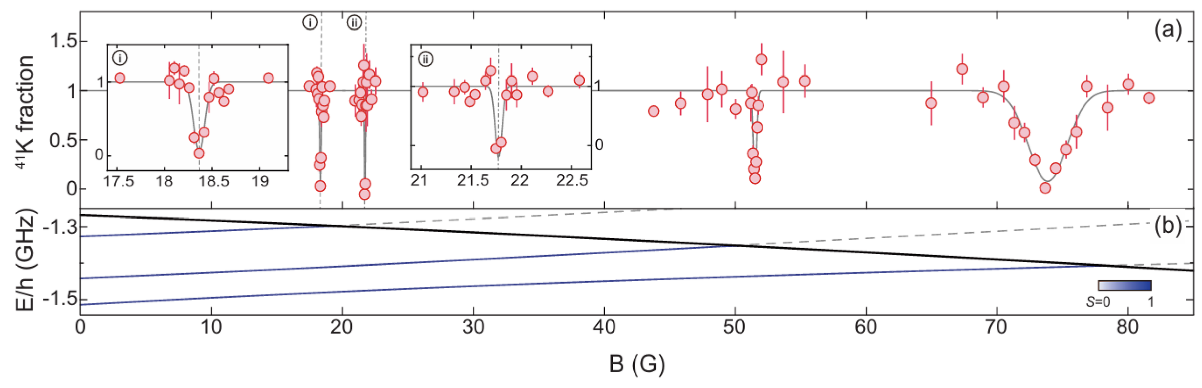
[Sympathetic cooling in optical dipole trap to dual BEC of Na & ^{41}K]

➢ Efficient cooling of both species sets a good starting point for molecule association!

Feshbach Resonance of Na - ^{41}K

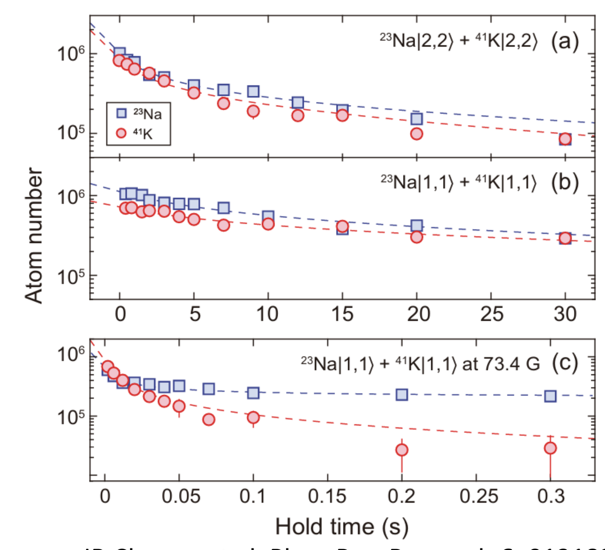


➢ Near Feshbach resonances, strong inelastic scattering occur, so atom loss spectroscopy can be performed.



[Na|1,1> + ^{41}K |1,1> atom loss spectroscopy]

➢ We searched 7 resonances of *s* - wave and *p* - wave collisional channel in three different combinations of Na|1,1> + ^{41}K|1,m$_F$> ,with spin states m$_F$ = 1, 0, and −1.



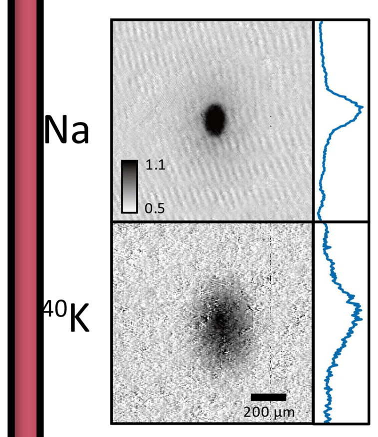
JR Chang., et al. Phys. Rev. Research **6**, 013183

➢ The measured 1/e lifetimes in **Na|1,1> + ^{41}K |1,1>** is 16s and 20s respectively, which is 4~5 times longer than |2,2> mixture. This can be compared to the lifetime observed in Na-^{39}K(240ms).

➢ Lifetime in unitary regime shows rapid decay.

^{23}Na - ^{40}K Feshbach Molecules

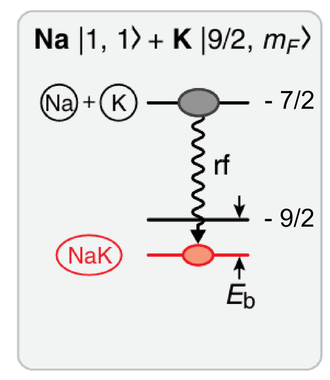
Degenerate Bose-Fermi mixture



➢ Further cooling in ODT after rapid Na ground state($|F=1, m_F=1\rangle$) transfer reached **degenerate Bose-Fermi mixture of Na & ^{40}K** with ~10^5 atoms.

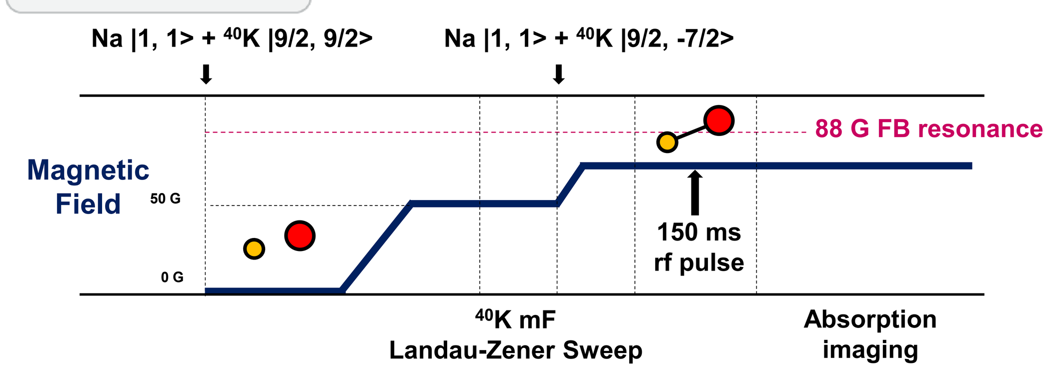
➢ **[Degenerate Mixture of Na^{40}K in ODT, 10ms TOF]**

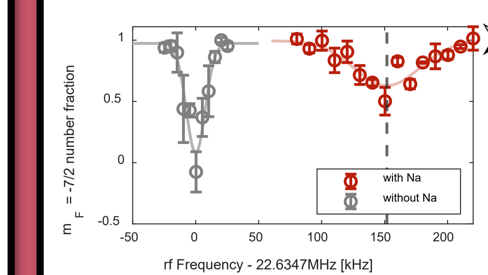
RF Association of Na^{40}K Feshbach Molecules



➢ Na & ^{40}K mixture is transferred to the weakly bound state via rf pulse: "Radio Frequency(rf) Association"

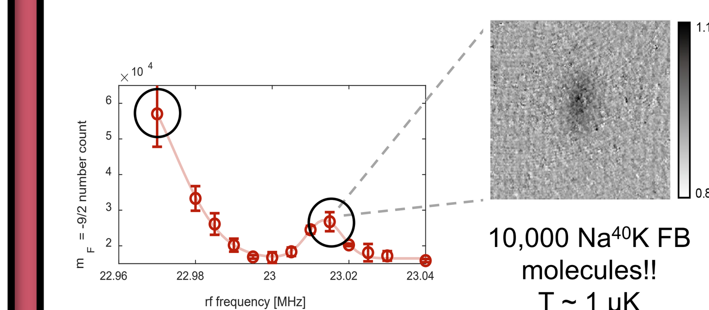
➢ If rf pulse is slightly larger than resonance frequency, this binding energy gap can make molecule.





[Molecular loss spectroscopy]

➢ Molecular loss can be observed by imaging remaining ^{40}K atoms. Loss dip can be observed near bare atom transition, gapped about binding energy.

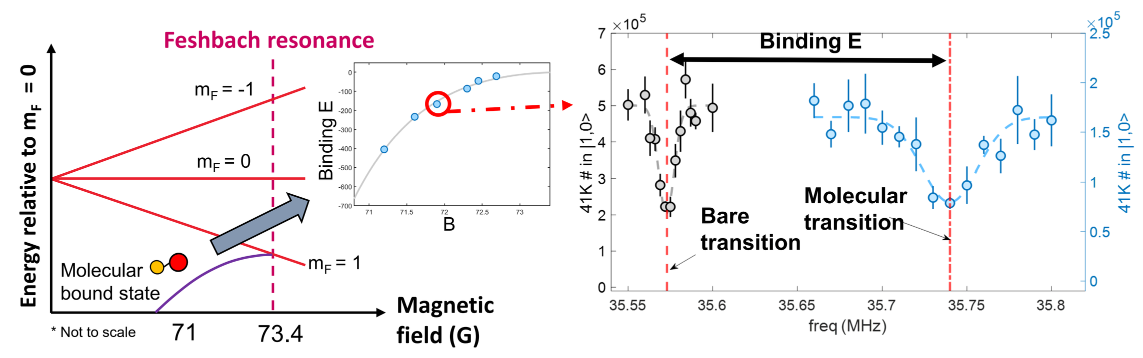


[Molecular direct image]

➢ Arrival spectra of FB molecule in 86.2 G. From this, we could get the direct image of Na^{40}K FB molecules.

RF Loss Spectroscopy

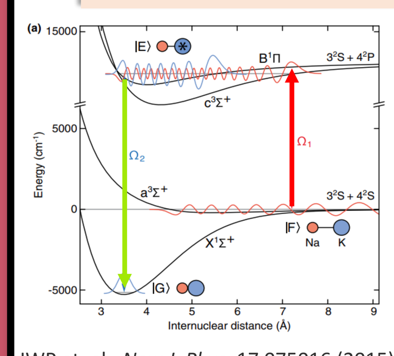
➢ FB resonance can be characterized via rf spectroscopy.



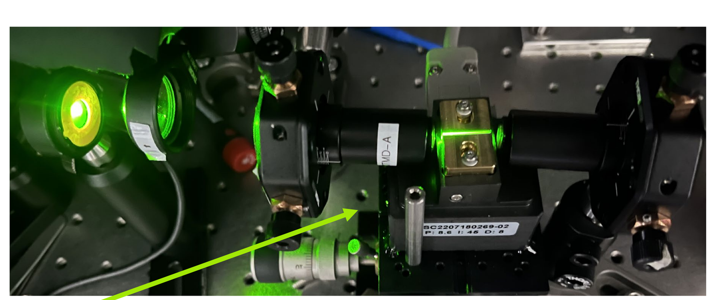
➢ Since weakly bound FB molecules can be imaged by the single atom's resonant beam, we expected it will be able to take direct image of Na^{41}K FB molecules. However, bosonic gases have more serious inelastic loss problem compared with fermion.

Towards Ground State NaK

Ground State NaK

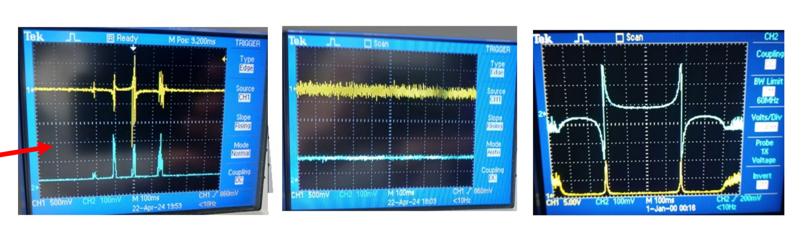


JWP et. al., *New J. Phys.* 17 075016 (2015)



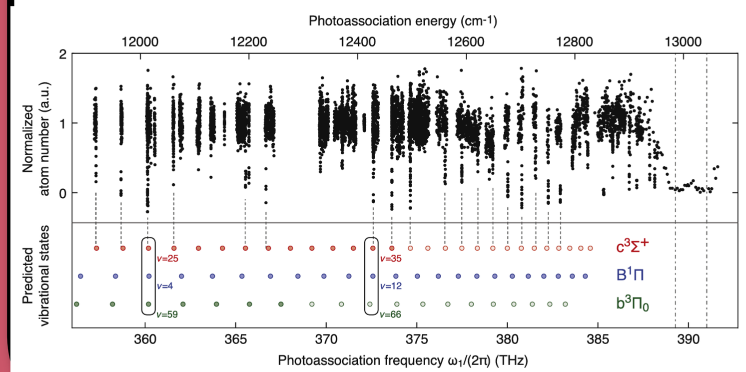
[1134nm ECDL laser frequency doubling to 567nm]

[STIRAP Laser System]



[PDH lock for 567nm and 804nm with ULE cavity]

➢ A STIRAP laser system is being constructed for Na^{40}K & Na^{41}K transitions. (804nm & 567nm)

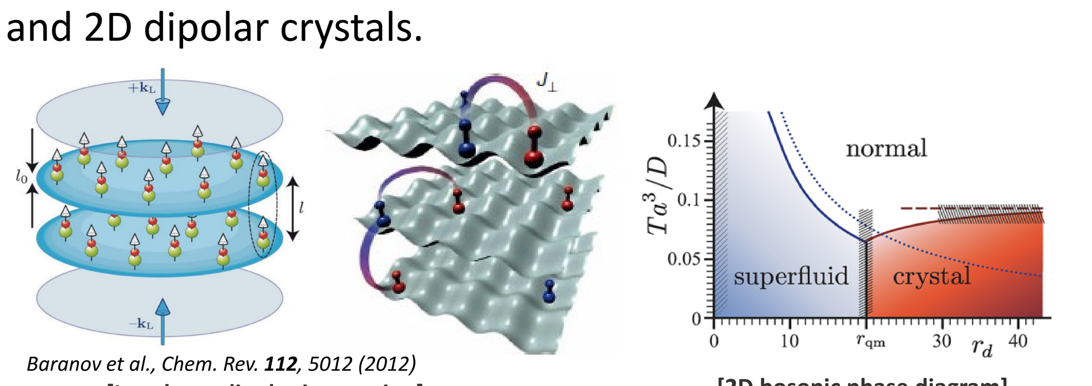


JWP et. al., *New J. Phys.* 17 075016 (2015)

➢ Molecular spectroscopy needs to be performed to reveal a suitable Na^{41}K STIRAP path.

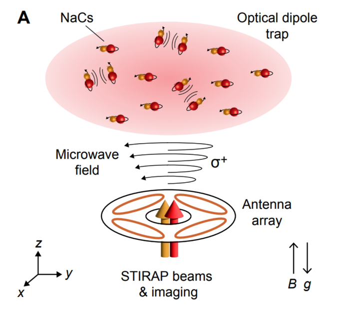
Physics Objectives

➢ **Interlayer paired superfluidity**: With this system, we can explore exotic quantum phase such as paired superfluidity and 2D dipolar crystals.

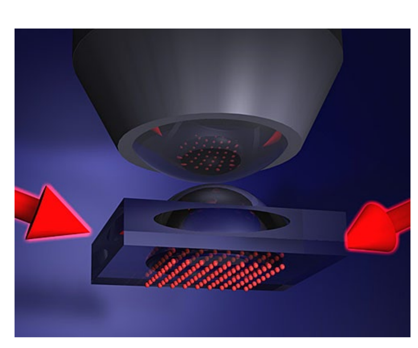


Baranov et al., *Chem. Rev.* **112**, 5012 (2012)
[Interlayer dipolar interaction] [2D bosonic phase diagram]

➢ **Deep quantum degeneracy of NaK Gases**: Quantum degenerate gases of dipolar molecules can be achieved by implementing microwave-shielded(MW) evaporative cooling.



Niccolò Bigagli et al. arXiv:2303.16845 (2023.4)



IMG from Markus Greiner lab, Havard

➢ **Quantum simulation**: With the optical lattice setup at science cell, we can perform quantum simulation of many body physics - extended Hubbard models and spin Hamiltonians - that required long-range interaction.