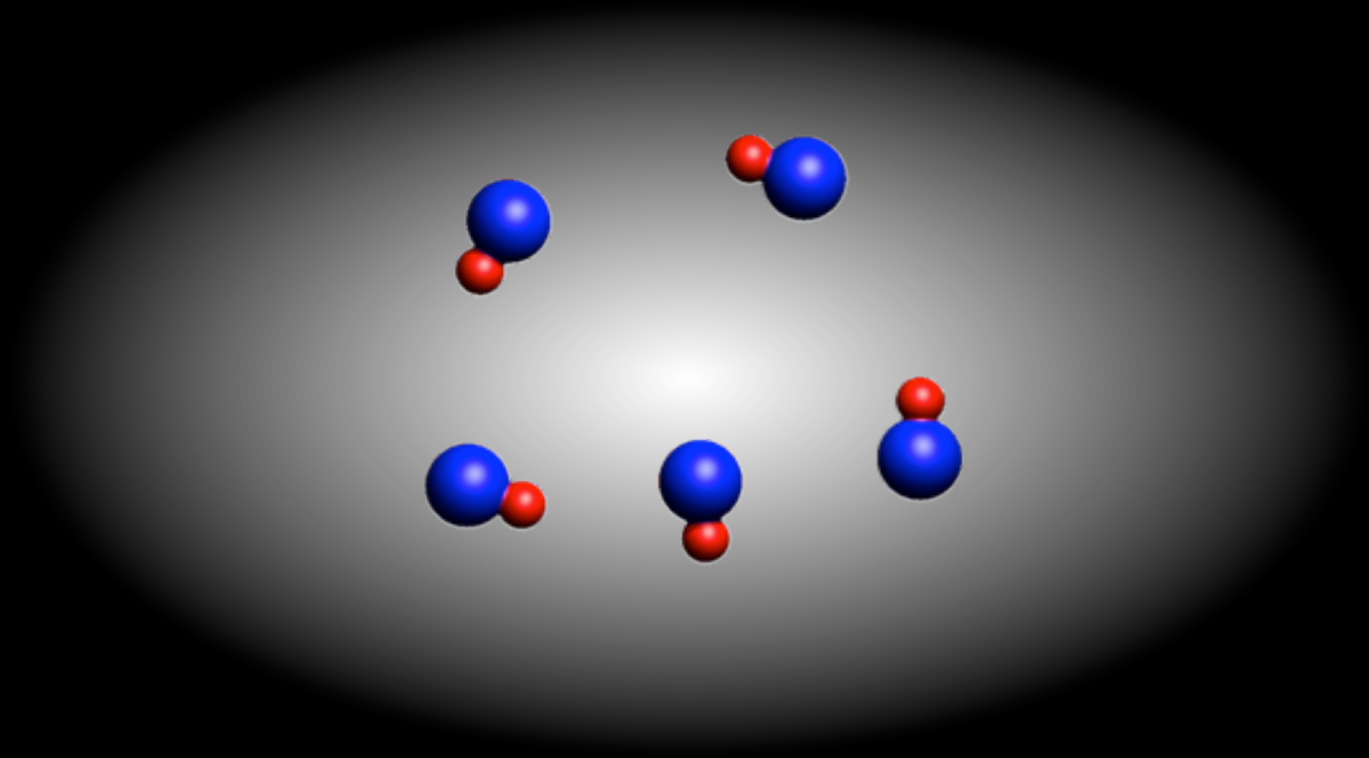
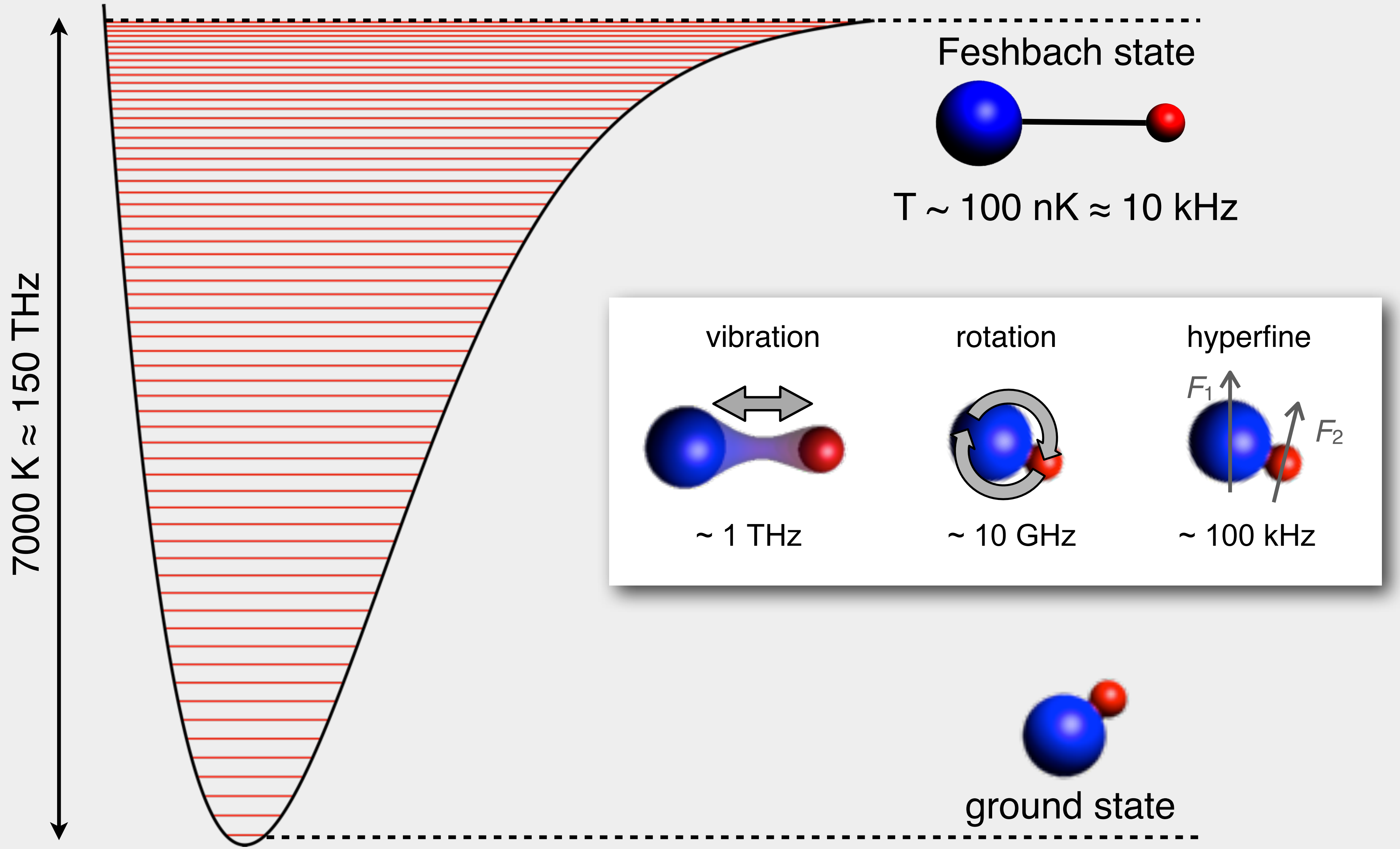
New Science with Ultracold Molecules, Santa Barbara, March 15, 2013

Towards Chemically Stable Ground State Molecules of NaK



Sebastian Will
Jee Woo Park
Jennifer Schloss
Martin Zwierlein

Feshbach molecules - a far way from home...



7000 K ≈ 150 THz

Feshbach state

T ~ 100 nK ≈ 10 kHz

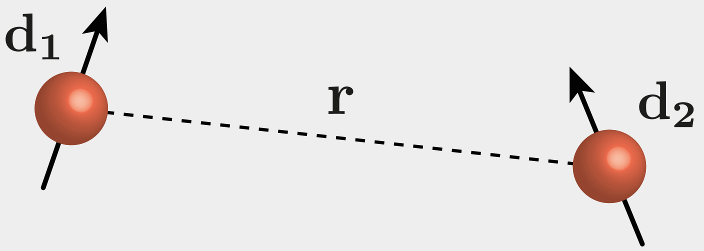
vibration	rotation	hyperfine
~ 1 THz	~ 10 GHz	~ 100 kHz

ground state

Why dipolar interactions?

Dipolar interactions:

- are long-range
- are anisotropic
- can be attractive or repulsive



$$\boxed{V_{\mathrm{dd}} = \frac{1}{4\pi\epsilon_0}\frac{\mathbf{d_1}\cdot\mathbf{d_2} - 3(\mathbf{d_1}\cdot\hat{\mathbf{r}})(\mathbf{d_2}\cdot\hat{\mathbf{r}})}{r^3}}$$

Ultracold dipolar many-body systems:

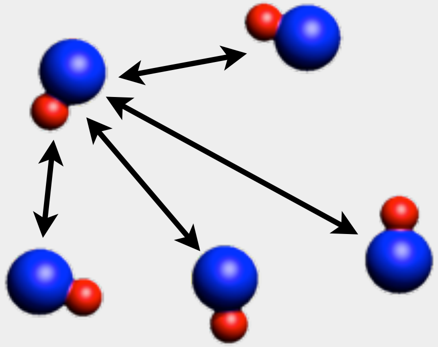
- interesting Hamiltonians
- dimensionality: 0D, 1D, 2D, 3D

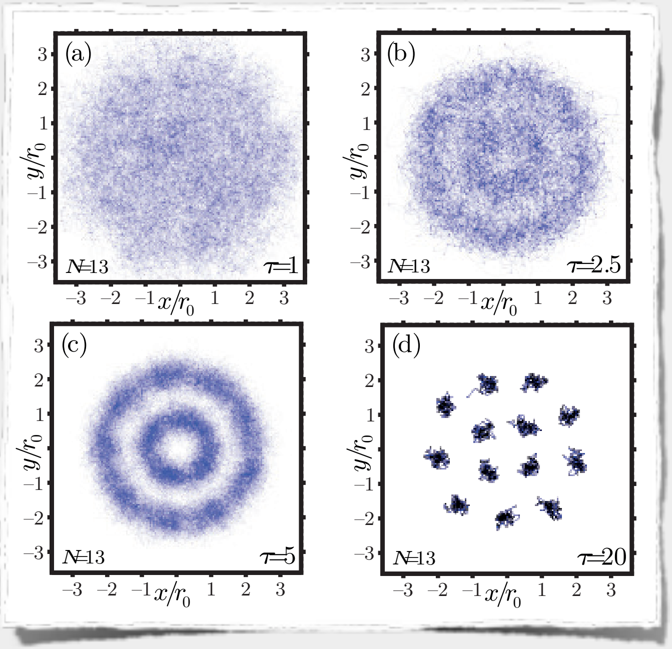
see e.g. Carr *et al.*, NJP, 11 055049 (2009),
Baranov *et al.*, Chem. Rev. 112, 5012 (2012)

Why dipolar fermionic molecules?

Bialkali **fermionic molecules** in the rovibrational **ground state:**

- clean implementation of a **dipolar quantum gas**
- direction and **strength of interactions** are **tunable**
- **dipolar interactions** can **dominate**





Pupillo *et al.*, PRL **104**, 223002 (2010)

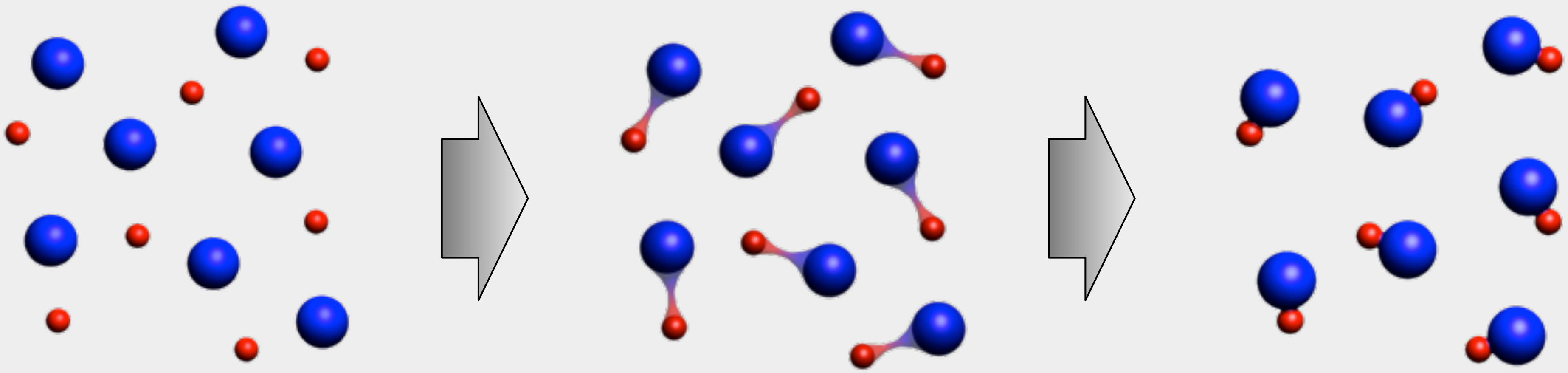
Intriguing experimental possibilities:

- **exotic superfluids**
- **non-trivial ordering** (1D, 2D)
- **quantum magnetism**
- **quantum information** applications
- **quantum chemistry**

$$p_x + ip_y$$

Cooper and Shlyapnikov, PRL **103**, 155302 (2009)

Pioneering work at JILA and Innsbruck



Degenerate Bose-Fermi mixture of ^{40}K and ^{87}Rb

Near-degenerate gas of KRb Feshbach molecules

Near-degenerate gas of ground state molecules

Feshbach association:		**Raman transfer (STIRAP)**
Binding energy:	100 kHz	➜ 100 THz ~ 0.5 eV
Internuclear distance:	300 a_0	➜ 8 a_0
Dipole moment:	5 x 10^{-11} D	➜ up to 0.56 D

K.-K. Ni *et al.,* Science 322, 231 (2008)
J. G. Danzl *et al.*, Science 321, 1062 (2008)

Chemical stability in the ground state

fermionic bialkali molecule	chemically stable ground state
LiNa	✘
LiK	✘
LiRb	✘
LiCs	✘
NaK	✔
KRb	✘
KCs	✔

NaK and **KCs** are the only stable combinations!

Also **stable against trimer formation** in molecule-molecule collisions

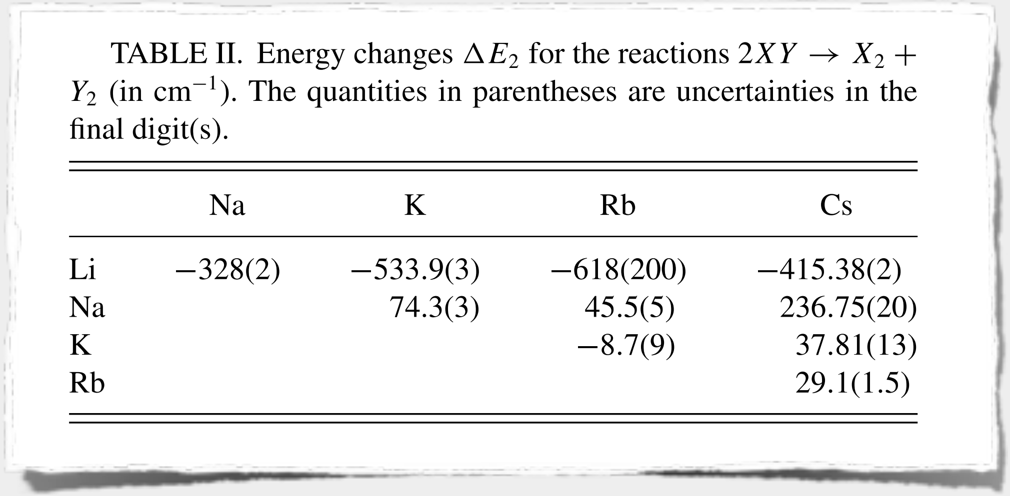


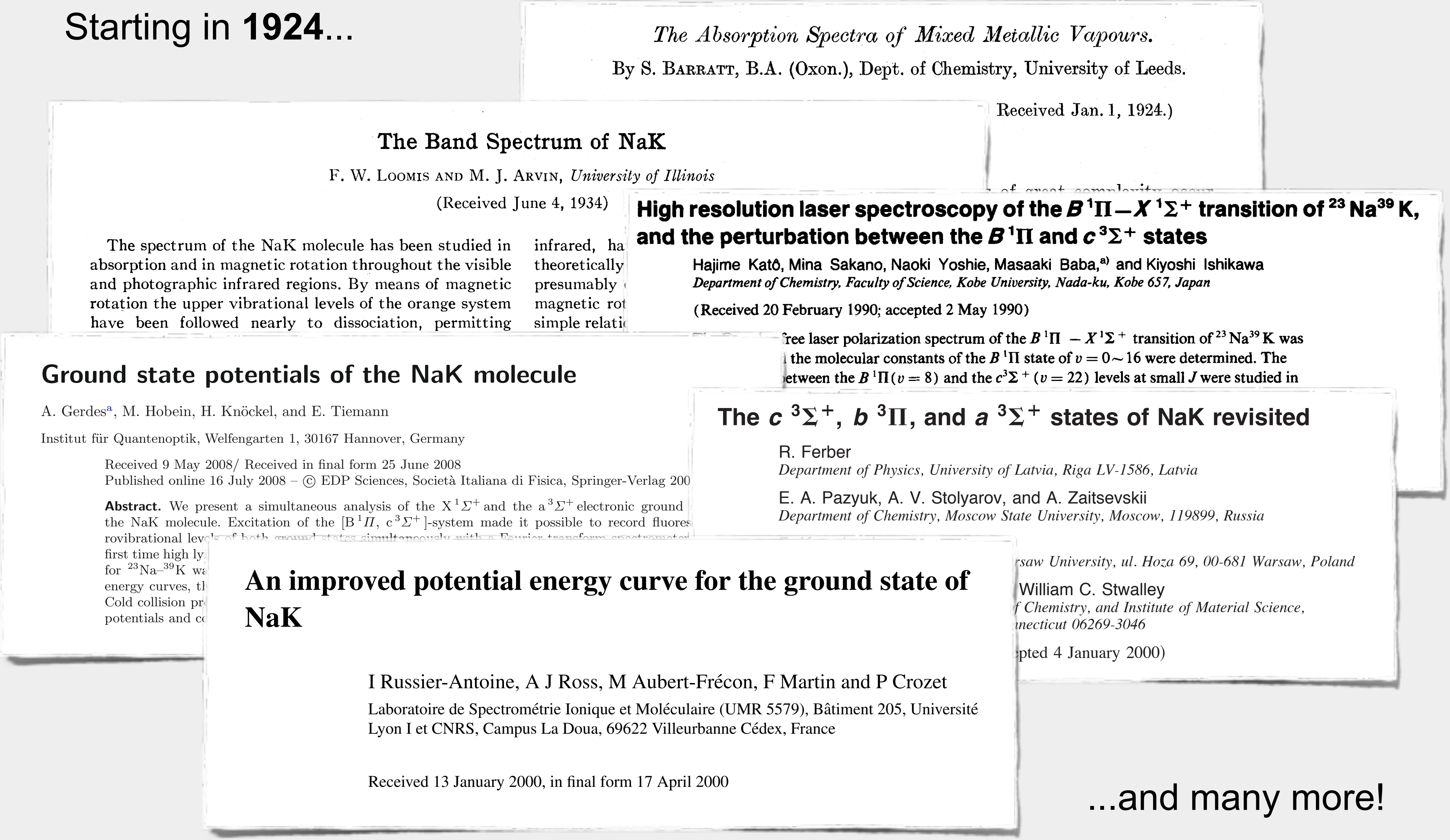
TABLE II. Energy changes ΔE_2 for the reactions $2XY \rightarrow X_2 + Y_2$ (in cm^{-1}). The quantities in parentheses are uncertainties in the final digit(s).

	Na	K	Rb	Cs
Li	−328(2)	−533.9(3)	−618(200)	−415.38(2)
Na		74.3(3)	45.5(5)	236.75(20)
K			−8.7(9)	37.81(13)
Rb				29.1(1.5)

see Zuchowski and Hutson, PRA, **81**, 060703 (2010)

A molecule with a long history...

Starting in **1924**...



The Absorption Spectra of Mixed Metallic Vapours.

By S. Barratt, B.A. (Oxon.), Dept. of Chemistry, University of Leeds.

Received Jan. 1, 1924.)

The Band Spectrum of NaK

F. W. Loomis and M. J. Arvin, *University of Illinois*

(Received June 4, 1934)

The spectrum of the NaK molecule has been studied in absorption and in magnetic rotation throughout the visible and photographic infrared regions. By means of magnetic rotation the upper vibrational levels of the orange system have been followed nearly to dissociation, permitting

infrared, ha
theoretically
presumably
magnetic rot
simple relati

High resolution laser spectroscopy of the $B\,^1\Pi - X\,^1\Sigma^+$ transition of ^{23}Na^{39}K, and the perturbation between the $B\,^1\Pi$ and $c\,^3\Sigma^+$ states

Hajime Katô, Mina Sakano, Naoki Yoshie, Masaaki Baba,[a] and Kiyoshi Ishikawa
Department of Chemistry, Faculty of Science, Kobe University, Nada-ku, Kobe 657, Japan

(Received 20 February 1990; accepted 2 May 1990)

free laser polarization spectrum of the $B\,^1\Pi - X\,^1\Sigma^+$ transition of ^{23}Na^{39}K was
the molecular constants of the $B\,^1\Pi$ state of $v = 0 \sim 16$ were determined. The
etween the $B\,^1\Pi(v = 8)$ and the $c^3\Sigma^+(v = 22)$ levels at small J were studied in

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Ground state potentials of the NaK molecule

A. Gerdes[a], M. Hobein, H. Knöckel, and E. Tiemann

Institut für Quantenoptik, Welfengarten 1, 30167 Hannover, Germany

Received 9 May 2008/ Received in final form 25 June 2008
Published online 16 July 2008 – © EDP Sciences, Società Italiana di Fisica, Springer-Verlag 200

Abstract. We present a simultaneous analysis of the $X\,^1\Sigma^+$ and the $a\,^3\Sigma^+$ electronic ground
the NaK molecule. Excitation of the $[B\,^1\Pi,\ c\,^3\Sigma^+]$-system made it possible to record fluores
rovibrational lev
first time high ly
for ^{23}Na–^{39}K wa
energy curves, th
Cold collision pr
potentials and co

The $c\ ^3\Sigma^+$, $b\ ^3\Pi$, and $a\ ^3\Sigma^+$ states of NaK revisited

R. Ferber
Department of Physics, University of Latvia, Riga LV-1586, Latvia

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Department of Chemistry, Moscow State University, Moscow, 119899, Russia

rsaw University, ul. Hoza 69, 00-681 Warsaw, Poland

William C. Stwalley
f Chemistry, and Institute of Material Science,
nnecticut 06269-3046

pted 4 January 2000)

An improved potential energy curve for the ground state of NaK

I Russier-Antoine, A J Ross, M Aubert-Frécon, F Martin and P Crozet

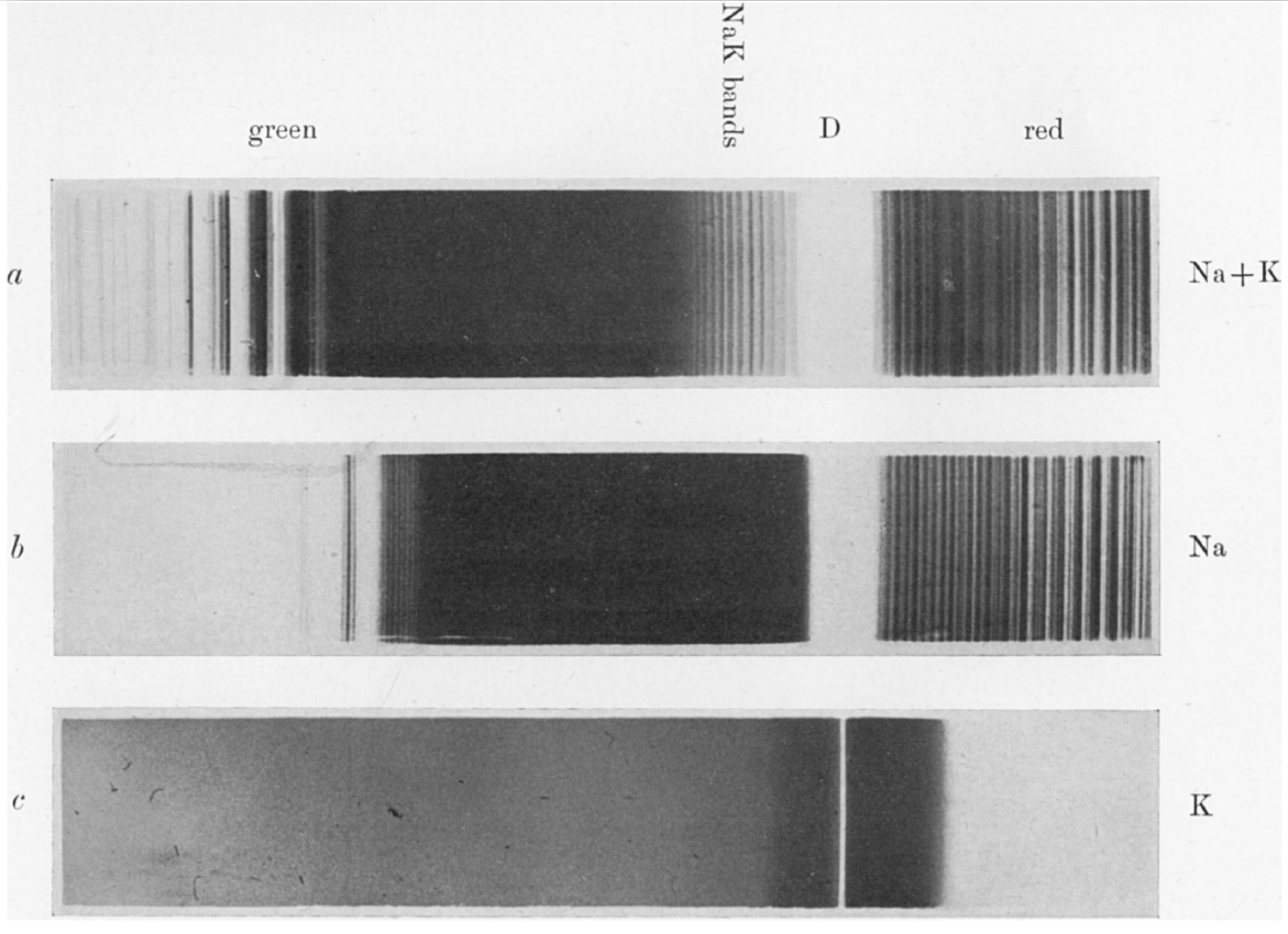
Laboratoire de Spectrométrie Ionique et Moléculaire (UMR 5579), Bâtiment 205, Université Lyon I et CNRS, Campus La Doua, 69622 Villeurbanne Cédex, France

Received 13 January 2000, in final form 17 April 2000

...and many more!

Features of NaK

- **textbook diatomic molecule** - first spectra recorded in 1924



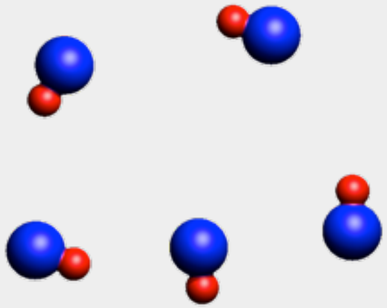
"The Absorption Spectra of Mixed Metallic Vapours",
S. Barratt, Proc. Roy. Soc. London, Series A, 105, 221 (1924)

Features of NaK

- **textbook diatomic molecule** - first spectra recorded in 1924

  Barratt (1924), Walter & Barratt (1928), Ritschl & Villars (1928),
  Loomis & Arven (1934), Sinha (1948), Cowley (1969), Breford & Engelke (1978),
  Demtröder (1979), McCormack & McCafferey (1979), Ross (1985), Kato (1989),...

- **chemically stable** in its ground state



$$\boxed{\mathrm{NaK} + \mathrm{NaK} \nrightarrow \mathrm{Na_2} + \mathrm{K_2}}$$

$2 \times 5274\ \mathrm{cm}^{-1} = 10548\ \mathrm{cm}^{-1} > 10474\ \mathrm{cm}^{-1} = 6022\ \mathrm{cm}^{-1} + 4451\ \mathrm{cm}^{-1}$

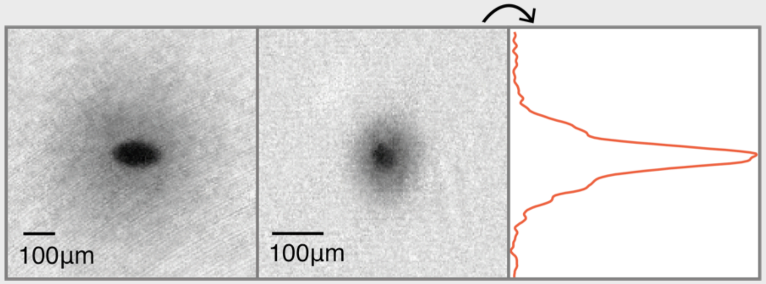
- large induced electric dipole moment of **2.72 Debye**

Dipolar interaction energy up to 30% of E_{Fermi}

Worldwide efforts:
MIT, Hannover, Munich, Trento, Chin. Acad. of Science, HKUST

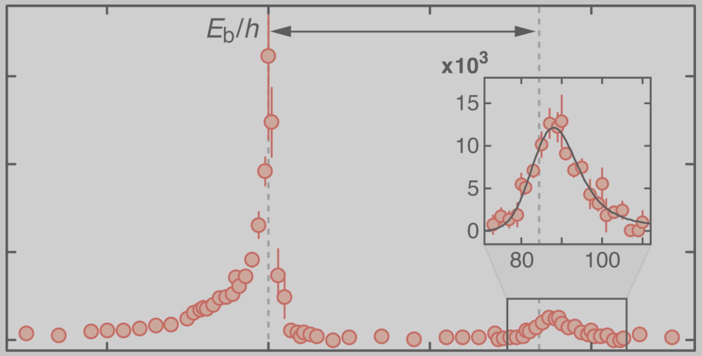
Zuchowski and Hutson, PRA, **81**, 060703 (2010)
Wormsbecher *et al.*, J. Chem. Phys., 74, 6983 (1981)

Quantum degenerate ^{23}Na^{40}K Bose-Fermi mixture and its Feshbach resonances



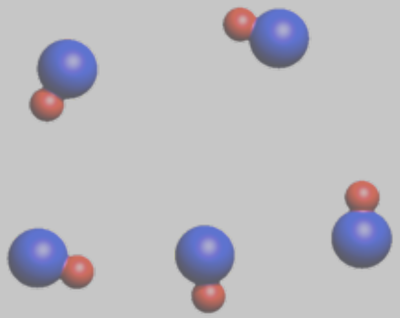
see Park *et al.*, Phys. Rev. A 85, 051602 (R) (2012)

Ultracold fermionic Feshbach molecules of ^{23}Na^{40}K



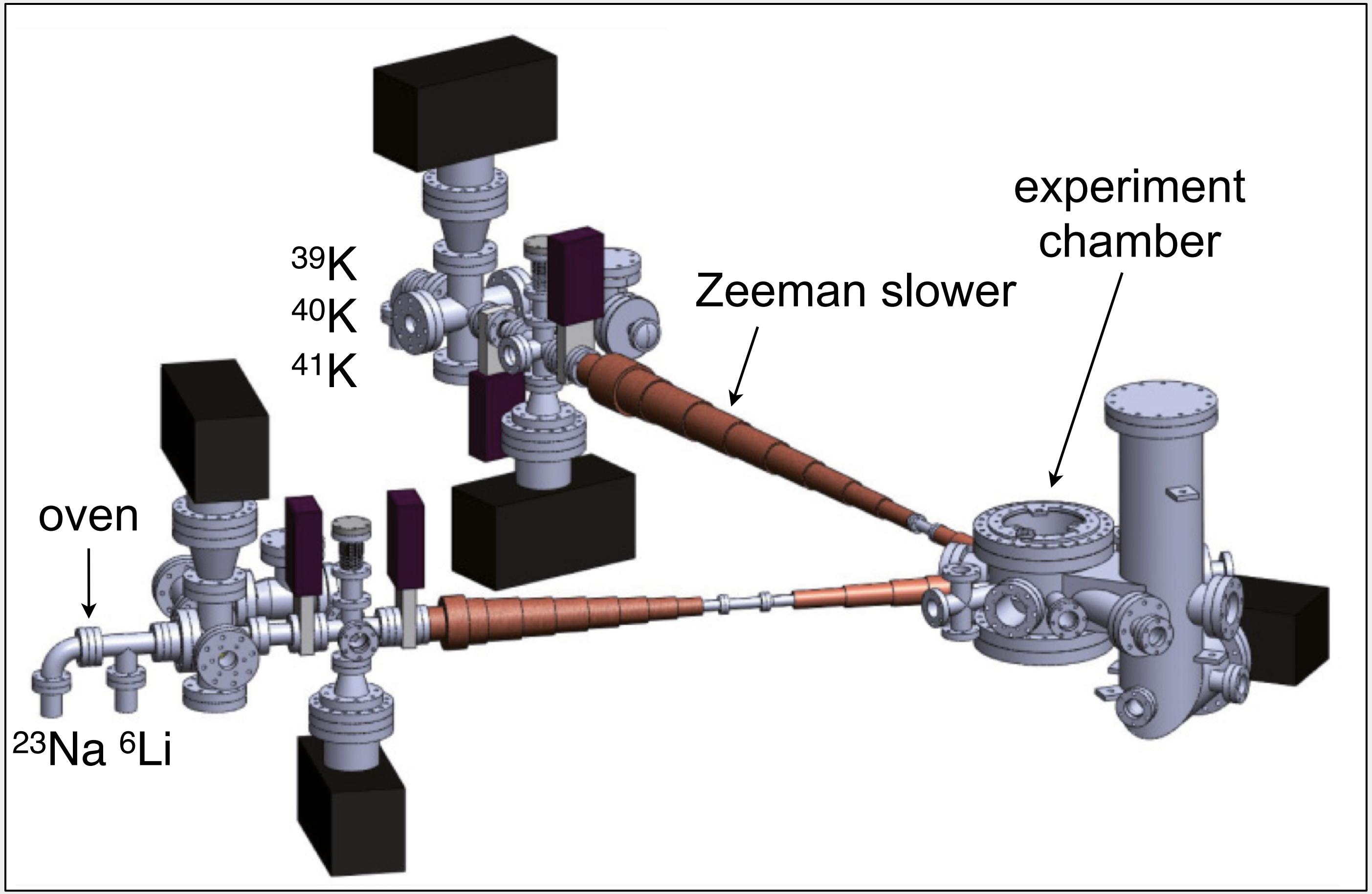
see Wu et al., PRL 109, 085301 (2012)

Towards fermionic ground state molecules of ^{23}Na^{40}K



Experimental setup

see Wu *et al.*, Phys. Rev. A **84**, 011601 (R) (2011)



Studies with

Bose

Fermi

Bose-Bose

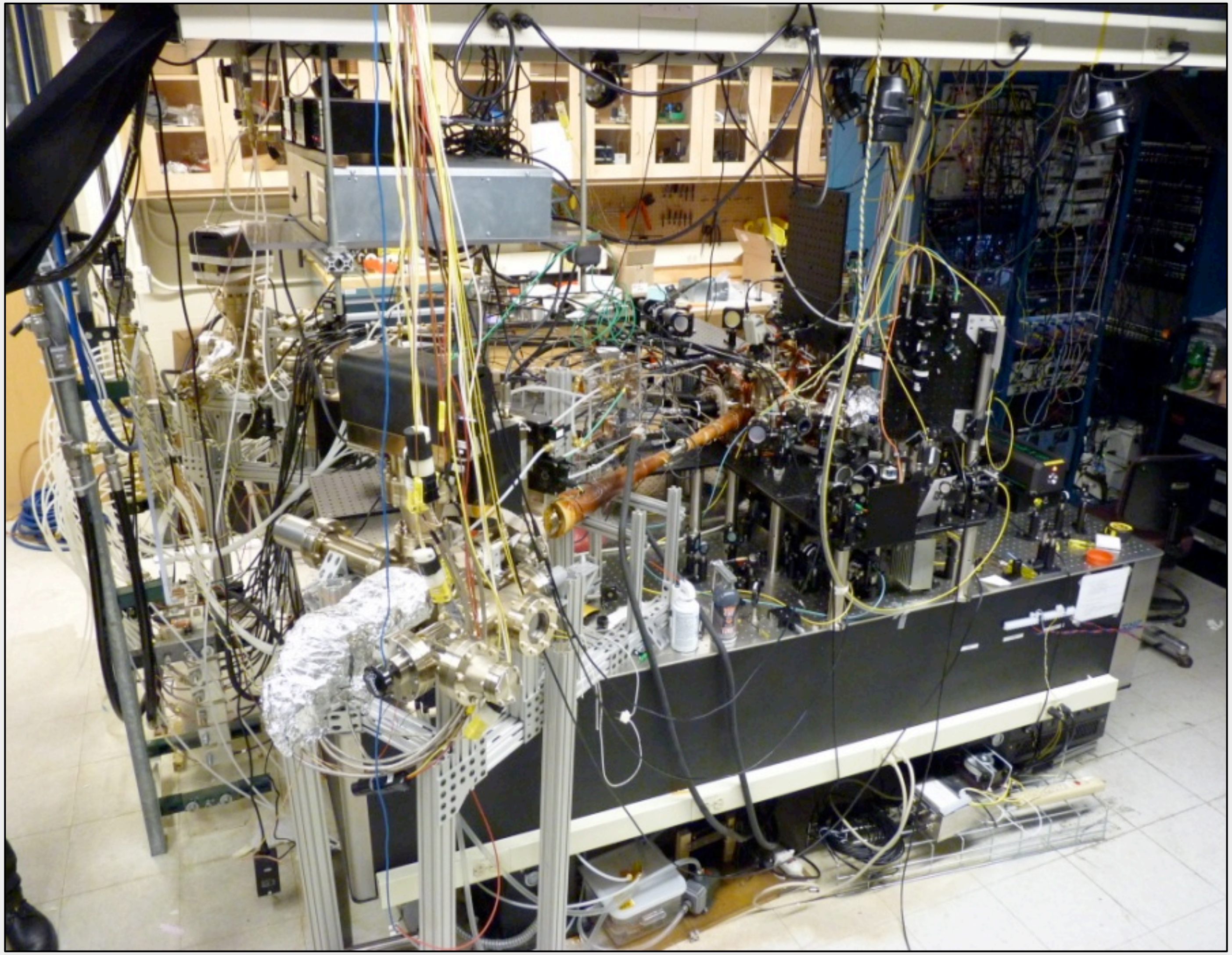
Bose-Fermi

Fermi-Fermi

systems

possible!

Experimental setup - for real



Simultaneous loading of all species possible!

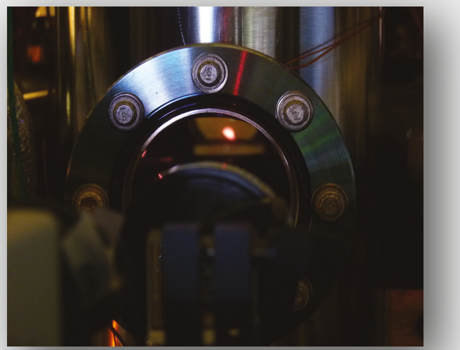
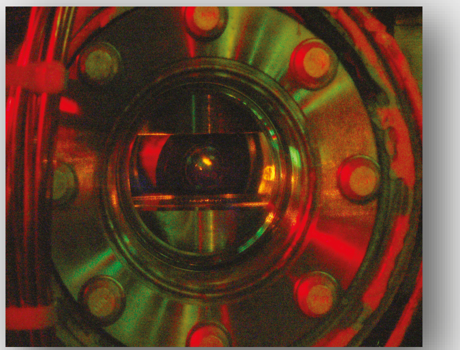
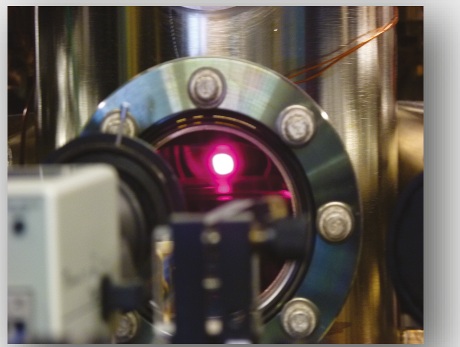
^{23}Na MOT: 10^{9} atoms

^{40}K MOT: 10^{7} atoms

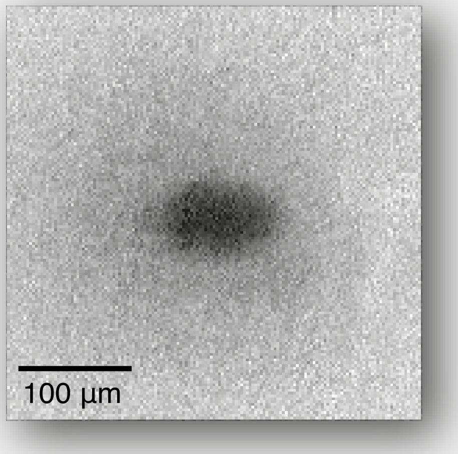
only 0.01% abundance

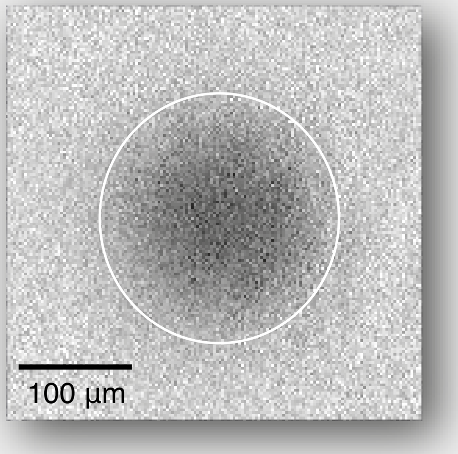
Triple degeneracy

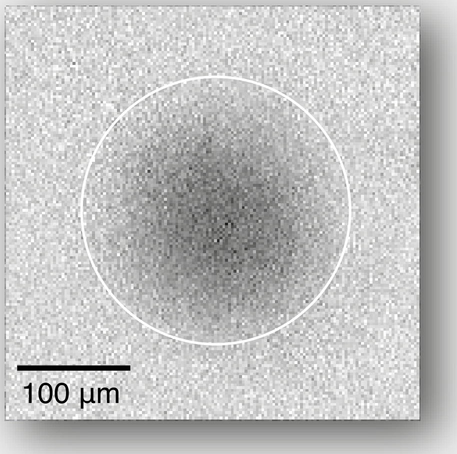
see Wu *et al.*, Phys. Rev. A **84**, 011601 (R) (2011)

^{41}K **^{40}K** **^{6}Li**

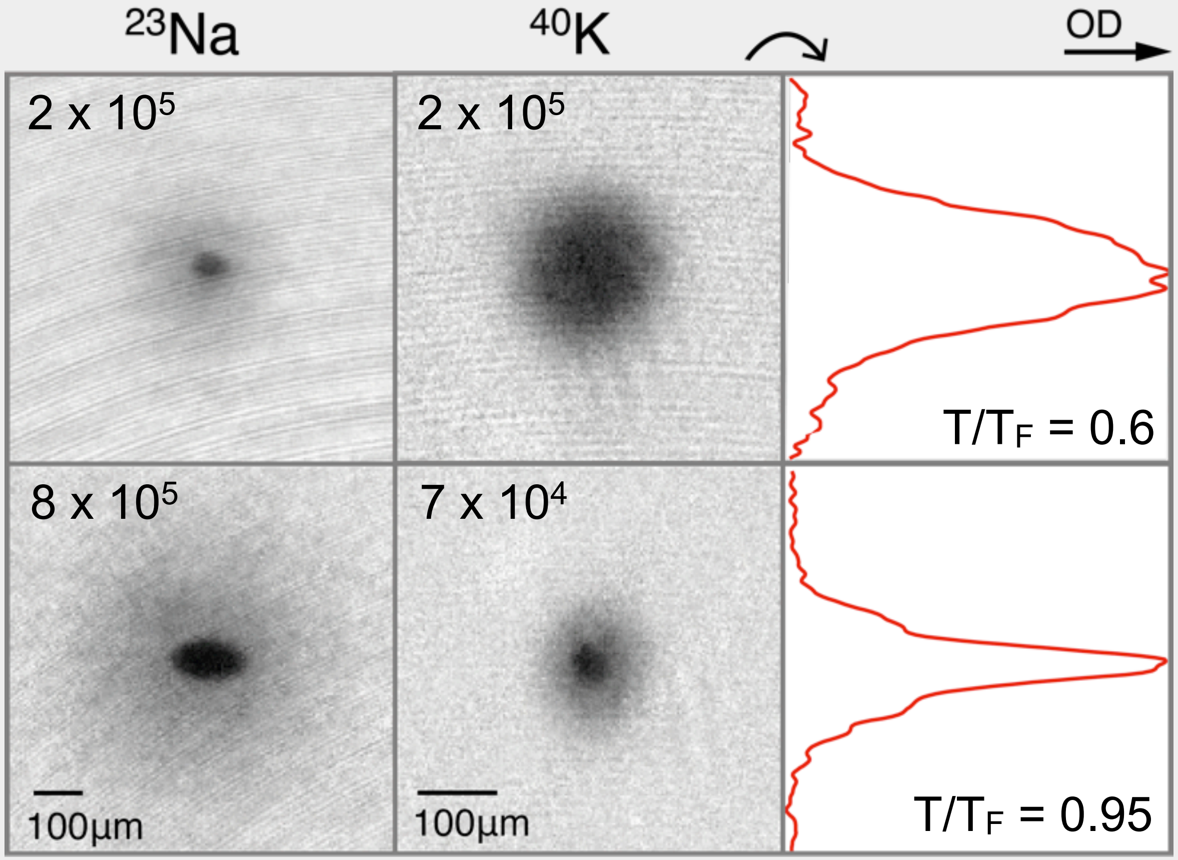






Sodium-Potassium: A new Bose-Fermi mixture

see Park *et al.*, Phys. Rev. A **85**, 051602 (R) (2012)



Efficient sympathetic cooling of ^{40}K using ^{23}Na

Sharp **increase of central density** in ^{40}K

Strongly attractive interactions between **Na** and **K**!

Mean-field energy k_B x 6 µK (for $a_{bg} = -690\ a_0$)

Only 4 sec RF evaporation in magnetic trap plus 4 sec in optical trap!

Sympathetic cooling of NaK

see Park *et al.*, Phys. Rev. A **85**, 051602 (R) (2012)

Cooling efficiency

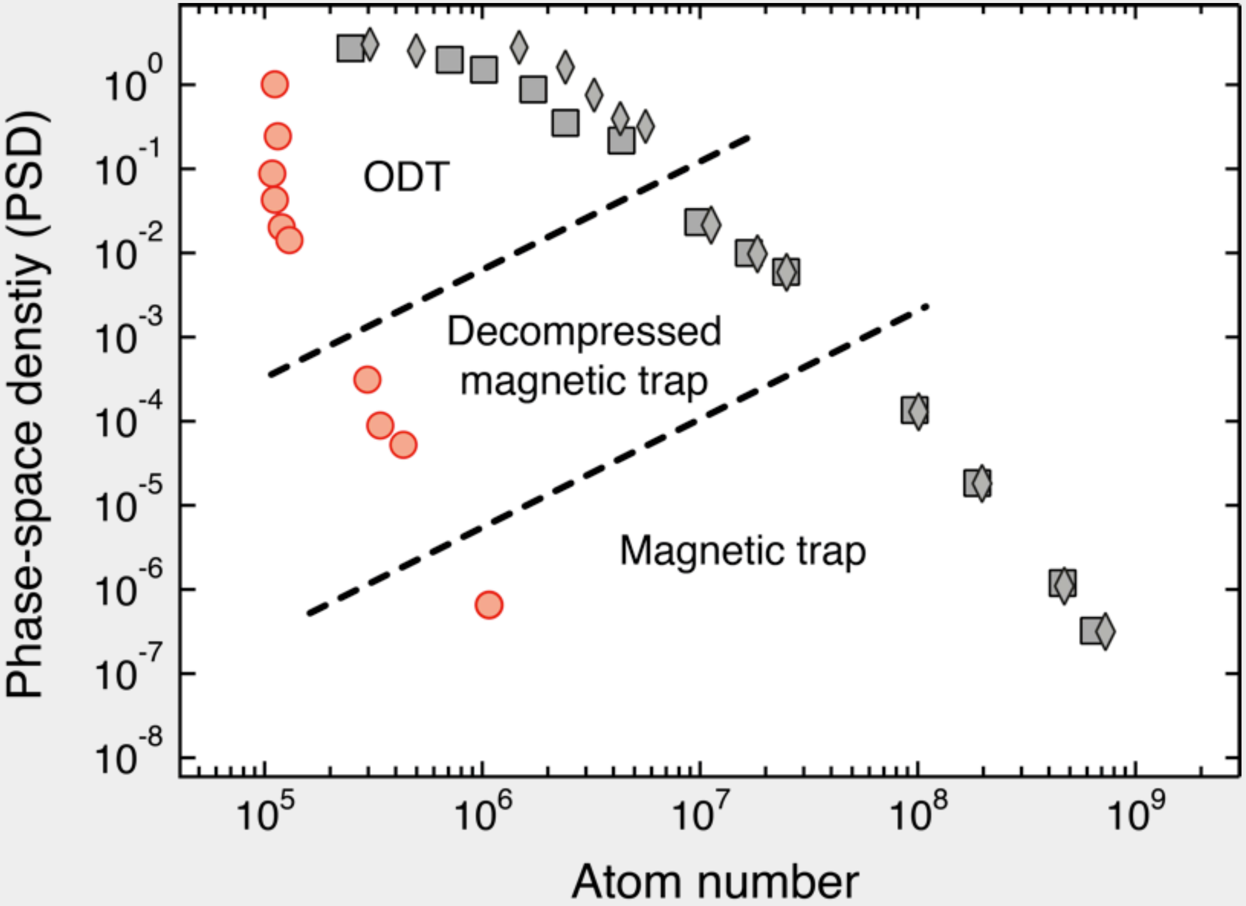
$$\Gamma = -\frac{d\ln(\mathrm{PSD})}{d\ln(N)}$$

Magnetic trap: $\Gamma_{\mathrm{Na}} = 2.7$

$\Gamma_{\mathrm{K}} = 4.6$

Optical trap: $\Gamma_{\mathrm{Na}} = 1$

$\Gamma_{\mathrm{K}} = 15.3$

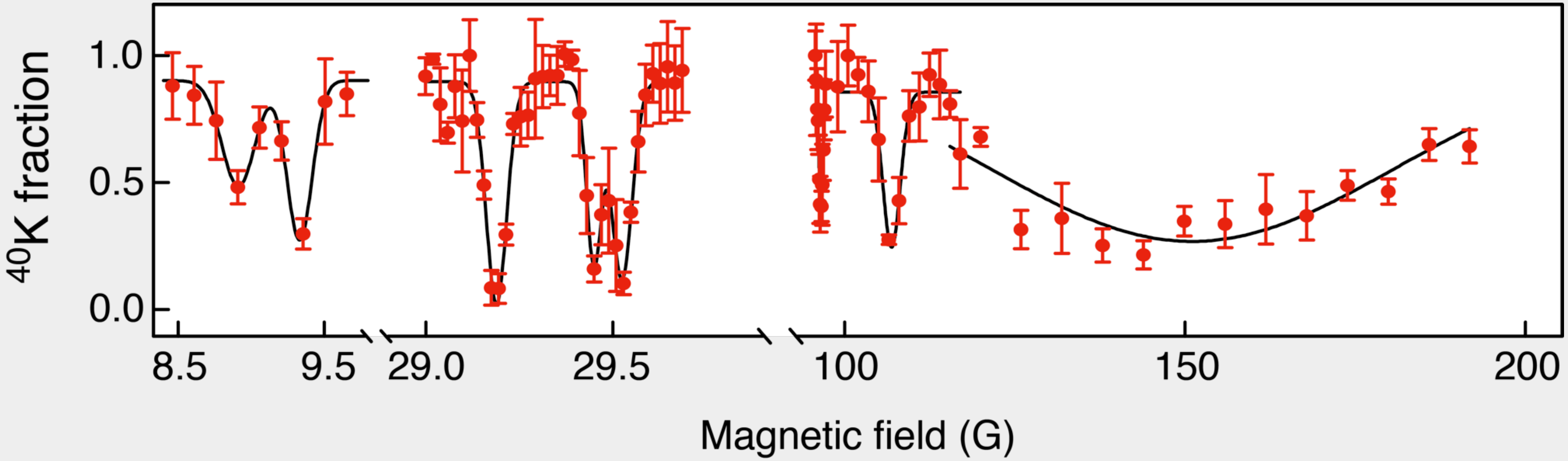


^{40}**K** can be **efficiently cooled** by ^{23}Na!

Observation of Feshbach resonances

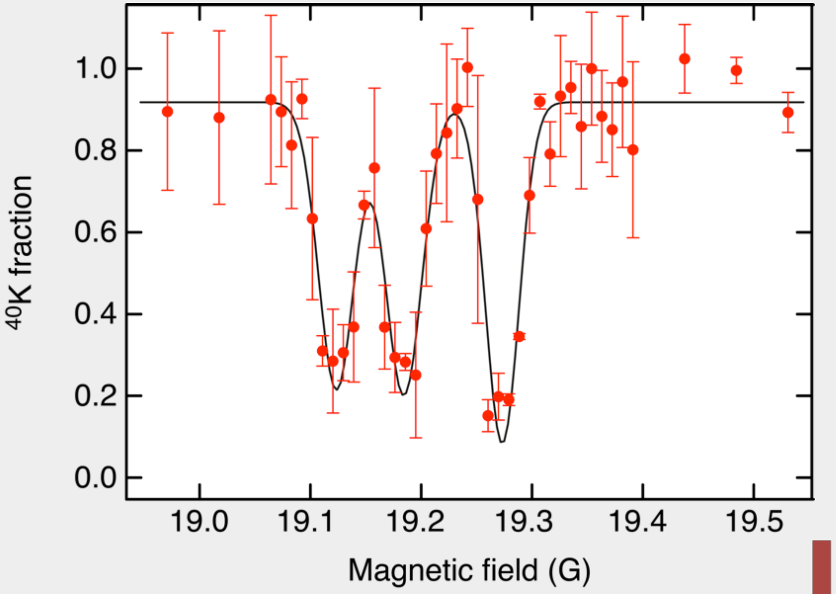
see Park *et al.*, Phys. Rev. A **85**, 051602 (R) (2012)

Feshbach loss spectroscopy for Na |1,+1〉 and K |9/2,-5/2〉



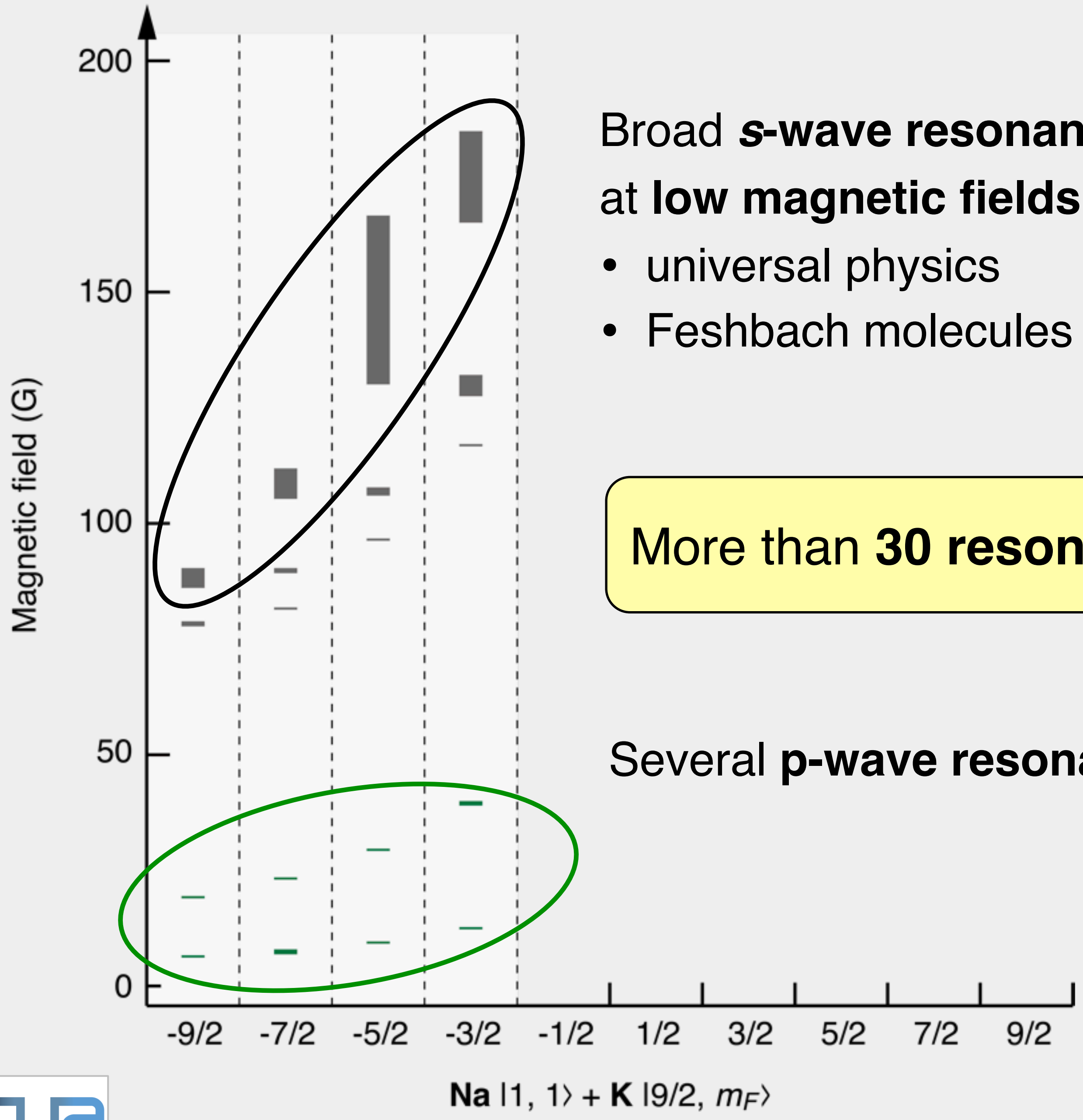
p-wave resonances:

Several ***p*-wave multiplets at low fields** resolved!



Experimentally observed resonances

see Park *et al.*, Phys. Rev. A **85**, 051602 (R) (2012)



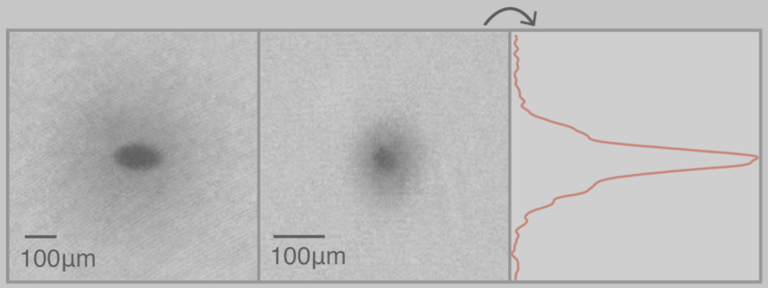
Broad ***s*-wave resonances** in a Bose-Fermi mixture at **low magnetic fields**:

- universal physics
- Feshbach molecules

More than **30 resonances below 200 G!**

Several **p-wave resonances** at low field

Quantum degenerate ^{23}Na^{40}K Bose-Fermi mixture and its Feshbach resonances



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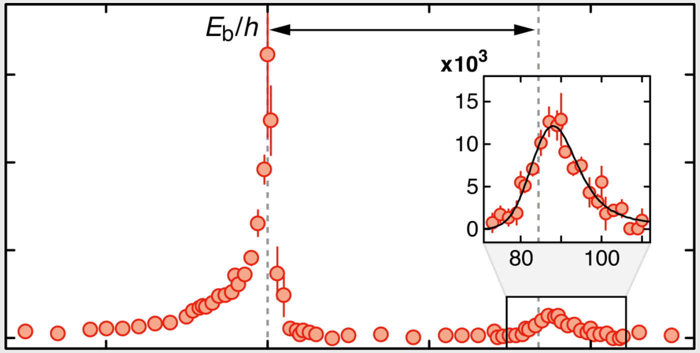
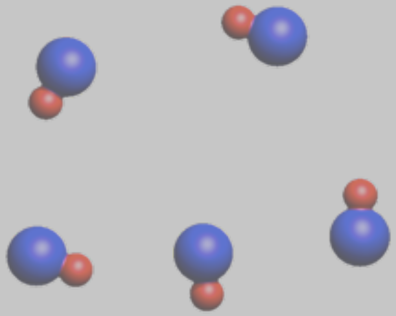
Ultracold fermionic Feshbach molecules of ^{23}Na^{40}K



see Wu et al., PRL 109, 085301 (2012)

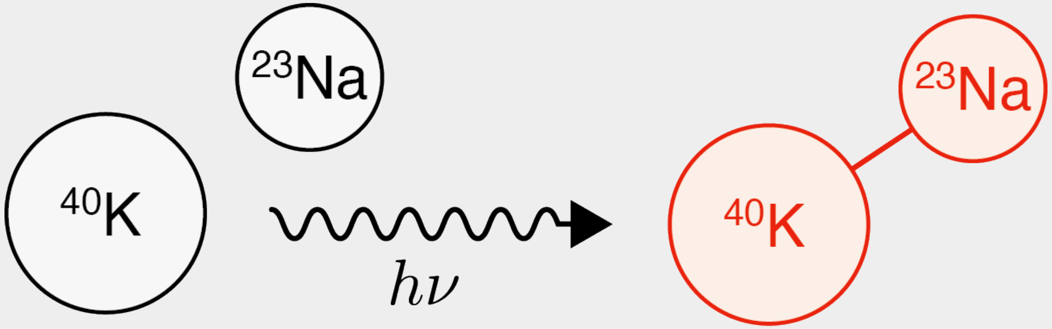
Towards fermionic ground state molecules of ^{23}Na^{40}K



RF spectroscopy on molecules

Why **RF spectroscopy?**

- Yields a lot of **information about the system** (↔ Feshbach ramp)
- For wide Feshbach resonances: **Molecular wavefunction can a have** large extent and **good overlap with** two **unbound atoms.**



„atoms on a stick"

Typical atom numbers:

^{23}Na: 150.000 atoms

^{40}K: 150.000 atoms

T for optimized phase space overlap:

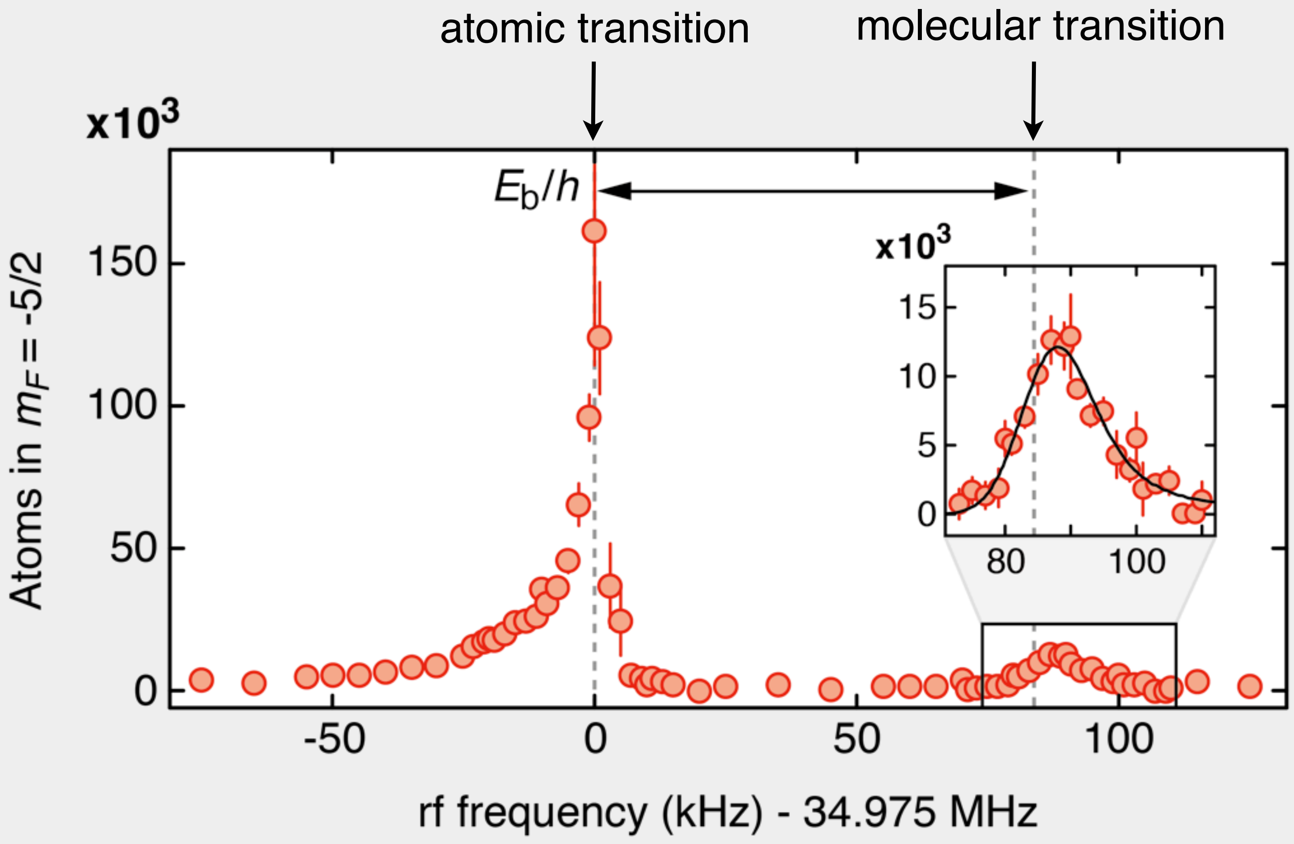
^{23}Na: around T_C

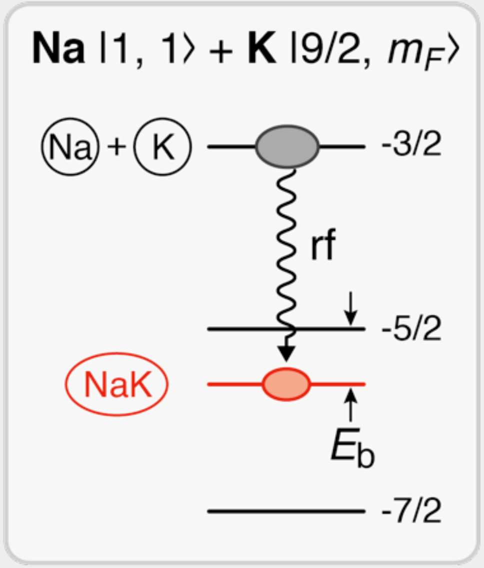
^{40}K: corresponding to $T/T_F = 0.4$

Blackman pulse

Association spectrum

$B = 129.4$ G

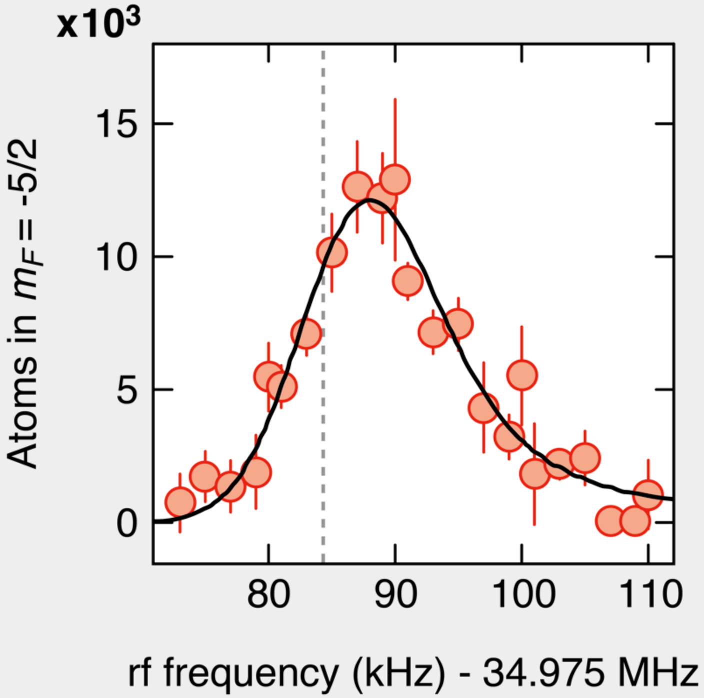



Na |1, 1⟩ + **K** |9/2, m_F⟩

- atomic **mean-field tail** due to repulsion
- about **15%** molecule **conversion efficiency**

see Wu *et al.*, PRL **109**, 085301 (2012)

Lineshape of the molecule peak



$E_b = h$ x 84(6) kHz

- convoluted with rf Fourier width
- width compatible with temperature

Probability density for Na-K pairs with relative kinetic energy ϵ :

$$p(\epsilon) = \rho(\epsilon)\lambda_M^3 \exp\left(-\frac{\mu}{M}\frac{\epsilon}{k_\mathrm{B}T}\right)$$

$$\Gamma_\mathrm{mol}(\nu) \propto \mathcal{F}(h\nu - E_\mathrm{b})p(h\nu - E_\mathrm{b})$$

$$\mathcal{F}(\epsilon) \propto (1 + \epsilon/E_\mathrm{b})^{-2}$$

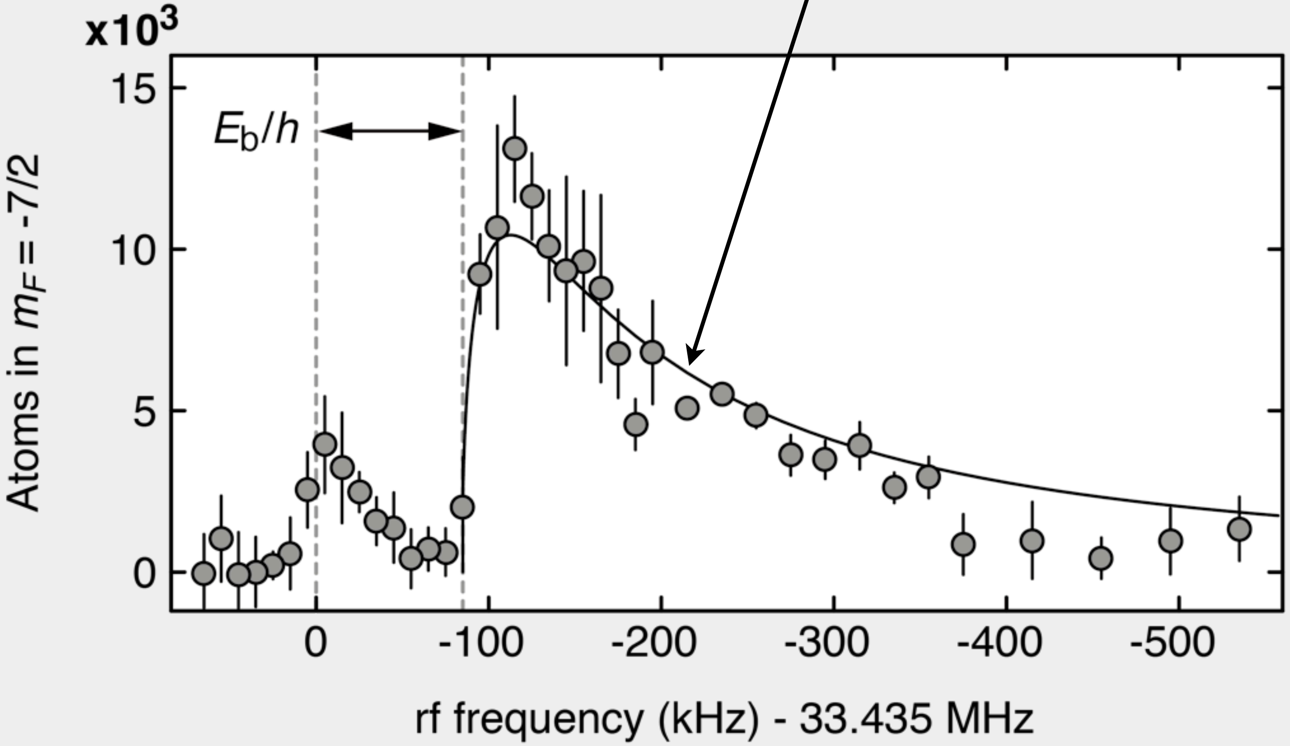
Franck-Condon factor between unbound Na-K pair and bound Feshbach molecule

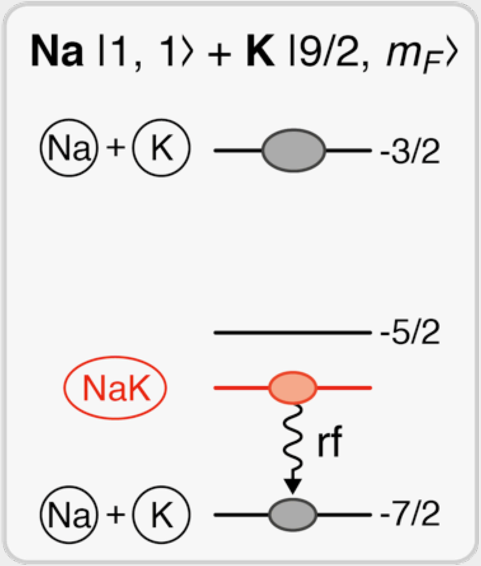
Related work: Chin and Julienne, PRA 71, 012713 (2005), Klempt *et al.*, PRA 78, 061602 (2008)

Dissociation spectrum

$B = 129.4$ G

fit model $\propto \theta(\nu - \nu_\mathrm{b}) \frac{\sqrt{\nu - \nu_\mathrm{b}}}{\nu^2}$

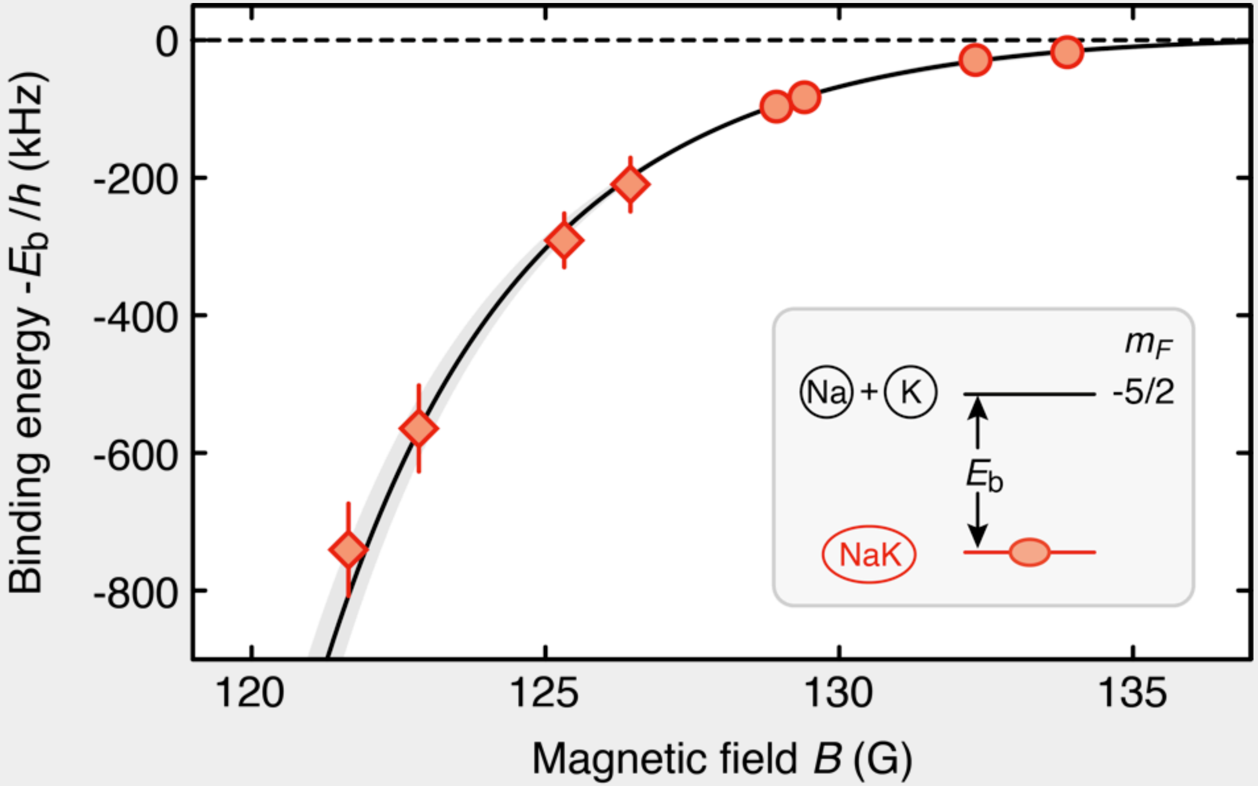




$E_\mathrm{b} = h \times 85(8)$ kHz

In lifetime measurements: Dissociation ensures **exclusive detection of molecules**!

Binding energy versus magnetic field



$$E_\mathrm{b} \approx \frac{\hbar^2}{2\mu(a-\bar{a})^2}$$

$$a(B) \approx a_\mathrm{bg}\left(1+\frac{\Delta B}{B-B_0}\right)$$

a_{bg} = -690(130) a_0

ΔB = 29(2) G

B_0 = 139.7(2.1) G

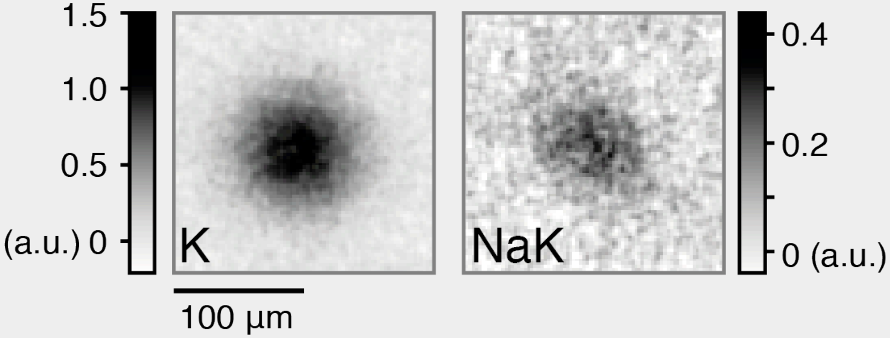
Molecules are open-channel dominated over a large field range

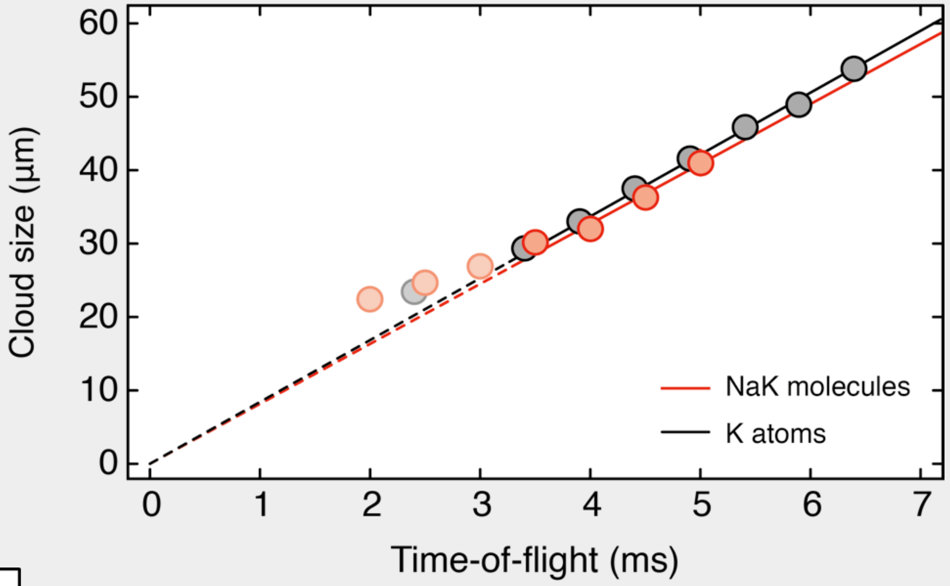
“two atoms on a stick”

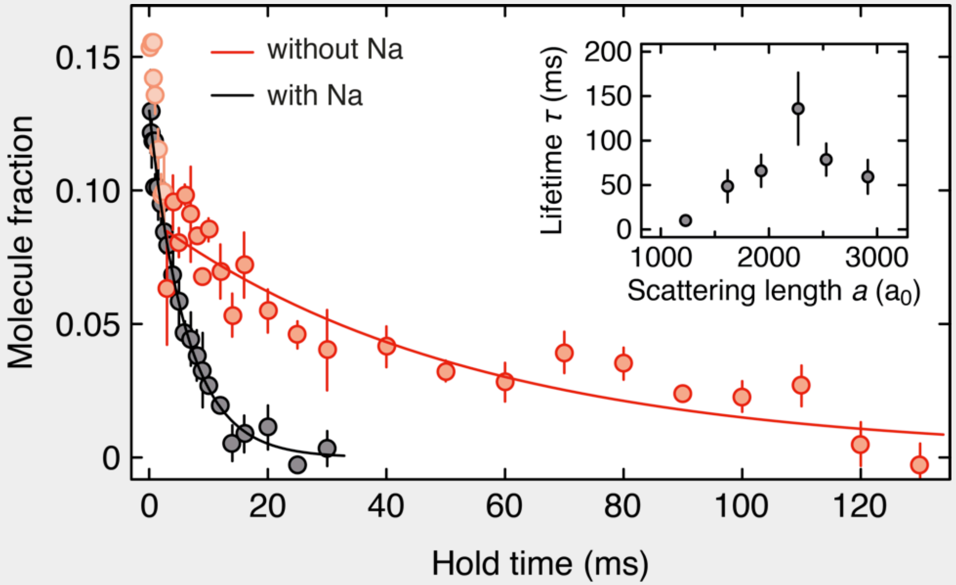
➜ Significant singlet admixture

see Wu *et al.*, PRL **109**, 085301 (2012)

Number, Temperature and Lifetime



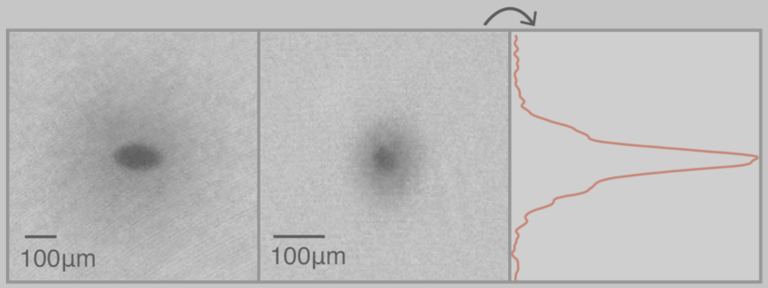




- up to 20% conversion efficiency of ^{40}K yields **2 x 10^4** molecules
- average kinetic energy **500 nK**
- longest lifetime of **~140 ms** observed

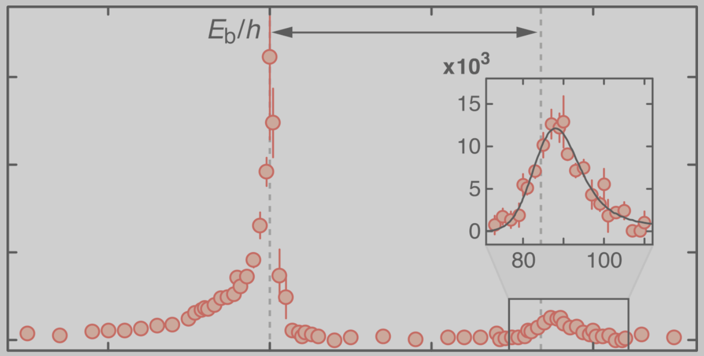
see Wu *et al.*, PRL **109**, 085301 (2012)

Quantum degenerate ^{23}Na^{40}K Bose-Fermi mixture and its Feshbach resonances



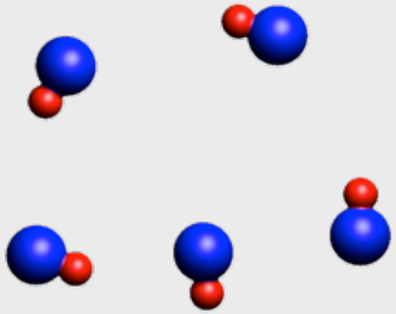
see Park *et al.*, Phys. Rev. A 85, 051602 (R) (2012)

Ultracold fermionic Feshbach molecules of ^{23}Na^{40}K

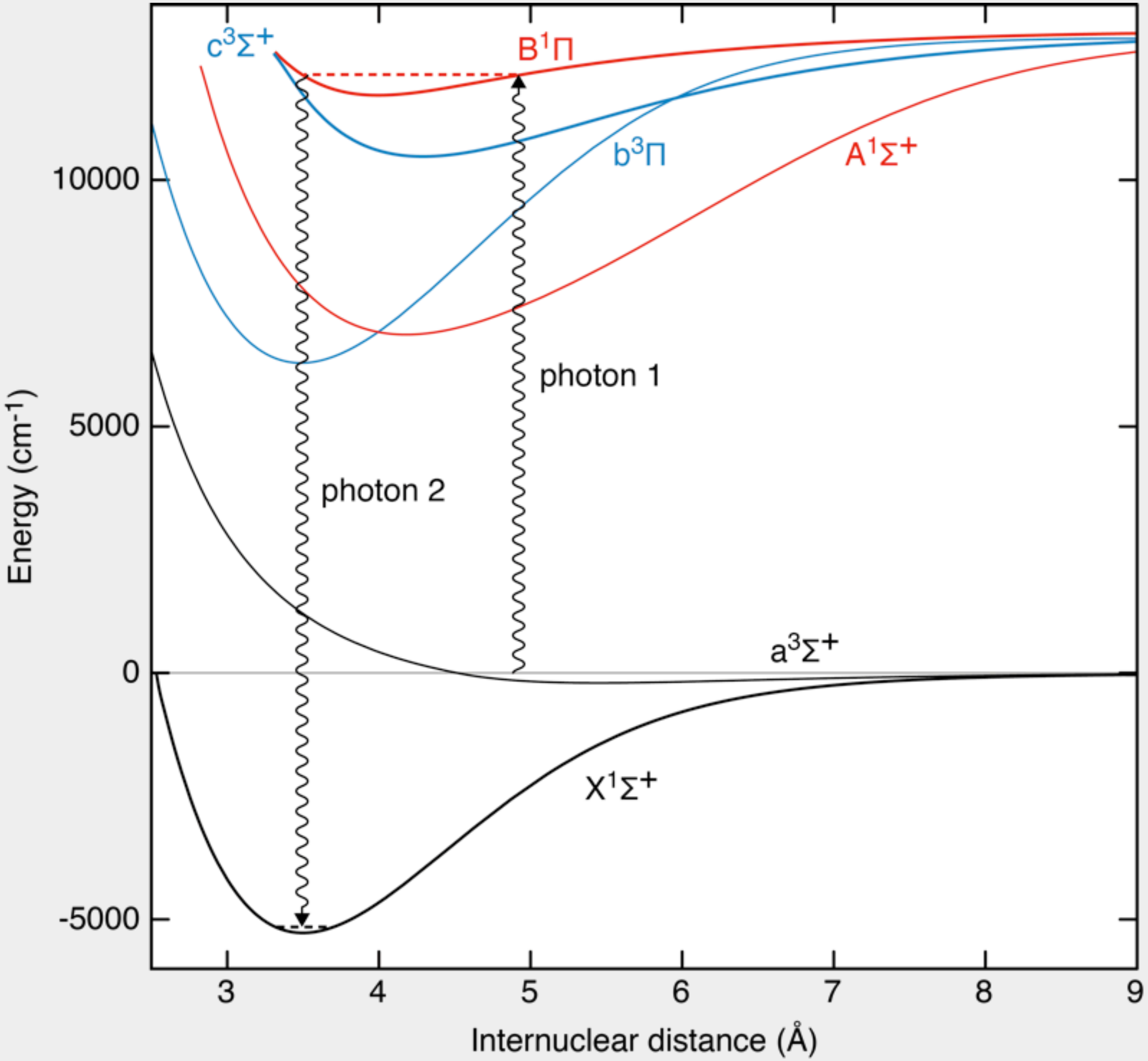


see Wu et al., PRL 109, 085301 (2012)

Towards fermionic ground state molecules of ^{23}Na^{40}K



Towards ground state molecules of NaK



- Similar strategy as for KRb

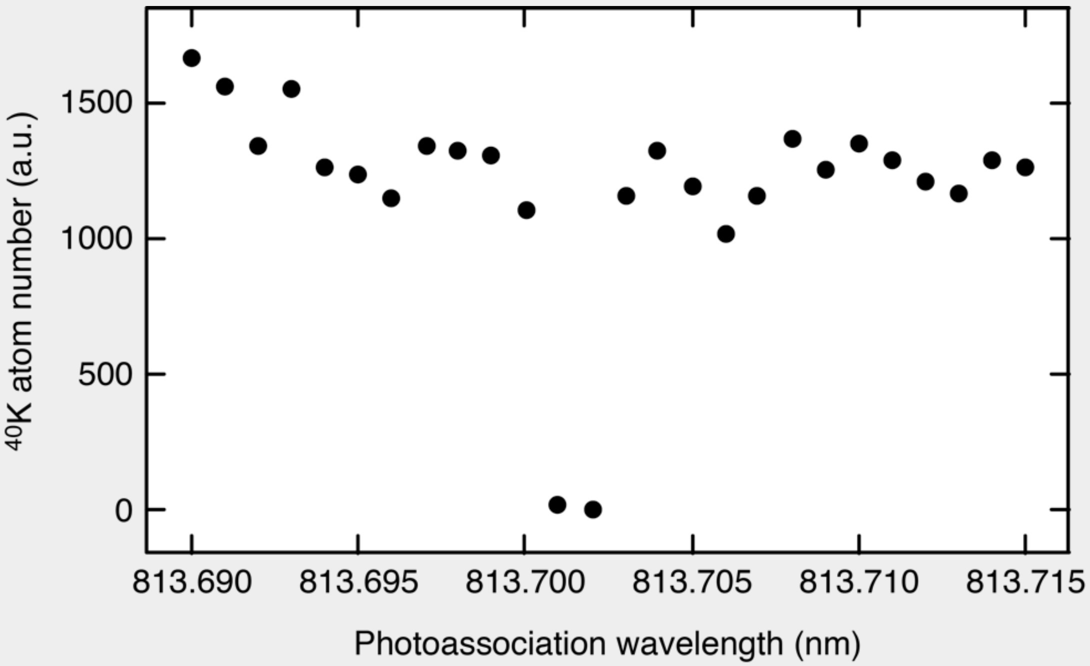
STIRAP: Coherent, adiabatic transfer of loosely bound **Feshbach molecules to** the $X^1\Sigma^+$ rovibrational **ground state**

- Spin-orbit coupling mixes $B(1)^1\Pi \longleftrightarrow c(2)^3\Sigma^+$
- Must know which intermediate excited state to use ➜ need spectroscopic information
- $^{23}Na^{39}K$ is a well studied bialkali molecule!

see e.g. Gerdes, Hobein, Knöckel, Tiemann, Eur. Phys. J. D 49, 67-73 (2008)
for vast data on NaK, see references therein

Photoassociation

- based on **mass-scaled prediction**, do photoassociation spectroscopy
- for simplicity, Photoassociation performed on **atomic mixture**
- tunable Ti:Sapph laser capable of doing **20 GHz scans**

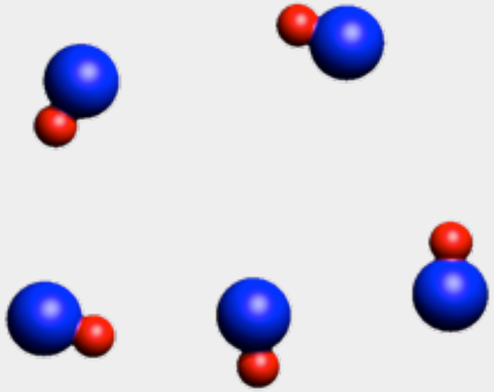


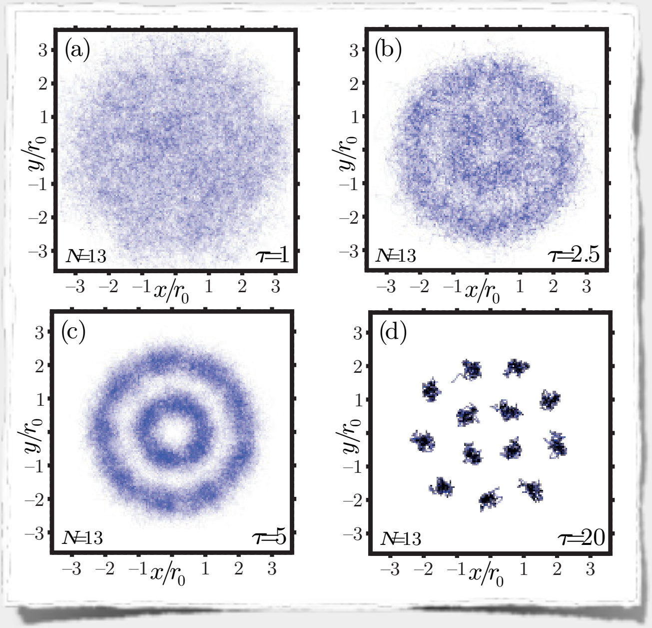
Signature of an NaK transition:

- Simultaneous loss of Na and K
- No loss of K without presence of Na (and vice versa)

What‘s next?

- **Photoassociation measurements** and **understand lines**
- Phase-coherent **Raman laser system** (lock to comb or cavity)
- **Dark-resonance/Autler-Townes** spectroscopy
- Getting ground state molecules via **STIRAP**
- **Lifetime measurement**
- **Installing electrodes**
- …

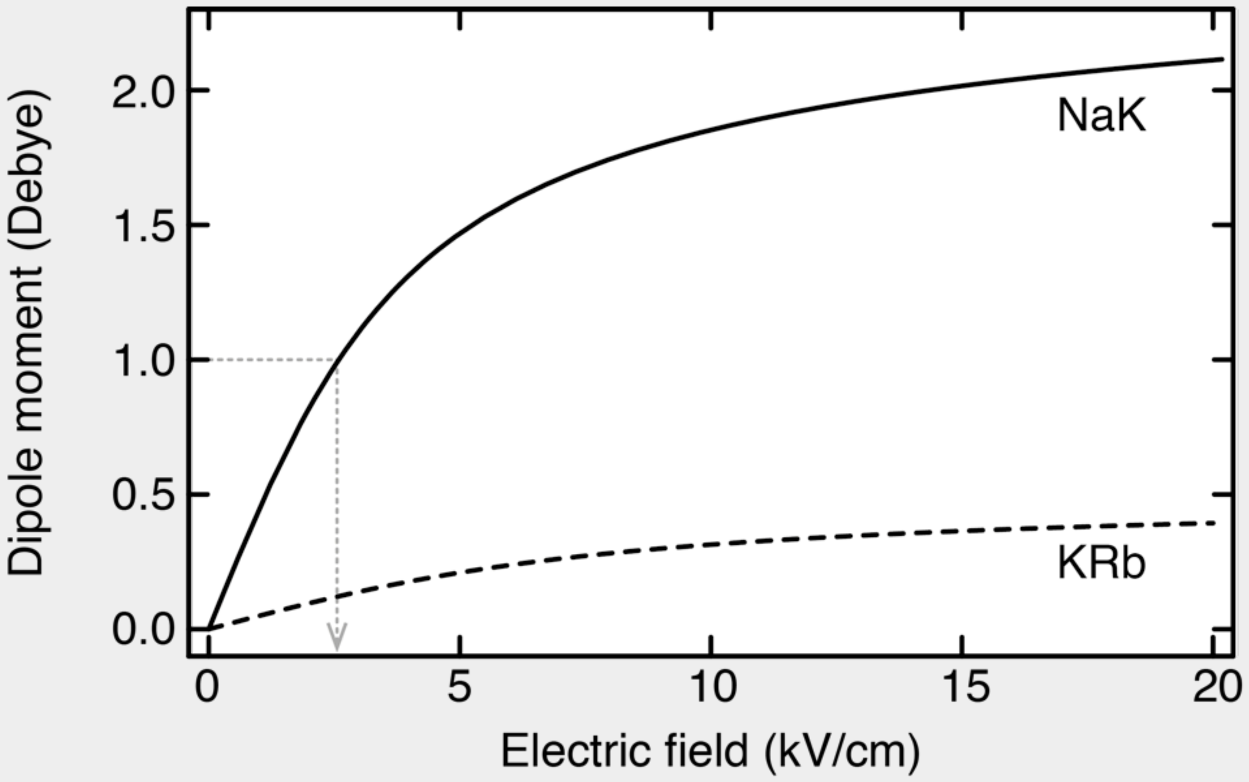




Pupillo *et al.*, PRL **104**, 223002 (2010)

Aligning the dipoles...

Induced dipole moment of NaK in v=0:



Dipole moment:

NaK:	d= 2.72 Debye
RbK:	d= 0.574 Debye

Rotational constant:

NaK:	B= 2.71 GHz
RbK:	B= 1.11 GHz

Dipole moment larger than **1 Debye** already **at 3 kV/cm!**

Dipole length and its consequences for NaK

Characteristic range of dipole-dipole interactions:

$$a_\mathrm{d} = \frac{d^2 m}{4\pi\epsilon_0\hbar^2}$$

“dipole length”

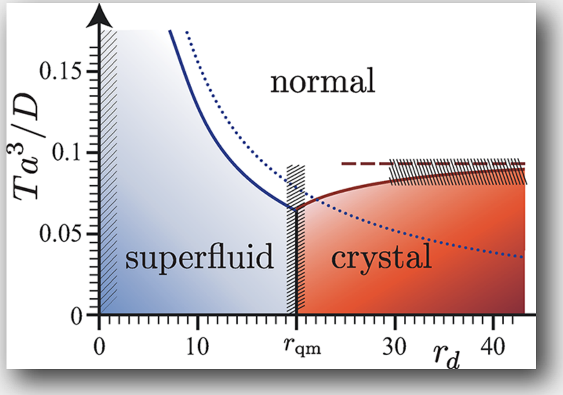
$a_\mathrm{d} \approx 1\mu\mathrm{m}$ for 1 Debye

$a_\mathrm{d} \approx 7\mu\mathrm{m}$ for 2.7 Debye

Ratio of interaction energy and kinetic energy at mean interparticle spacing:

$$r_\mathrm{d} = \frac{a_\mathrm{d}}{a_\mathrm{sp}}$$

“dipole interaction parameter”



For $n_\mathrm{NaK} \approx 10^{11} \ldots 10^{13}\,\mathrm{cm}^{-3}$ ➜ $r_\mathrm{d} \approx 0.4 \ldots 15$

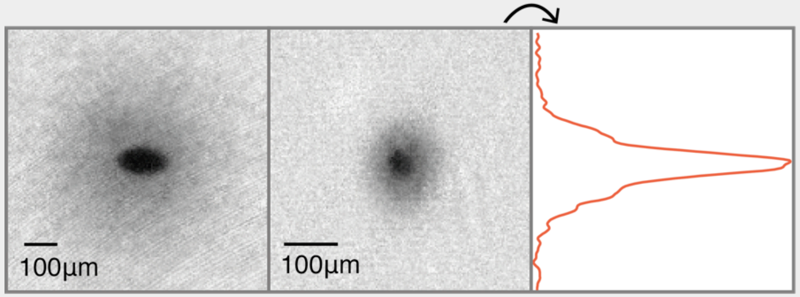
$r_\mathrm{d} \gg 1$: For example, **competition** between **superfluidity and crystallization!**

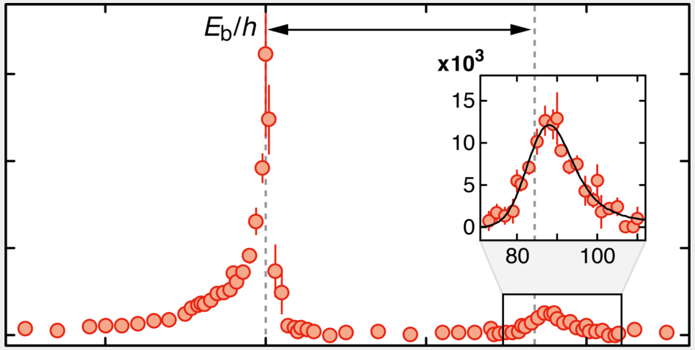
see Büchler et al., PRL, 98, 60404 (2007)

Baranov *et al.*, Chem. Rev. 112, 5012 (2012)

Conclusions

- More than **30 Feshbach resonances** at low magnetic fields



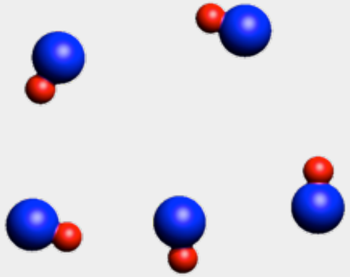


NaK Feshbach molecules have nice properties:

- **long lifetime** close to FBR
- open-channel dominated over wide range

Unique opportunity to create **fermionic NaK ground state molecules**

- **chemically stable**
- **large induced dipole moment** (2.72 Debye)
- **strongly dipolar Fermi gases** possible



Thank you!

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