Magnetic Feshbach resonances between a single ion and ultracold atoms

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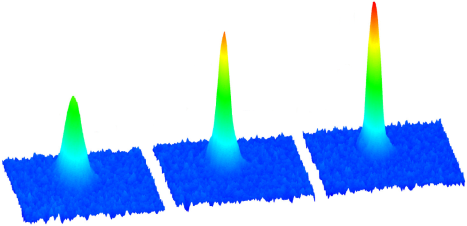
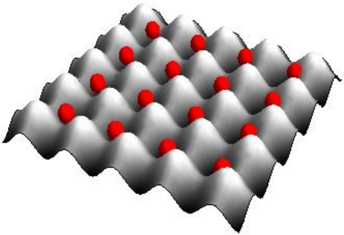
KITP, Santa Barbara
May 25, 2022

Ultracold **ion-atom** systems

Ultracold atoms



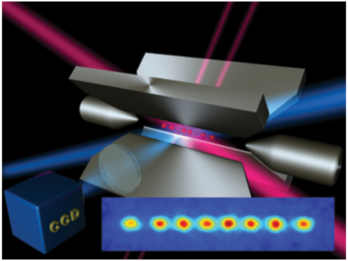
Bloch et al., Rev. Mod. Phys. 80, 885 (2008)

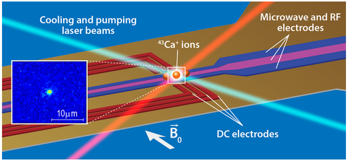


(relatively)

- **large number** of atoms
- **long coherence** time
- **controllable**
- fully **quantum** matter

Trapped ions





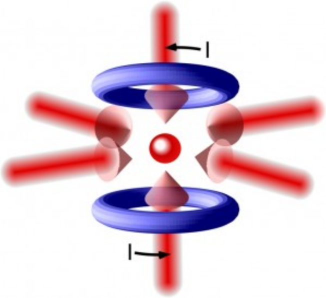
Leibfried et al., Rev. Mod. Phys. 75, 281, (2003)

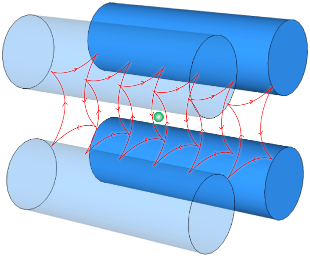
- **small number** of ions
- **strongly** interacting
- fully **controllable**
- **transferable** to technology

Cold hybrid ion-atom systems

Tomza et al., Rev. Mod. Phys. 91, 035001 (2019)

Combining the best of two worlds

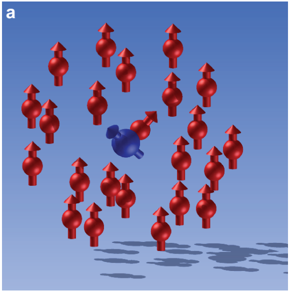




Trapped (ultra)cold **atoms** + laser-cooled trapped **ion(s)**

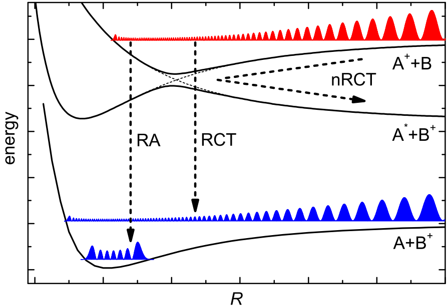
Cold hybrid ion-atom systems

Tomza et al., Rev. Mod. Phys. 91, 035001 (2019)



- cold (controlled) **chemistry**
- precision **measurements**
- **quantum** simulation, computation and sensing

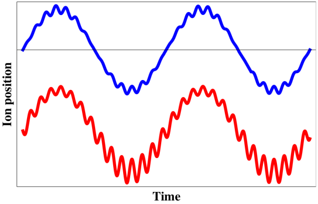
Microscopic theory of ion-atom systems

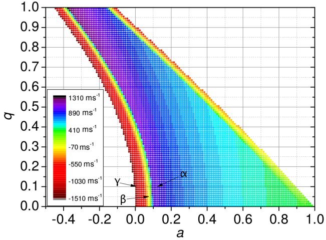


Challenges

- (non)Radiative charge transfer and association **losses**
- **Control** of ion-atom interaction strength
- Reaching *s*-**wave** regime
- Temperature limit due to **miromotion** in Paul trap

Micromotion in Paul trap

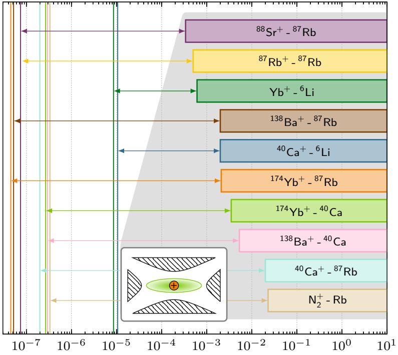


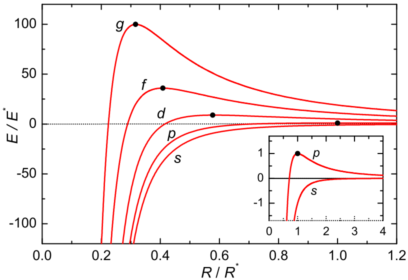


Micromotion in Paul trap **hinders** reaching ultralow temperatures

Krych and Idziaszek, Phys. Rev. A 91, 023430 (2015)
Chen et al., Phys. Rev. Lett. 112, 143009 (2014)
Cetina et al., Phys. Rev. Lett. 109, 253201 (2012)

Experimental realizations before 2018





$$V(R) \rightarrow -\frac{C_4}{R^4}$$

$$E^* = \frac{\hbar^2}{2\mu(R^*)^2}, \qquad R^* = \sqrt{\frac{2\mu C_4}{\hbar^2}}$$

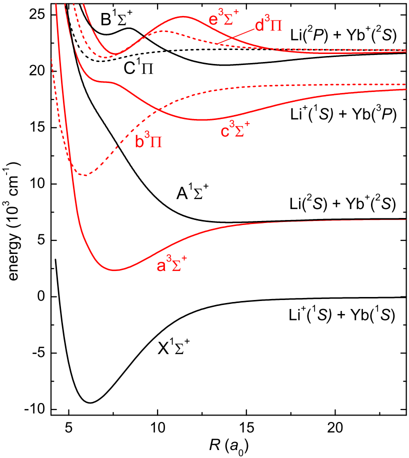
s-wave **quantum regime**:

$$E_{\mathrm{coll}} \leqslant E^*$$

Favorable Yb^{+}+Li system

Ab initio electronic structure

M. Tomza et al., Phys. Rev. A 91, 042706 (2015)



Radiative losses?

Spontaneous radiative **charge transfer**,

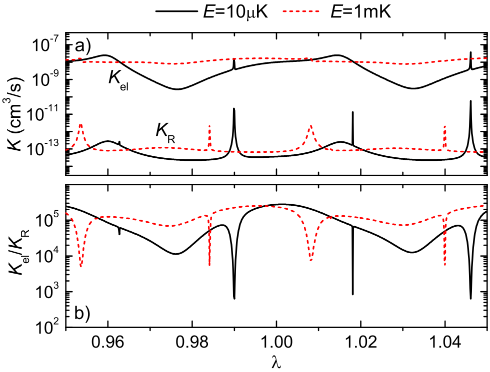
$$\mathrm{Yb}^+ + \mathrm{Li} \rightarrow \mathrm{Yb} + \mathrm{Li}^+ + h\nu\,,$$

or radiative **association**,

$$\mathrm{Yb}^+ + \mathrm{Li} \rightarrow \mathrm{LiYb}^+(v, l) + h\nu\,.$$

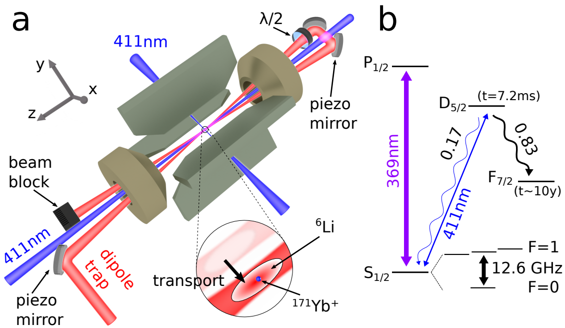
Elastic and reactive scattering

M. Tomza et al., Phys. Rev. A 91, 042706 (2015)



Experiment of Rene Gerritsma - University of Amsterdam

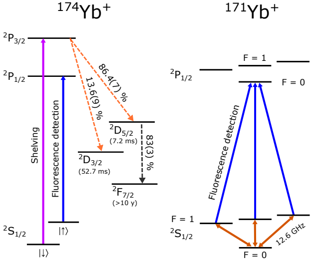
J. Joger, H. Furst, N. Ewald, T. Feldker, M. Tomza, R. Gerritsma, Phys. Rev. A 96, 030703(R) (2017)

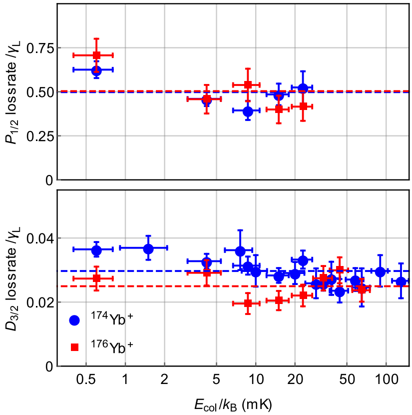


Charge dynamics

Charge exchange vs isotope and electronic state

J. Joger et al., Phys. Rev. A 96, 030703(R) (2017)



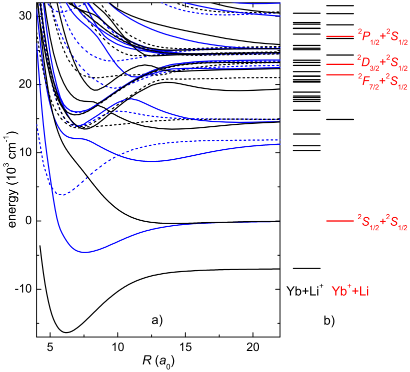


State	^{174}**Yb**$^+$	^{176}**Yb**$^+$	^{171}**Yb**$^+$
$^2S_{1/2}$	$\leq 10^{-3}$	$\leq 2\times10^{-4}$	$\leq 2\times10^{-4}$
$^2P_{1/2}$	0.50(4)(20)	0.50(6)(20)	–
$^2D_{3/2}$	0.030(1)(11)	0.025(1)(10)	–
$^2F_{7/2}$	0.46(3)(16)	0.41(3)(14)	–

Table: Loss rates in units of Langevin collisions for the isotopes $^{174}Yb^+$, $^{176}Yb^+$, $^{171}Yb^+$ in ground and excited states at a collision energy of $E_{col}/kB = 1\,mK$.

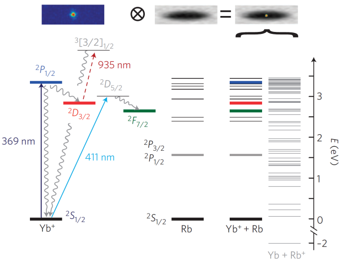
Charge transfer for excited-state ions?

J. Joger et al., Phys. Rev. A 96, 030703(R) (2017)



Comparison to Yb$^+$+Rb

L. Ratschbacher et al., Nature Phys. 8, 649 (2012)



Opposite pattern for $^2F_{7/2}$ and $^2D_{3/2}$

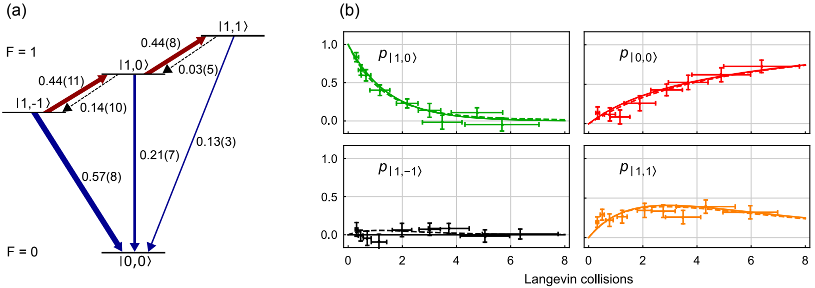
Huge spin-orbit coupling ($^2F_{7/2} \gg ^2 P_{1/2} > ^2 D_{3/2}$)?
Large density of states?
Nature of surrounding thresholds?

Qualitative explanation:
Nature of surrounding thresholds!

Spin dynamics

Dynamics of a single ion spin impurity - experiment

H. Furst, T. Feldker, N. Ewald, J. Joger, M. Tomza, R. Gerritsma, Phys. Rev. A 98, 012713 (2018)



Multichannel Quantum Scattering calculations

Hamiltonian for nuclear motion:

$$\hat{H} = -\frac{\hbar^2}{2\mu}\frac{1}{R}\frac{d^2}{dR^2}R + \frac{\hat{\mathbf{l}}^2}{2\mu R^2} + \hat{V}(R) + \hat{V}^{ss}(R) + \hat{V}^{so}(R) + \hat{H}_{A^+} + \hat{H}_B \,, \tag{1}$$

where

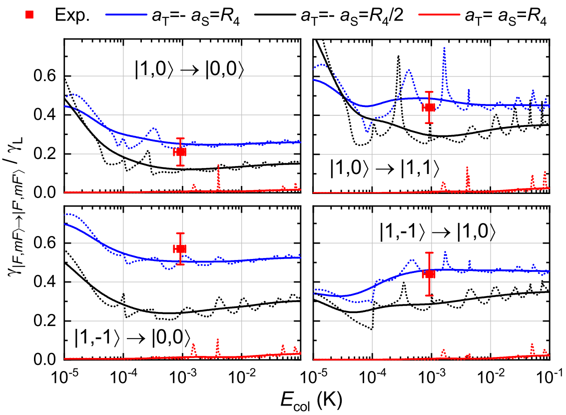
$$\hat{V}(R) = \sum_{S,M_S} V_S(R)|S, M_S\rangle\langle S, M_S| \,. \tag{2}$$

$$\hat{H}_j = \zeta_j \hat{\mathbf{i}}_j \cdot \hat{\mathbf{s}}_j + g_e\mu_B \hat{\mathbf{s}}_j \cdot \mathbf{B} + g_j\mu_N \hat{\mathbf{i}}_j \cdot \mathbf{B} \tag{3}$$

Solved with renormalized **Numerov propagator**

Dynamics of a single ion spin impurity - theory

H. Furst, T. Feldker, N. Ewald, J. Joger, M. Tomza, R. Gerritsma, Phys. Rev. A 98, 012713 (2018)

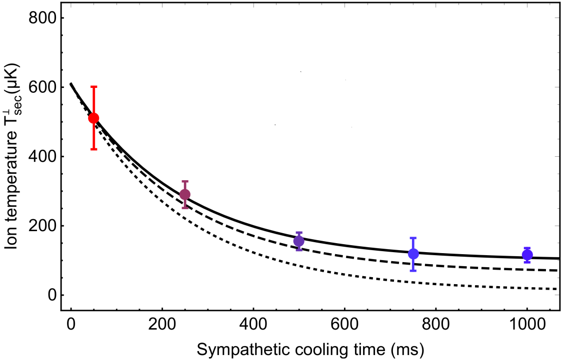


$$\sigma(E)_{\mathrm{ex}} \approx \frac{4\pi}{k^2} \sum_{l=0}^{\infty} (2l+1) \sin^2(\delta_l^{\mathrm{S}}(E) - \delta_l^{\mathrm{T}}(E))$$

Towards quantum regime

Buffer gas cooling of a trapped ion to the quantum regime

Feldker, Fürst, Hirzler, Ewald, Mazzanti, Wiater, Tomza, Gerritsma, Nature Phys. 16, 413 (2020)



$$^{171}\mathrm{Yb}^{+}\ (600\mu\mathrm{K}) + 10^{4}\times{}^{6}\mathrm{Li}\ (2\mu\mathrm{K}) \rightarrow {}^{171}\mathrm{Yb}^{+}\ (98\mu\mathrm{K},\ \bar{n}\approx 5.8)$$

Collision energy for mass-imbalanced ion-atom mixture

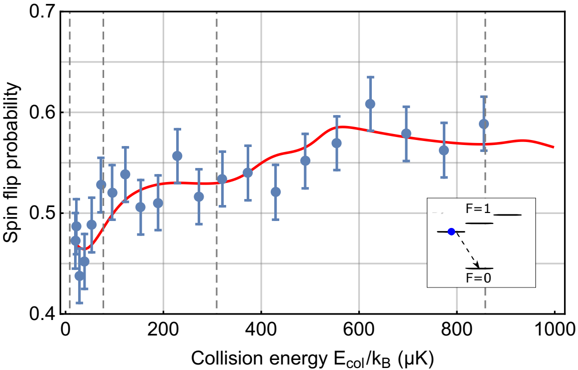
Feldker, Fürst, Hirzler, Ewald, Mazzanti, Wiater, Tomza, Gerritsma, Nature Phys. 16, 413 (2020)

$$E_{\mathrm{coll}} = \frac{\mu}{m_{\mathrm{i}}} E_{\mathrm{i}} + \frac{\mu}{m_{\mathrm{a}}} E_{\mathrm{a}}, \qquad m_{\mathrm{i}} \gg \mu$$

Type of motion	$E_{kin}/k_B(\mu K)$	$E_{col}/k_B(\mu K)$
Radial secular ion	$2 \times 21(9)$	1.4(0.6)
Intrinsic micromotion	$2 \times 21(9)$	1.4(0.6)
Axial secular ion	65(18)	2.2(0.4)
Excess micromotion	44(13)	1.5(0.4)
Total ion energy	**193(42)**	**6.6(1.4)**
Atom temperature	$3/2 \times 2.3(0.4)$	3.3(0.6)
Total collision energy	—	**9.9(2.0)**

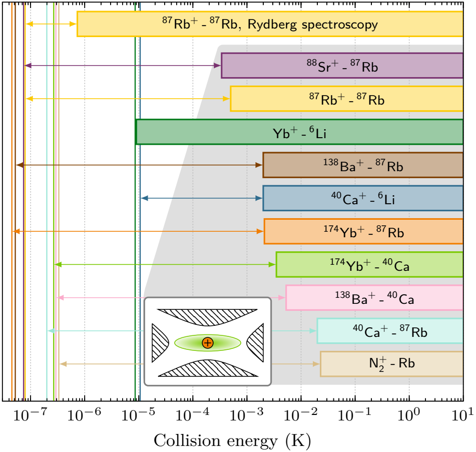
Shape resonances and scattering lenghts

Feldker, Fürst, Hirzler, Ewald, Mazzanti, Wiater, Tomza, Gerritsma, Nature Phys. 16, 413 (2020)



$a_S = 1.2(0.3)R^*$, $a_T = -1.5(0.7)R^*$

Experimental realizations in 2020

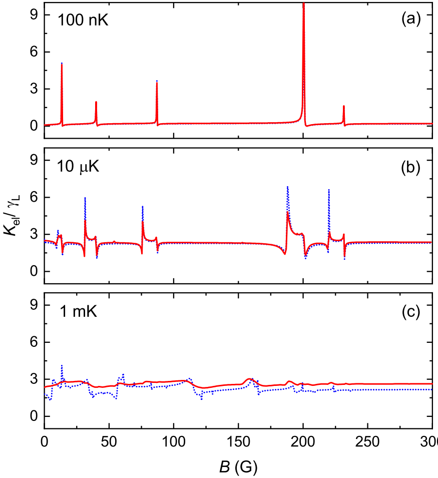


$$E^* = \frac{\hbar^2}{2\mu(R^*)^2}, \qquad R^* = \sqrt{\frac{2\mu C_4}{\hbar^2}}$$

Towards quantum control

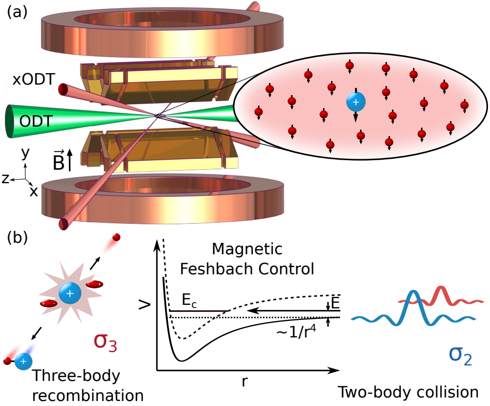
Prospects for magnetically tunable Feshbach resonances

M. Tomza, C. P. Koch, R. Moszynski, Phys. Rev. A 91, 042706 (2015)
H. Furst, T. Feldker, N. Ewald, J. Joger, M. Tomza, R. Gerritsma, Phys. Rev. A 98, 012713 (2018)



Experiment of Tobias Scheatz - University of Freiburg

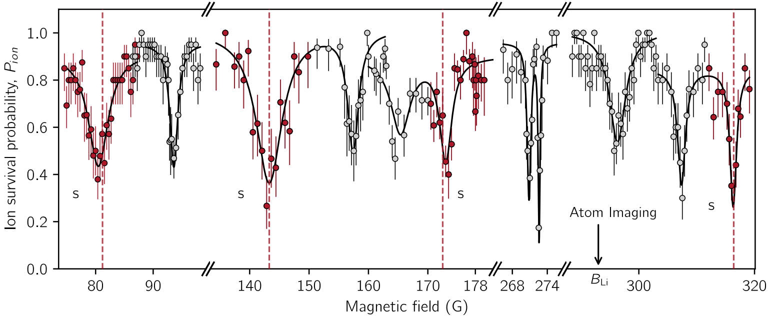
P. Weckesser, F. Thielemann, D. Wiater, A. Wojciechowska, L. Karpa, K. Jachymski, M. Tomza, T. Walker, T. Schaetz, Nature 600, 429 (2021)



Observation of magnetically tunable Feshbach resonances

P. Weckesser, F. Thielemann, D. Wiater, A. Wojciechowska, L. Karpa, K. Jachymski, M. Tomza, T. Walker, T. Schaetz, Nature 600, 429 (2021)

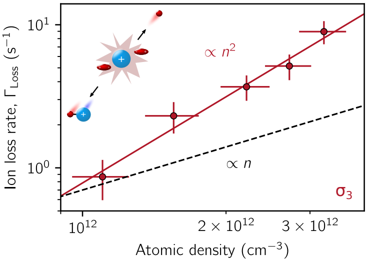
$$^{138}\mathrm{Ba}^{+}|1/2,\pm1/2\rangle + {}^{6}\mathrm{Li}\ |1/2,-1/2\rangle$$

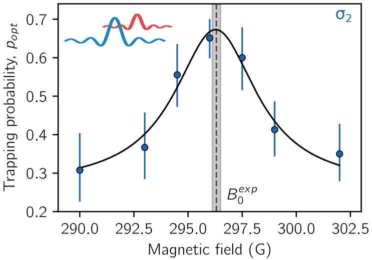


$$^{138}\mathrm{Ba}^{+} + {}^{6}\mathrm{Li} + {}^{6}\mathrm{Li} \rightarrow {}^{138}\mathrm{Ba}^{6}\mathrm{Li}^{+} + {}^{6}\mathrm{Li}$$

Three-body vs two-body collisions

P. Weckesser, F. Thielemann, D. Wiater, A. Wojciechowska, L. Karpa, K. Jachymski, M. Tomza, T. Walker, T. Schaetz, Nature 600, 429 (2021)





Initial Feshbach resonances assigment

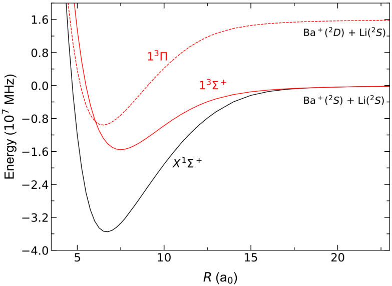
Assuming perturbative second-order spin-orbit coupling
M_F^{at}=-1 with M_F^{mol}=0

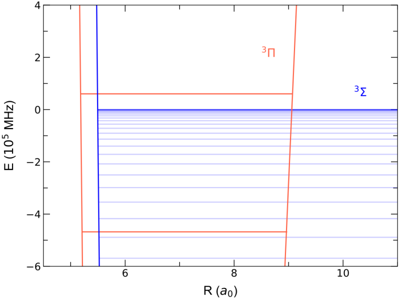
B_0^{expt} (G)	Δ_0^{expt} (G)	$B_{0,\mathrm{s}}^{\mathrm{theo}}$(G)
80.47(21)	4.2(1.1)	81.2
93.59(9)	1.6(4)	*d*-wave
143.29(31)	5.3(1.3)	143.3
157.42(19)	2.2(7)	*p*-wave
165.4(4)	4.0(1.1)	*p*-wave
173.0(2)	2.5(5)	172.5
270.86(5)	0.76(24)	*d*-wave
272.59(3)	0.4(1)	*d*-wave
296.31(19)	3.4(7)	*p*-wave
307.38(14)	1.6(5)	*p*-wave
316.31(11)	1.3(5)	316.4

Huge second-order spin-orbit coupling

$$\hat{H}_{\text{spin-spin}} = \left(-\frac{\alpha^2}{R^3} + \lambda_{\text{SO}}(R)\right)\left[3\hat{s}^z_{\text{Yb}^+}\hat{s}^z_{\text{Li}} - \hat{s}_{\text{Yb}^+}\cdot\hat{s}_{\text{Li}}\right],$$

$$\lambda_{\text{SO}}(R) = \frac{2}{3}\frac{|\langle a^3\Sigma^+|H_{\text{SO}}|b^3\Pi\rangle|^2}{V_{b^3\Pi}(R) - V_{a^3\Sigma^+}(R)},$$

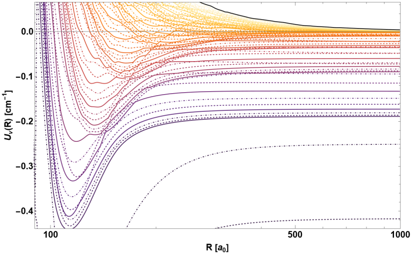


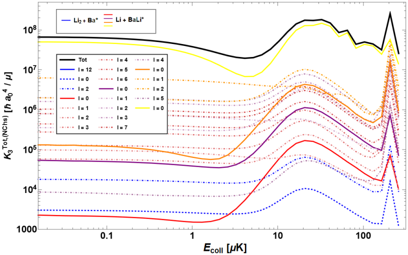


non-perturbative, short-range, single free parameter

Quantum three-body calculations

$^{138}Ba^{+}+^{7}Li+^{7}Li$

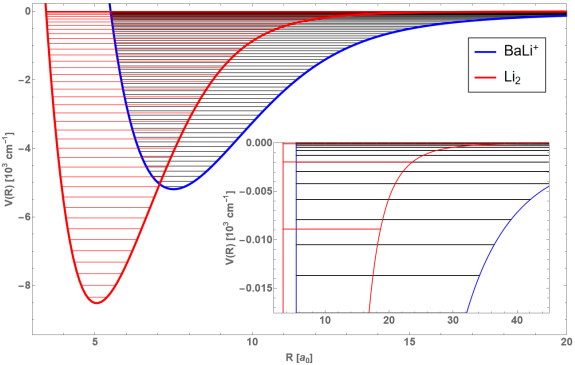




in collaboration with **Jose P. D'Incao**

Different energy and lenght scales

$Ba^+ + Li + Li \to BaLi^+(v,l) + Li$ vs $Li_2(v,l) + Ba^+$



Summary

Theoretical guidance and explanation for:

- Observation of **cold collisions** between Yb^+ ions and Li atoms
- Dynamics of a single **ion spin impurity** in a spin-polarized atomic bath
- **Buffer gas cooling** of a trapped ion to the **quantum regime**
- Fist observation of **shape resonances** and determination of ion-atom **scattering lengths**
- Fist observation of **Feshbach resonances**

Next steps

- Full assignment of Feshbach resonances
- Resolving three-body recombination
- Including the impact of micromotion and trapping
- All-optical ion-atom experiments deeply in the quantum regime
- Efimov physics in ion-atom-atom systems
- Polaron physics in ion-atom experiments

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Tobias Schaetz, Freiburg
Stefan Willitsch, Basel
Roee Ozeri, Weizmann

Theory:
Jose D'Incao, JILA

erc

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Thank you!

more details:
Phys Rev. A 91, 042706 (2015)
Nature Phys. 16, 413 (2020)
Nature 600, 429 (2021)

related:
Nature Commun. 10, 5429 (2019)
Phys. Rev. Lett. 120, 153401 (2018)

review:
Rev. Mod. Phys. 91, 035001 (2019)