Manipulation des Interactions dans les Gaz Quantiques

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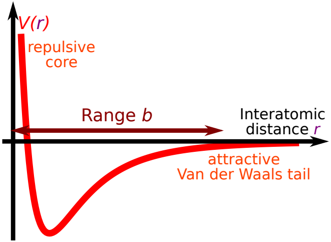
11 juillet 2011

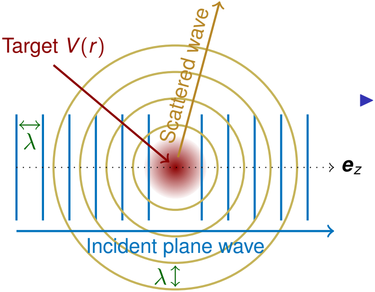
LPTMS, Université Paris–Sud

Outline

Introduction: Ultracold collision between two atoms

- Interaction modelled by the rotationally invariant potential $V(r)$ whose range is b.





- For very low energies $E = \hbar^2 k^2/m$ such that $\lambda = 2\pi/k \gg b$: isotropic scattering

  $\Psi_{s\text{–wave}}(r) \propto \sin[k(r-a)]/kr$

  where a is the scattering length.

- Effective interaction: $V_{\mathrm{eff}} = \dfrac{4\pi\hbar^2}{m}\, a\, \delta(r)$

Ultracold interaction properties are encoded in the single real number a.

Manipulation of interactions: Why?

1. Bose–Einstein condensates

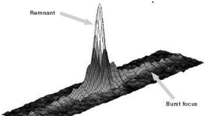
Vary magnitude and sign of a

$\longrightarrow$ explore various behaviours of quantum gas.

"Attractive" $a<0$ — BEC collapses

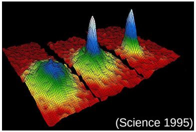
"Perfect Gas" $a=0$

"Repulsive" $a>0$ — BEC is stable



(Nature 2001)

Cornell & Wieman


(Science 1995)

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2. Metrology

Cold collisions cause a change in the transition frequency:

$$\delta\nu \propto n\,(a_{\beta\beta} - a_{\alpha\alpha}) \qquad (n = \text{atomic density})$$

Tune $(a_{\beta\beta} - a_{\alpha\alpha}) \longrightarrow$ control clock shift.

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3. Explore novel quantum phases (crystal of composite bosons)

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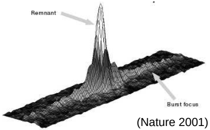

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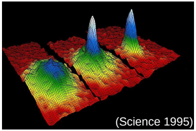

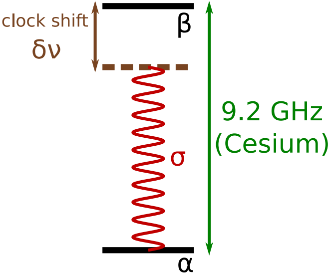

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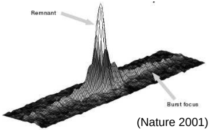

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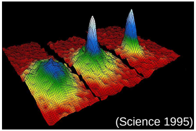
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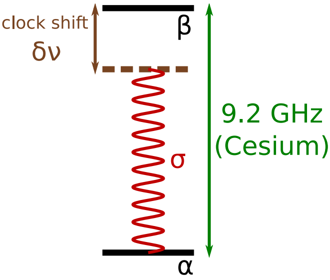

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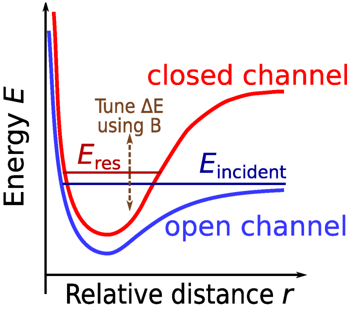
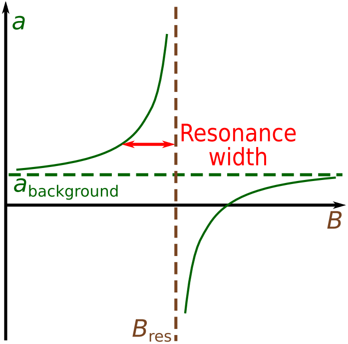
Feshbach resonances in a static magnetic field

- Using a static B, tune the energy of a scattering state of the two atoms in one internal state to resonance with a bound state in a different internal state.





- Broad Feshbach resonances ($\Delta B \gtrsim 10G$) = valuable tools

Example: $^7\mathrm{Li}$: $B_{res} = 700\,G$, $\Delta B = 200\,G$

Outline

Introduction: interactions in ultracold gases

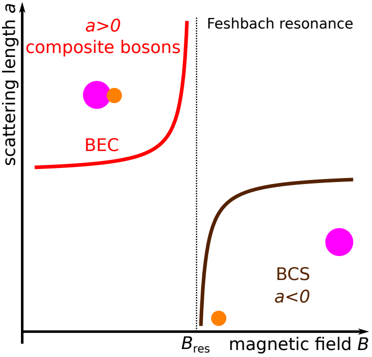
A two–dimensional crystal of composite bosons

Microwave–induced Feshbach resonances

Summary

Composite bosons in a heteronuclear Fermi mixture

- Start from an ultracold gas of fermionic atoms containing two different species, *e.g.* $^{6}\mathrm{Li}$ and $^{40}\mathrm{K}$.



- Using a Feshbach resonance, tune scattering length to $a > 0$ $\longrightarrow$ bosonic $^{6}\mathrm{Li}$–$^{40}\mathrm{K}$ dimers appear.

- Weakly bound ($|E_b| \lesssim k_\mathrm{B} \cdot 10\,\mu\mathrm{K}$) and large: size $\sim 1000\,$Å
- Long lifetime: $\sim 1\,\mathrm{s}$ at densities $10^{13}\,\mathrm{atoms/cm^3}$ due to Pauli repulsion between identical fermions.

Effective interaction between composite bosons

- Heavy atoms: 2D motion. Light atoms: 3D (2×3) or 2D (2×2) motion.
- Born–Oppenheimer approach.

  Zero–range interaction between heavy and light fermions.

  Dilute: mean distance $\overline{R}$ between dimers $>$ molecular size κ_0^{-1}.

- $U_{2\times 3}$ and $U_{2\times 2}$ are repulsive.
- Functions of $\kappa_0 R$.

  κ_0 determined by scattering length a.

- Both potentials $\propto |\varepsilon_0| = \frac{\hbar^2 {\kappa_0}^2}{2m}$

  - Competition with zero–point vibrations $\propto 1/M$.

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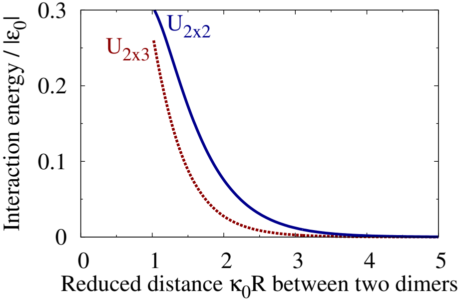

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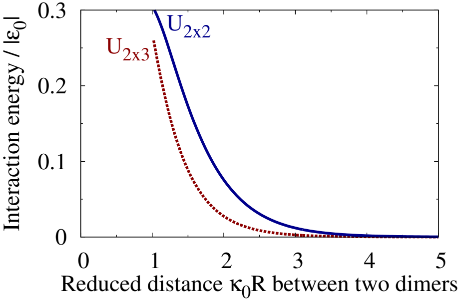

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Gas–Crystal phase diagram at $T = 0$

- Phase (gas or crystal) results from competition between repulsive interaction ($\propto 1/m$) and zero–point vibrations ($\propto 1/M$).
- Vary 2D density n and mass ratio M/m.

- Motion of heavy atoms is 2D.
  Motion of light atoms is 3D or 2D.
- Triangles and circles:
  Quantum Monte Carlo results.
- Dashed lines:
  harmonic/Lindemann
- Solid lines: low–n hard–disk limit.

Crystal expected for $M/m \gtrsim 100$ and appropriate densities.

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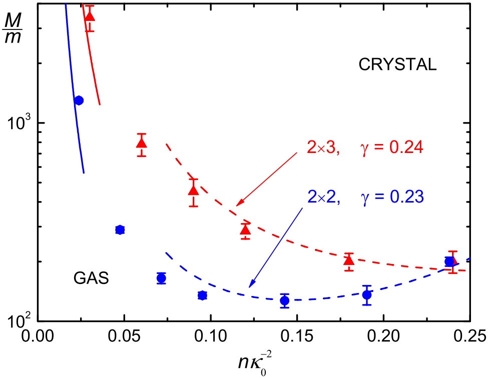

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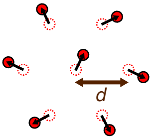
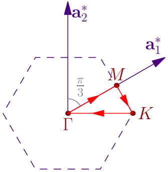
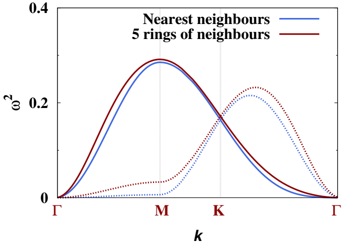
Two simple approaches to the phase diagram



Assume crystal has hexagonal lattice (confirmed by QMC)

1. Harmonic/Lindemann approach: valid for all 2D densities





First, assume crystalline phase:

$$H_{\text{harm}} = \sum_{\kappa} \hbar\omega_\kappa \, a_\kappa^\dagger \, a_\kappa$$

Evaluate RMS displacement l_0 of a dimer from lattice site.

Lindemann criterion: crystal melts when $l_0 > \gamma\, d$ $(\gamma \approx 0.24)$

2. For very low densities, model dimers by hard spheres

conserve dimer–dimer scattering length $a_{dd}(M/m)$

critical density: $n^{\text{crit}}(M/m) = 0.33/a_{dd}{}^2$ (Xing 1990)

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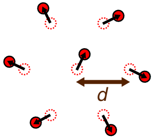

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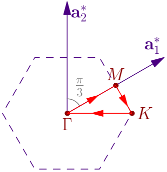

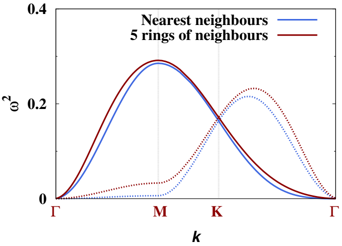

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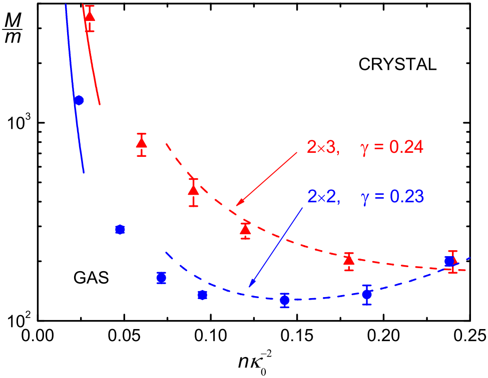

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Composite bosons: Prospects

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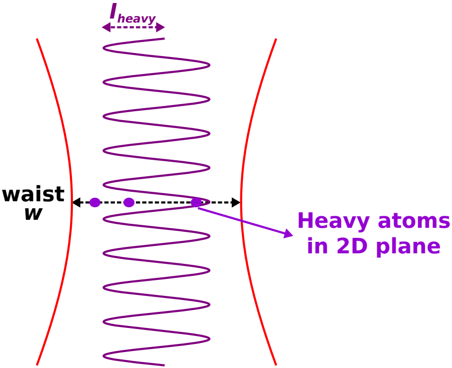

- Vary n by changing number of atoms
- Vertical optical lattice confines heavy atoms to 2D.
- To achieve 2x2 regime, add vertical optical lattice acting on light atoms.
- Horizontal optical lattice conveys effective mass M^* to heavy atoms.

Use *e.g.* $\Lambda_{horizontal} = 250\,\mathrm{nm}$, $M^* = 20M$, $a = 500\,\mathrm{nm}$ to observe crystal.

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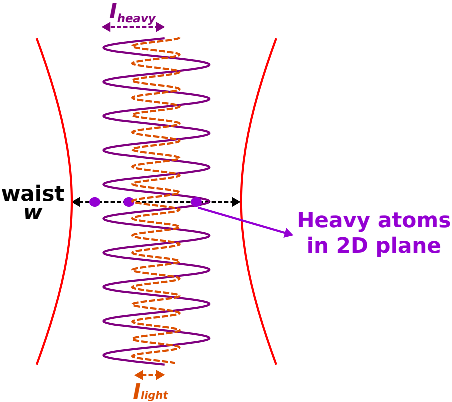

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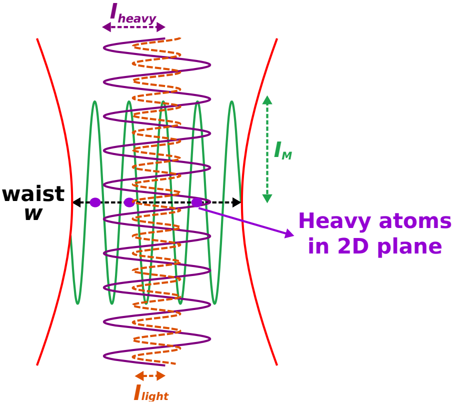

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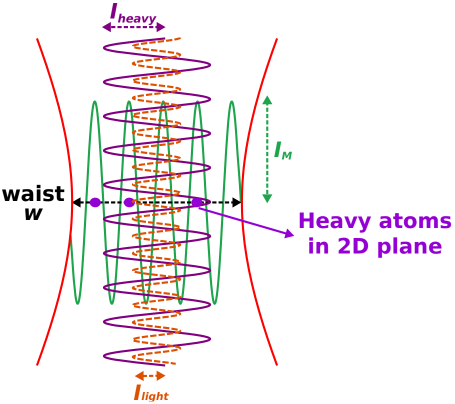

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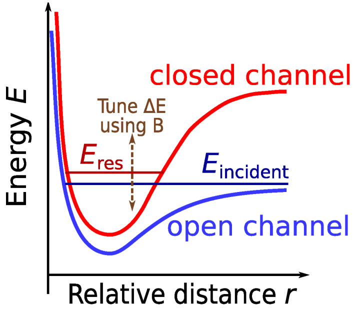
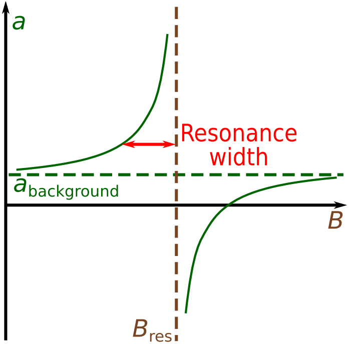




- Broad Feshbach resonances ($\Delta B \gtrsim 10G$) = valuable tools

  Example: $^7\mathrm{Li}$: $B_{res} = 700\,G$, $\Delta B = 200\,G$

Feshbach resonances in static B fields: Limitations

1. Resonances occur for fixed (often large) values of B.
2. Broad Feshbach resonances not available for all atoms.

- Examples: Feshbach resonances in

$$^{23}\mathrm{Na} \longrightarrow \quad \Delta B = 1\,G, \qquad B_{\mathrm{res}} = 1200\,\mathrm{G}$$

$$^{87}\mathrm{Rb} \longrightarrow \quad \Delta B = 0.2\,\mathrm{G}, \quad B_{\mathrm{res}} = 1000\,\mathrm{G}$$

$\longrightarrow$ harder to use in experiments.

$\Longrightarrow$ Look for **another way to tune the scattering length**.

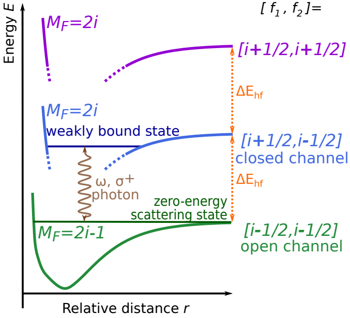
Alternatives to Feshbach resonances in static *B* fields

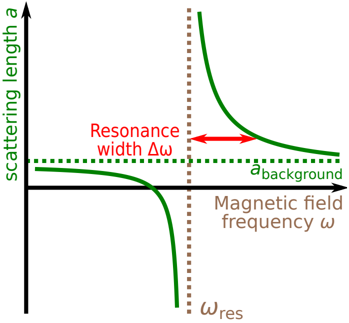
Resonances in a static magnetic field
proposed by Verhaar *et al.* (1992), first observed by Ketterle (1998).

- RF magnetic field
  (Moerdijk & Verhaar 1996)
- optical electric field
  (Fedichev *et al.* 1996, add experiment)
- Manipulate existing FFRs using MW or RF magnetic fields
  (Thompson et al 2005, Zhang et al 2009, Kaufman et al 2009)

Our suggestion:
Microwave–Induced Feshbach resonances

- 2 bosonic alkali atoms in a given internal state collide in the presence of a microwave oscillating magnetic field.
- If ω is tuned correctly, coupling to a bound state corresponding to different internal atomic states.





$$a(\omega) = a_{\text{background}}\left(1 + \frac{\Delta\omega}{\omega - \omega_{\text{res}}}\right)$$

A simple approach: the Two–Channel Model

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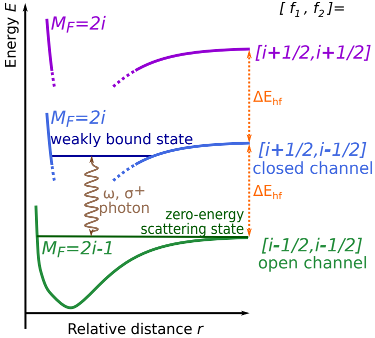

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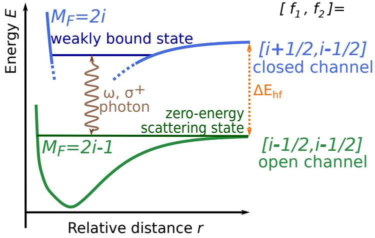

$$a(\omega) = a_{\mathrm{bg}}\,\left(1 + \frac{\Delta\omega}{\omega - \omega_{\mathrm{res}}}\right)$$

Res. frequency: $\hbar\omega^0_{\mathrm{res}} = \Delta E_{\mathrm{hf}} - |E_T|$ (energy of resonant bound state)

Res. width: $\Delta\omega \propto \frac{\mu}{a_{\mathrm{bg}}} B_0{}^2 \left|\langle \Psi_{\mathrm{closed}} | S^+ | \Psi_{\mathrm{open}} \rangle\right|^2$

$\Delta\omega$ scales with B_0^2. (So does a small shift on ω_{res}: $\omega_{\mathrm{res}} = \omega^0_{\mathrm{res}} + \alpha B_0{}^2$)

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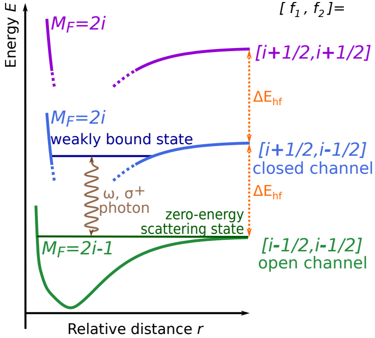

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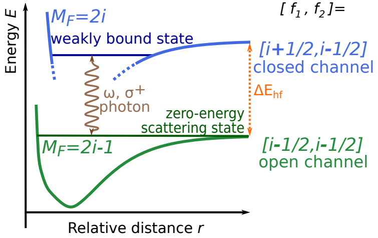

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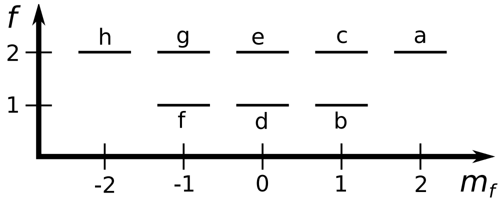
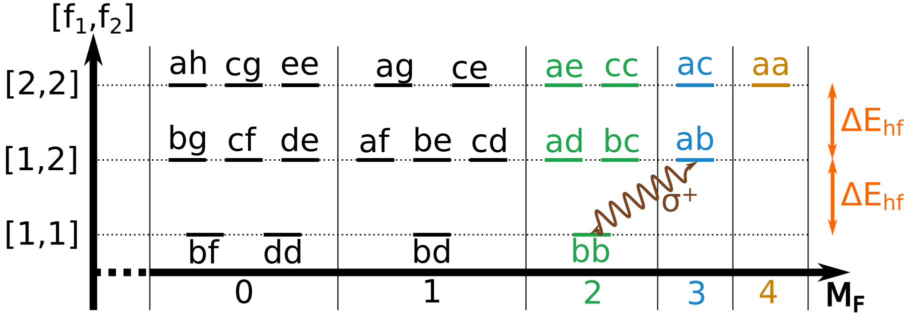
Internal states for alkali atoms with nuclear spin $3/2$

- Single–atom states
  for ^{7}Li, ^{23}Na, ^{87}Rb



- Two–atom states, σ^+–polarised mw with $\hbar\omega \approx \Delta E_{\mathrm{hf}}$
  connecting $|\,\mathrm{bb}\,\rangle$ to $|\,\mathrm{ab}\,\rangle$

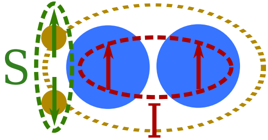


Beyond the two–channel model

Use realistic electronic potentials $V_S(r)$ and $V_T(r)$, which depend on total electronic spin S ($\boldsymbol{S} = \boldsymbol{s}_1 + \boldsymbol{s}_2$) $\rightarrow$ spin recoupling:

Atoms close together:

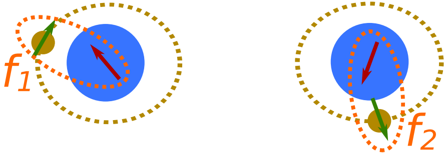
The two electronic spins couple together.



$$|V_T(r) - V_S(r)| \gg V_{\text{hyperfine}}$$

Atoms far apart:

The electronic spin of each atom couples with its nuclear spin.



$$|V_T(r) - V_S(r)| \ll V_{\text{hyperfine}}$$

Accounted for in the coupled–channel method.

Modelling the interaction between two alkali atoms

$$H = \frac{p^2}{2\mu} + \underbrace{V_{\mathrm{el}}(r)}_{V_S\,P_S + V_T\,P_T} + \underbrace{V_{\mathrm{hf}}}_{a_{\mathrm{hf}}\,(\boldsymbol{s}_1\cdot\boldsymbol{i}_1 + \boldsymbol{s}_2\cdot\boldsymbol{i}_2)} + \underbrace{\hbar\omega\,a^\dagger a}_{\text{photon en gies}} + \underbrace{W^{\sigma^+}}_{W_1\,(S^+ a + S^- a^\dagger)}$$

8 coupled channels: H is an 8×8 matrix, $|\,\Psi\,\rangle$ is an 8–comp. wavefunction.

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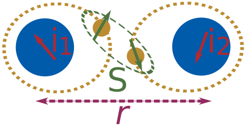

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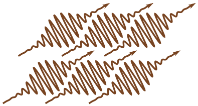

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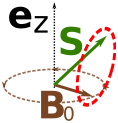

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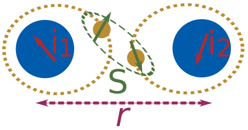

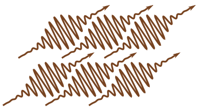

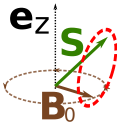

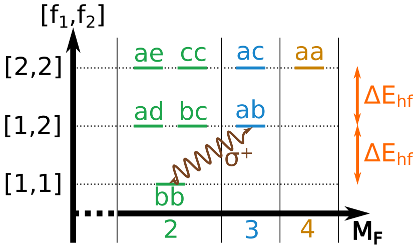

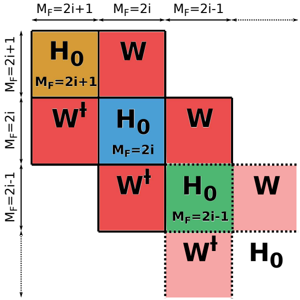

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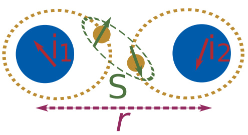
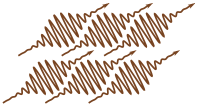
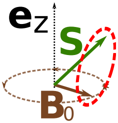
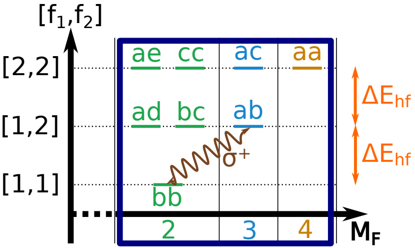
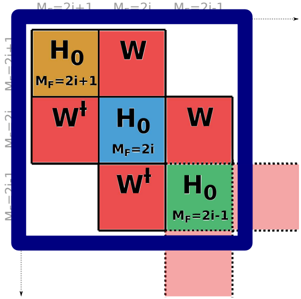






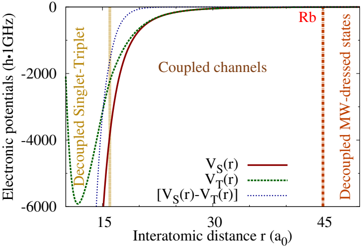




8 coupled channels: H is an 8×8 matrix, $|\,\Psi\,\rangle$ is an 8–comp. wavefunction.

How do we calculate multichannel wavefunctions?

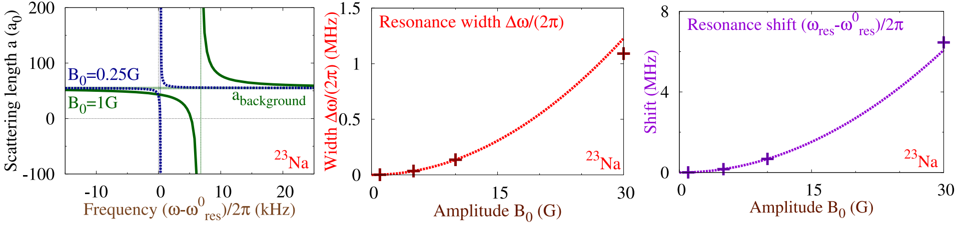
I use my own C++ implementation of the coupled–channel method.



- Inputs: electronic pots. V_S, V_T for $r \gtrsim 20a_0$ and scattering lengths a_S, a_T.
- Encode small–r Physics in "Accumulated Phase" boundary condition at finite r_0 [Verhaar *et al.*, PRA 2009].
  - Large–r boundary condition: atoms in relevant mw–dressed state.
  - Solve coupled Schrödinger equations numerically. One trick: take advantage of spin recoupling.

Output: Multichannel wavefunction $|\,\Psi\,\rangle$ for relative motion of two atoms.

The coupled–channel approach: Results



		^{7}Li	^{23}Na	^{41}K	^{87}Rb	^{133}Cs
$\lvert E_b \rvert / h$	(MHz)	12000	200	140	25	$5 \cdot 10^{-3}$
$\omega^0_{res}/2\pi$	(GHz)	12	1.6	0.12	6.8	9.2
$\Delta\omega_{CC}/2\pi$	(Hz/G^2)	6	1400	350	60	$-6 \cdot 10^{9}$

Narrow $\Delta\omega$ for ^{7}Li due to no weakly–bound state in closed channel.

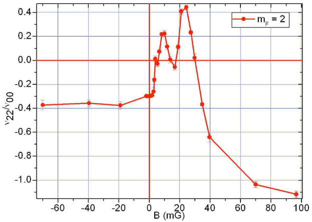
Narrow $\Delta\omega$ for ^{87}Rb due to $a_T = 99\,a_0$ being very close to $a_S = 90\,a_0$.

^{133}Cs: very weakly–bound state $\rightarrow$ non–hyperbolic resonance for $B_0 \gtrsim 4\,$mG.

SYRTE's static–field resonances in Cesium 133

- Atoms in $|\, f_1 = 4, m_1 = 0\,\rangle$ & $|\, f_2 = 3, M_F\,\rangle$, $M_F = 1$, 2, or 3.

Measured at SYRTE



Calculated (coupled channels)

- Due to *s*–wave triplet bound state with $|E_T| = h \cdot 5\,\mathrm{kHz}$.

- 3 triplet 2–atom states in $(f_1 = 4, f_2 = 3, M_F = 2) \to 3$ peaks.

Resonance positions B_{res} [mG]					
$M_F = 1$		$M_F = 2$		$M_F = 3$	
measured	calculated	measured	calculated	measured	calculated
	-11 ± 5				
	2.7		4.0		3.0
	5.1	8	7.2		4.2
18 ± 3	16.5	25	22	5 ± 1	5.5

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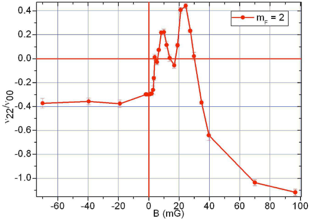

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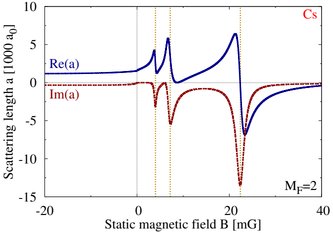

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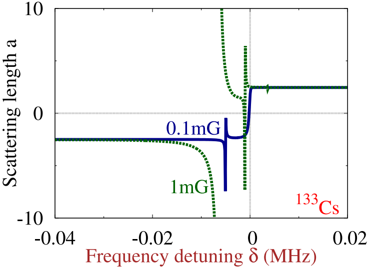
A giant MW–induced resonance in Cesium

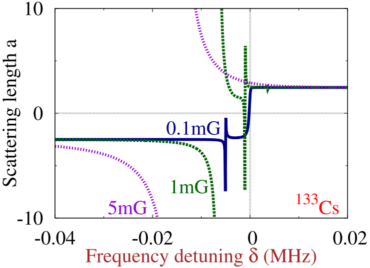


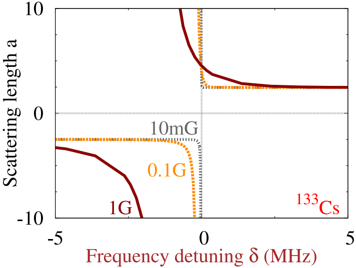
- $B_0 \lesssim 1\,\mathrm{mG}$: hyperbolic resonance with $\Delta\omega/2\pi = 6\,\mathrm{GHz}/G^2$
- Larger values of B_0: non–hyperbolic resonance.

Dressed–state effects important for $B_0 \gtrsim |E_T|/\mu_{\mathrm{B}} = 4\,\mathrm{mG}$

Lowest–energy dressed state is different for $\delta < 0$ and $\delta > 0$ $\longrightarrow$ different scattering lengths.

A giant MW–induced resonance in Cesium





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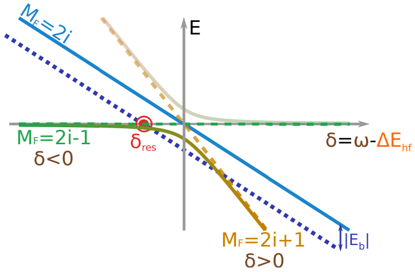

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Lowest–energy dressed state is different for $\delta < 0$ and $\delta > 0$

$\longrightarrow$ different scattering lengths.

MW–induced resonances: Conclusion and Outlook

	^{7}Li	^{23}Na	^{41}K	^{87}Rb	^{133}Cs
$\boldsymbol{\Delta\omega/2\pi}$ (Hz/G^2)	6	1400	350	60	$-6 \cdot 10^9$

- Realistic mw amplitudes: $B_0 \lesssim 10\,\mathrm{G}$

  Optimistic prospects for experiments with Na, K, Rb, Cs.

- Wide resonance in $^{133}\mathrm{Cs}$: width $\sim 5\,\mathrm{kHz}$ for $B_0 = 1\,\mathrm{mG}$.

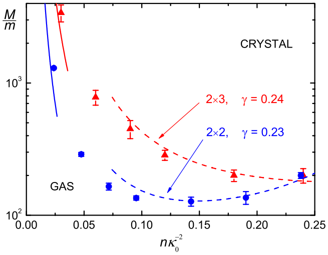
  Observable in a Cesium fountain clock.

- Our scheme can be transposed to fermionic atoms and heteronuclear mixtures.

- It can be used to tune the interaction in spinor gases.

- It can be used to improve control over clock shifts.

Manipulation of Interactions in Quantum Gases



- One novel quantum phase:

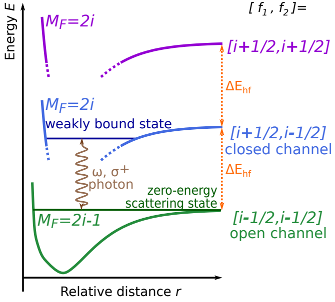
2D crystal of composite bosons

[PRL **99**, 130407 (2007)]

- A new way to manipulate interactions:

microwave–induced Feshbach resonances

[PRA **81**, 041603(R) (2010)]



Thanks to G. Shlyapnikov, J. Dalibard, C. Salomon, D. Petrov, S. Bize, P. Rosenbusch.