Rydberg Optical Feshbach Resonances

Rosario González-Férez

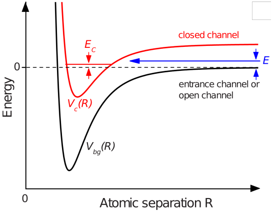
Instituto 'Carlos I' de Física Teórica y Computacional
Departamento de Física Atómica, Molecular, y Nuclear
Universidad de Granada, Spain

December 13, 2016

Introduction

Magnetic Feshbach resonances

- The hyperfine interaction couples a scattering state to a bound molecular level.
- Magnetoassociation: an adiabatic ramp of the magnetic field across the resonance



Optical Feshbach resonances

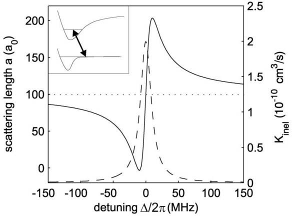


FIG. 1. Scattering length a (solid line) and inelastic collision rate coeffient $K_{\rm inel}$ (broken line) as a function of the laser detuning from the photoassociation resonance. The curves are based on Eqs. (1) and (2) for typical experimental parameters: $\Gamma_{\rm stim}/2\pi = 54$kHz, $\Gamma_{\rm spon}/2\pi = 20$MHz, $k_i = 2.47 \times 10^5 {\rm m}^{-1}$, $a_{\rm bg} = 100{\rm a}_0$ (dotted line). Inset: Scheme for optically coupling the scattering state with an excited molecular state.

M. Theis et al, PRL **93**, 123001 (2004)

Key parameters:

$$\ell_{\rm opt} = \frac{\Gamma_{\rm stim}}{k\gamma_m}$$ Optical length.

$\ell_{\rm opt} >> \bar{a}$ Large ratio of coherent to incoherent processes in the light coupling

$$s_{\rm res} = \frac{\ell_{\rm opt}\gamma_{\rm m}}{\bar{a}\bar{E}}$$ Pole strength

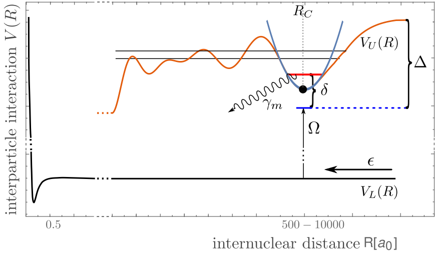
Broad and tuneable: $s_{\rm res} >> 1$

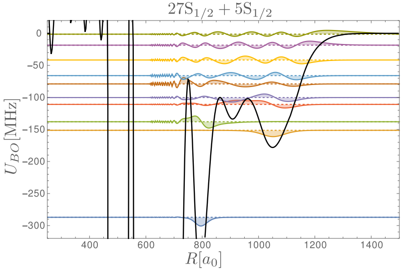
$\Gamma_{\rm stim}$ & γ_m stimulated and spontaneous emission rates

$\bar{a}$ & $\bar{E}$ mean scattering length and energy of the ground state potential

The Rydberg optical Feshbach resonances

The aim: Tune the scattering length of two colliding ground-state atoms by coupling the two-atom ground-state to an excited Rydberg-molecular state using off-resonant laser light.





- the ground-state atom and the Rydberg core are treated as point particles
- the interaction between the Rydberg electron and the neutral atom is described by the s and p-wave Fermi pseudopotentials
- The laser is off-resonantly coupled to the lowest eigenstate of the outer most potential minima
- the energy-dependent scattering lengths determined coupled channel calculations

The scattering length

Determined from coupled channel calculations solving the equation

$$\left[\frac{\partial^2}{\partial R^2} + \frac{2\mu}{\hbar^2}(\epsilon\mathbb{I} - V(R))\right]\Psi(R,\epsilon) = 0 \qquad V(R) = \begin{pmatrix} V_L(R) + V^\infty & \Omega \\ \Omega & V_U(R) + V^\infty - \hbar\omega - i\gamma_m/2 \end{pmatrix}$$

Estimated by the single resonance approximation:

$$\alpha(k) = \alpha_{\mathrm{bg}}(k) + \frac{\Gamma_{\mathrm{stim}}(k)\frac{[1+k^2\alpha_{\mathrm{bg}}(k)^2]}{k}}{\epsilon - \delta - k\alpha_{\mathrm{bg}}(k)\frac{\Gamma_{\mathrm{stim}}(k)}{2} + i\frac{\gamma_{\mathrm{m}}}{2}}.$$

$\alpha_{\mathrm{bg}}(k)$ ground state scattering length of the colliding atoms

γ_{m} spontaneous emission rate

$\Gamma_{\mathrm{stim}} = 2\pi\Omega^2 \left|F_\epsilon\right|^2$ stimulated emission rate

$F_\epsilon = \int \psi_L(\vec{R})\psi_U(\vec{R})d\vec{R}$ Franck-Condon factor

$\psi_L(\vec{R})$ & $\psi_U(\vec{R})$ the scattering and bound states wave functions

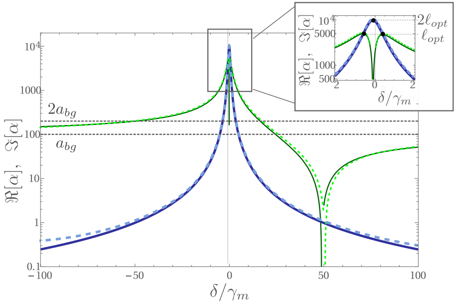
The Franck-Condon factor F_ϵ estimated by an harmonic oscillator approximation for the bound state

$$F_{\epsilon,\omega} = \sqrt[4]{\frac{8}{\pi\epsilon\omega}}\exp[\epsilon/\omega]\sin\left[\sqrt{2\mu\epsilon}(R_b - \alpha_{\mathrm{bg}})\right]$$

The results

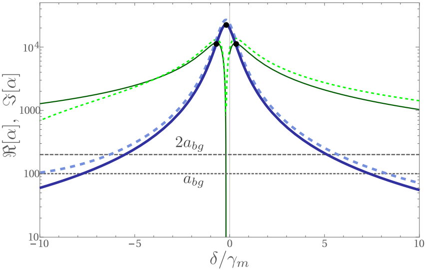
The scattering length

Coupling to the Rb($27S_{1/2}$)Rb($5S_{1/2}$) BOP



- $\Omega/(2\pi) = 0.5$ MHz
- Linewidth of the molecular state $\frac{\gamma_m}{2\pi} \simeq 144\text{kHz}$

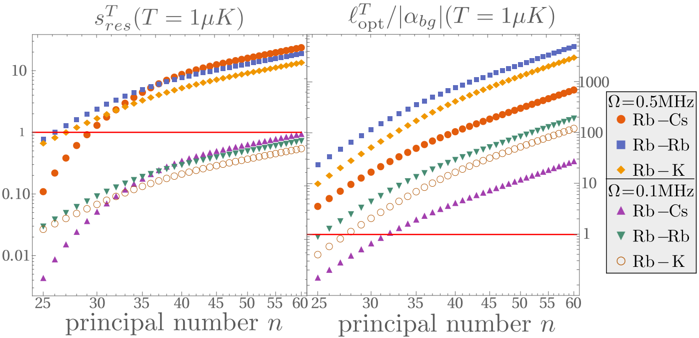
Coupling to the Rb($40S_{1/2}$)Rb($5S_{1/2}$) BOP



- $\Omega/(2\pi) = 0.2$ MHz
- Linewidth of the molecular state $\frac{\gamma_m}{2\pi} \simeq 54\text{kHz}$

To characterise the Rydberg OFR in an atomic ensemble at finite temperature, we compute the thermally-average pole strength and optical length:

$$s_{\rm res}^T = \int_\epsilon d\epsilon \, P_T(\epsilon)\ell_{\rm opt}(\epsilon)\frac{\gamma_m}{\bar{a}\bar{E}} \qquad \ell_{\rm opt}^T = \frac{s_{\rm res}^T \bar{a}\bar{E}}{\gamma_m}$$



As in usual OFRs: $\ell_{\rm opt}^T \propto \Omega^2$ and $s_{\rm res}^T \propto \Omega^2$

By increasing the excitation of the Rydberg state n or the Rabi frequency Ω

- $\ell_{\rm opt} >> \alpha_{\rm bg}$ Large ratio of coherent to incoherent processes in the light coupling
- $s_{\rm res} >> 1$ Broad and tuneable

Conclusions

Conclusions

- a novel mechanism for realising Feshbach resonances in cold gases using Rydberg molecular states.
- these Rydberg molecular states have long lifetimes and are present for any atomic species having a negative scattering length for the electron-atom collision
- this technique can be directly applicable to a variety of situations where the atoms do not enjoy magnetic Feshbach resonances
- the effective optical length and pole strength of this Rydberg optical Feshbach resonance can be tuned over several orders of magnitude

In collaboration with

- Paul S. Julienne, University of Maryland
- Guido Pupillo, Université de Strasbourg
- Nóra Sándor, Université de Strasbourg

Nóra Sándor, RGF, Paul S. Julienne, Guido Pupillo, arXiv:1611.07091