Observation of a microwave-induced Feshbach resonance for sodium atoms

M. Ballu, B. Mirmand, Z. Yao, T. Badr, H. Perrin and A. Perrin

Laboratoire de Physique des Lasers, CNRS and Université Sorbonne Paris Nord
99 avenue J.-B. Clément, F-93430 Villetaneuse, France

Background

- Having the ability to **modify the scattering length** of atoms gives the opportunity to study the different regime of **1D degenerate Bose gases** : weakly interacting to strongly interacting (Tonks).
- D. Papoular et al. predicted in 2010 the existence of a microwave (MW)-induced Feshbach resonance for all alkaline atoms [1]. The resonance frequency is close to the hyperfine splitting and the width depends on the square of the MW amplitude.
- **Sodium atom** looks favorable compared to other alkaline (excluding cesium which cannot be condensed in a magnetic trap) : $\Delta\omega(B_{\rm MW} = 1\ {\rm G}) = 2\pi \times 1.4\ {\rm kHz}$.

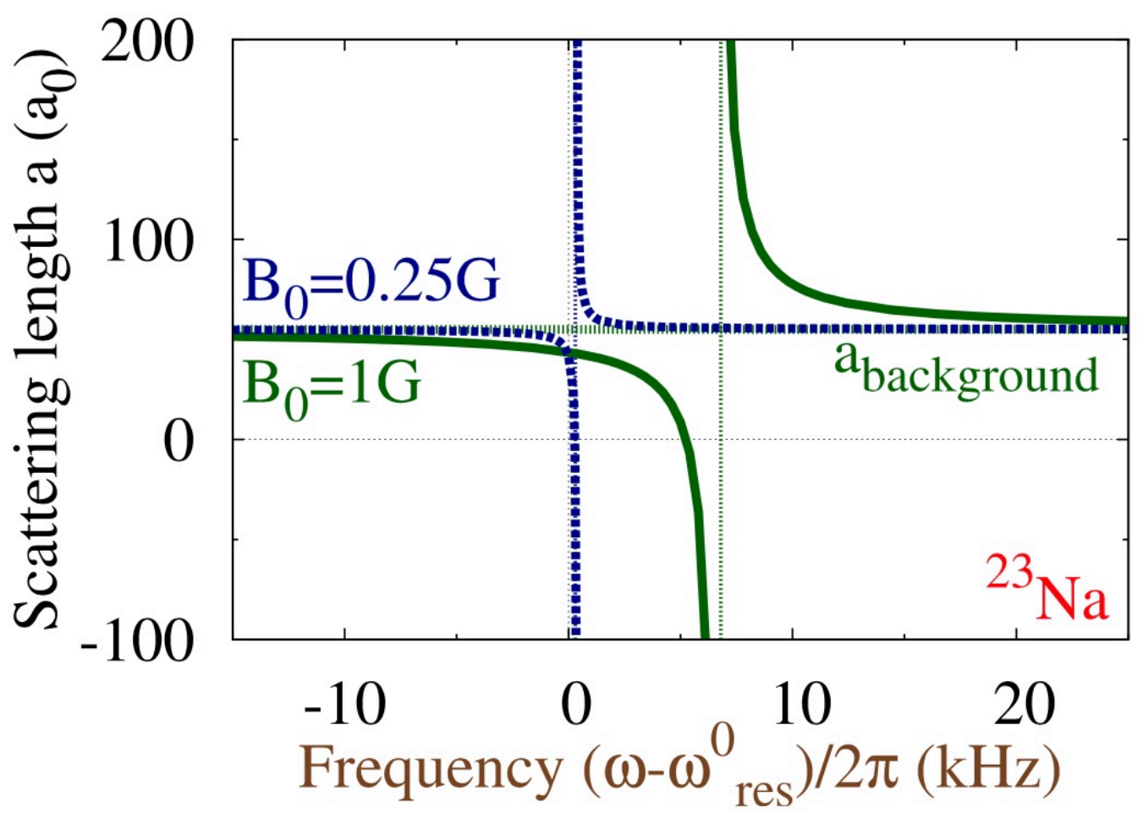
Objectives

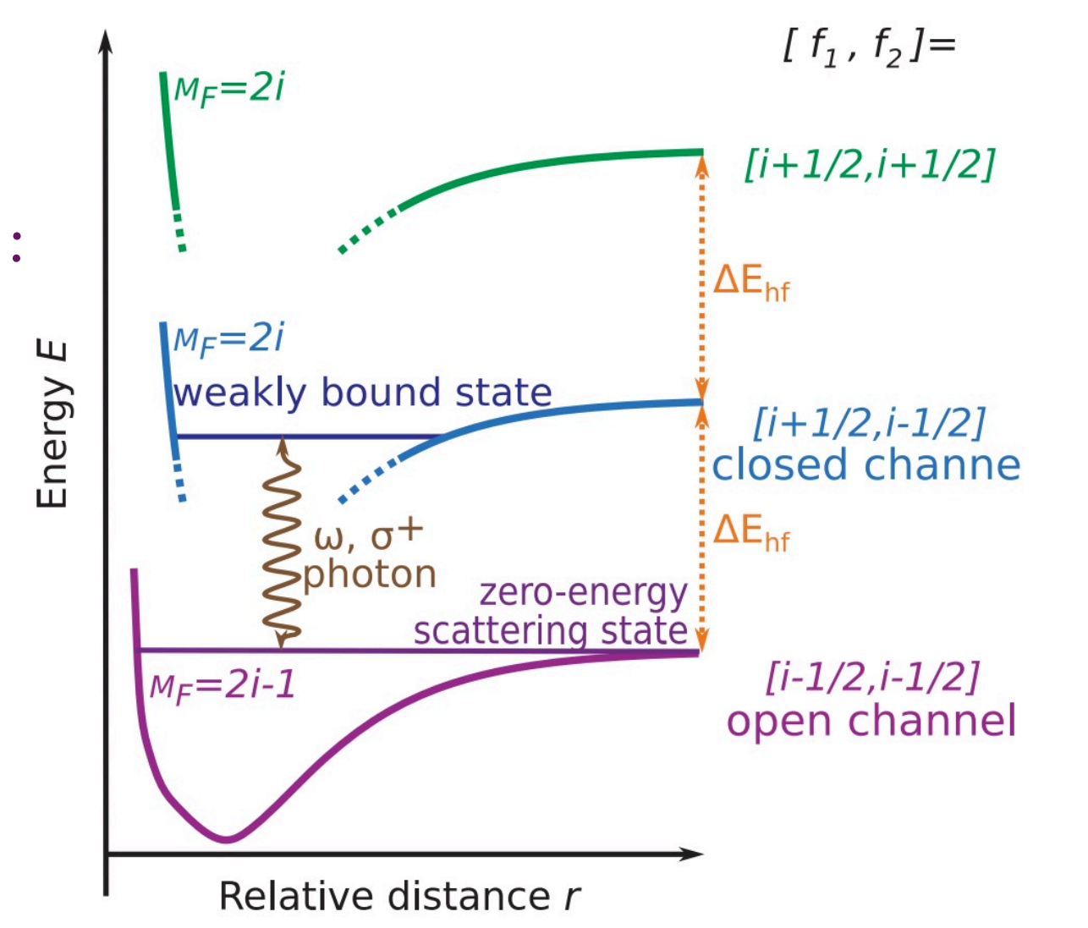
- Realize microwave spectroscopy to characterize the **molecular levels structure**.
- Shine strong microwave field to address sodium molecular resonance close to the hyperfine splitting. Characterize and mitigate the effect on the **magnetic confinement**.
- Demonstrate the **modification of the scattering length** of the atoms close to the transition by exciting the **radial breathing mode** of the elongated 3D cloud.

Principle

- Coupling of a free two-atom state to a **weakly bound molecular state** with a microwave field leads to a modification of the scattering length [1,2] :

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

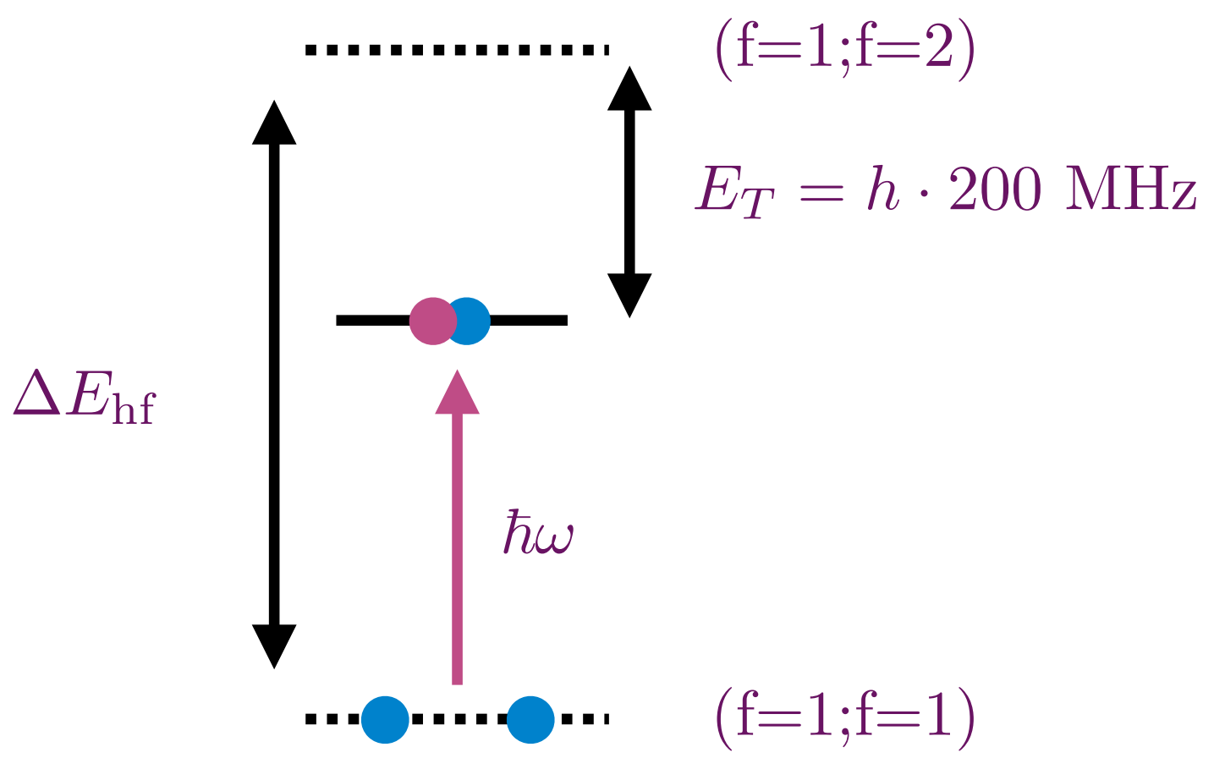




- Width of the resonance proportional to the **square of the microwave field amplitude** [1] :

$$\hbar\Delta\omega = \frac{1}{2\pi}\frac{\mu}{a_{\rm bg}\hbar^2}\left(\mu_B B_0\right)^2 \left|\left\langle \Psi_0^{(2i)} \middle| S^+ \middle| \Psi_{\mathbf{k=0}}^{(2i-1)} \right\rangle\right|^2$$

Molecular levels structure

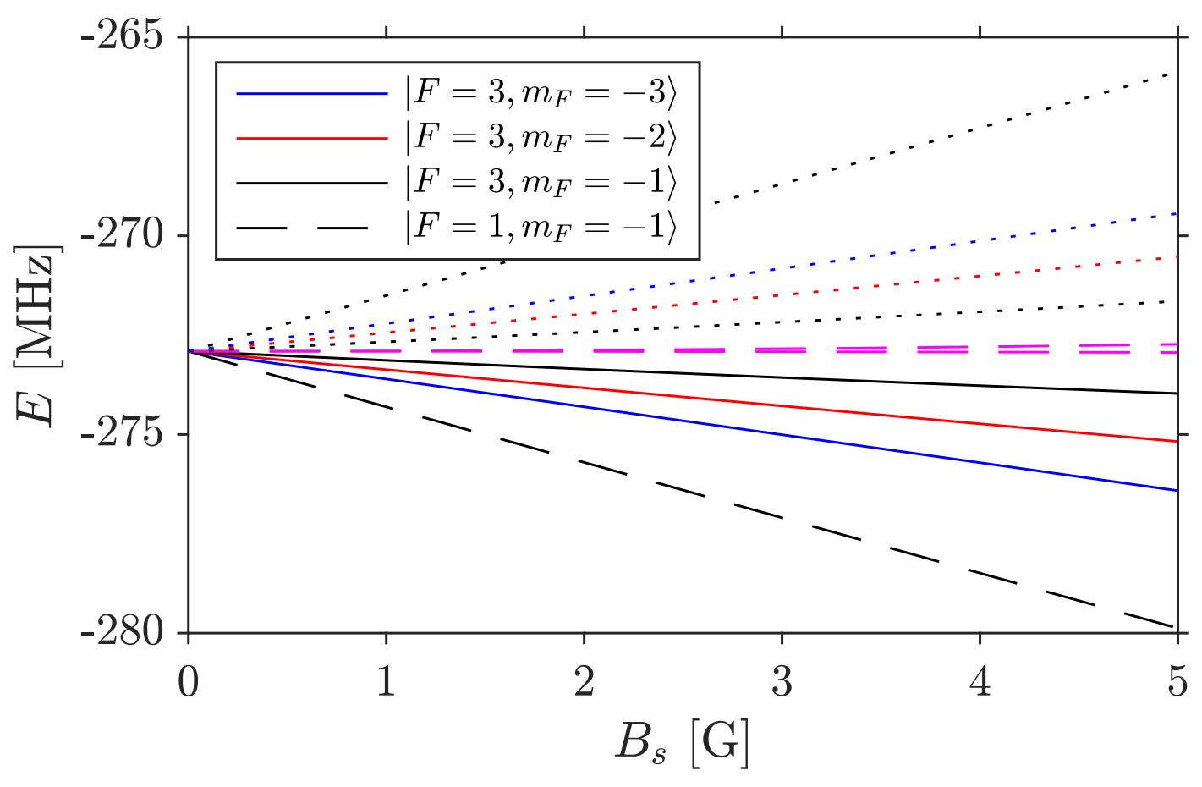


- **Interaction potential** between two alkaline atoms (singulet and triplet potential) :

$$\begin{aligned}\mathcal{V}(r) &= V_s(r)P_s + V_t(r)\\ &= V_D(r) + J(r)\mathbf{s}_1\cdot\mathbf{s}_2\end{aligned}$$

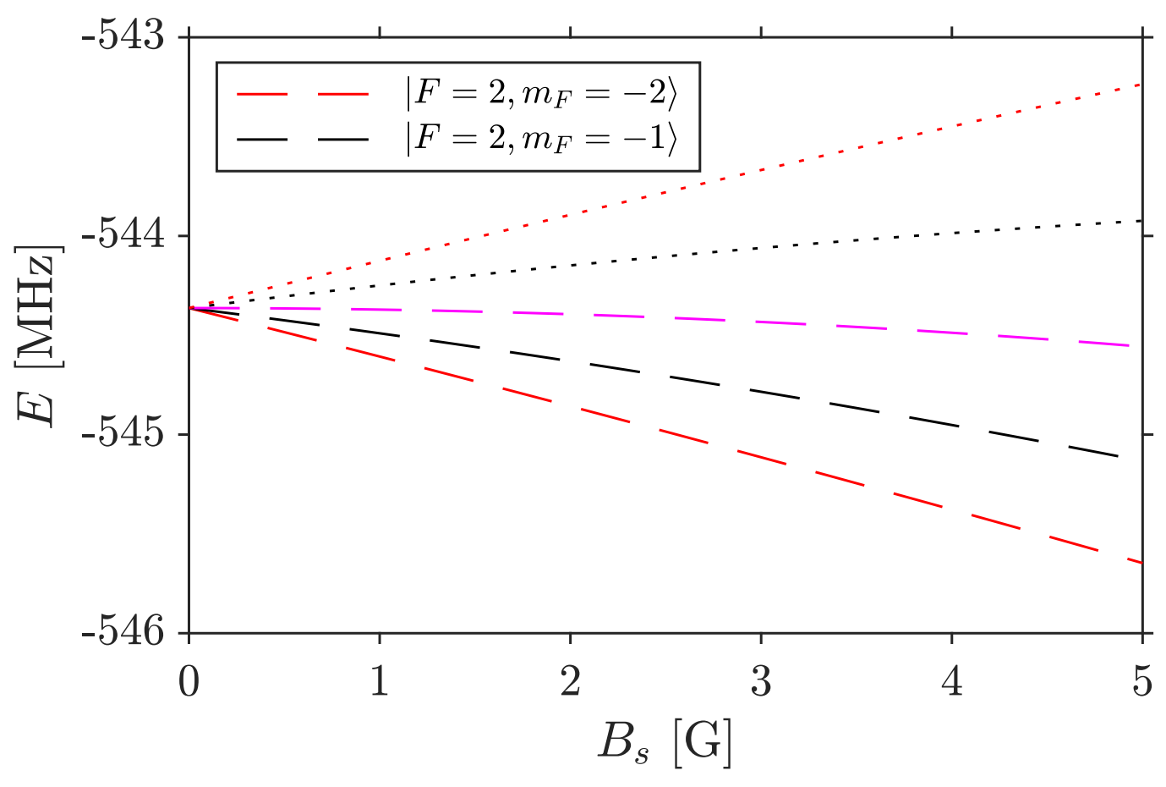
- **Approximation** for weakly bound state [2] (exchange interaction)

$$\mathcal{V}(r) \simeq U\ \mathbf{s}_1\cdot\mathbf{s}_2$$



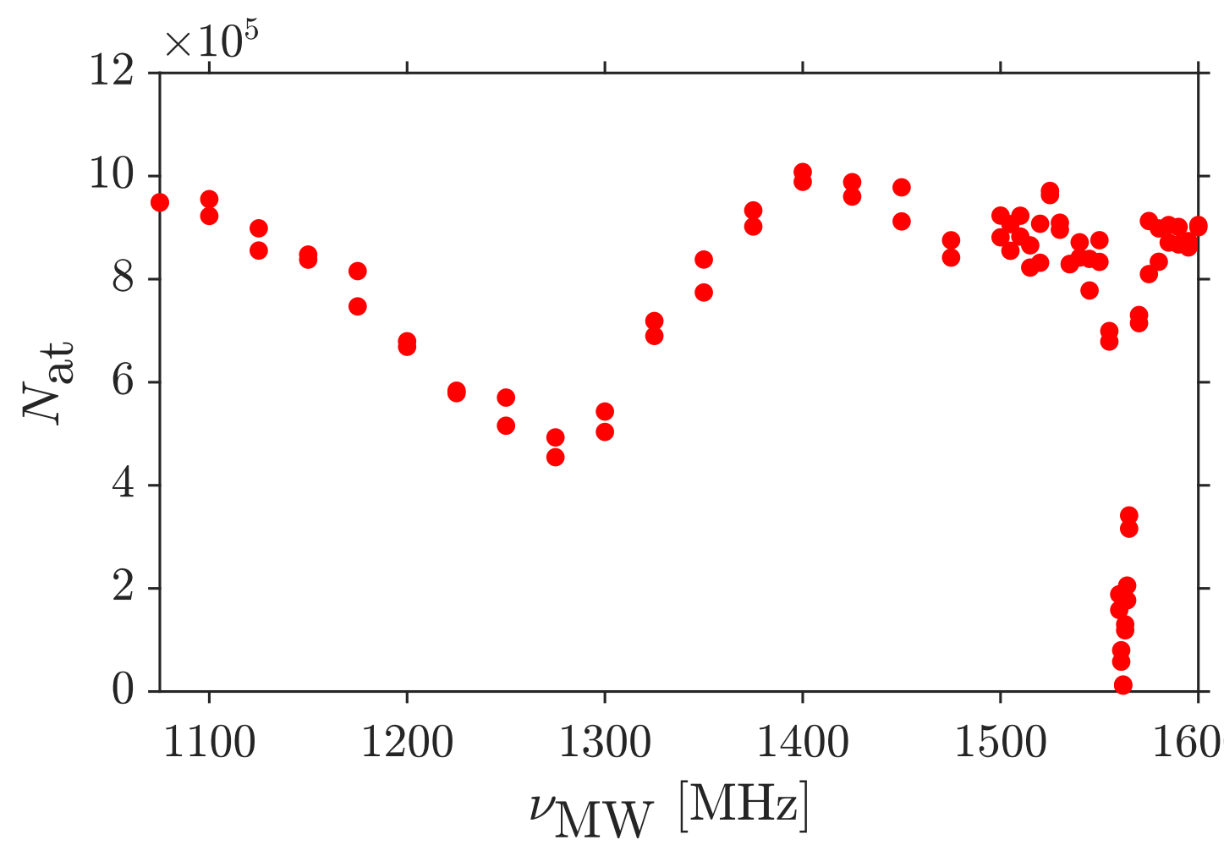
Energies of the F=1,3 molecular states.

- Rich **spin structure** split by the exchange interaction.

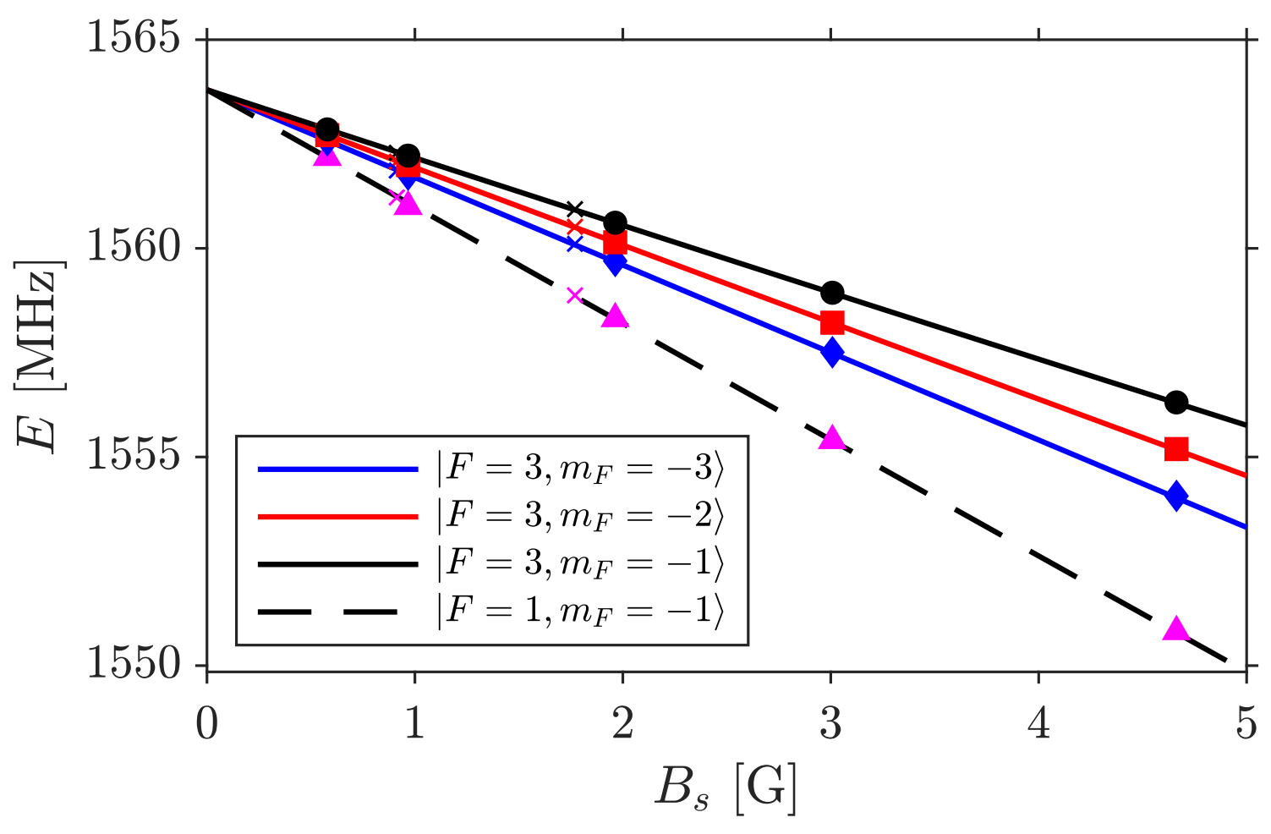


Energies of the F=2 molecular states.

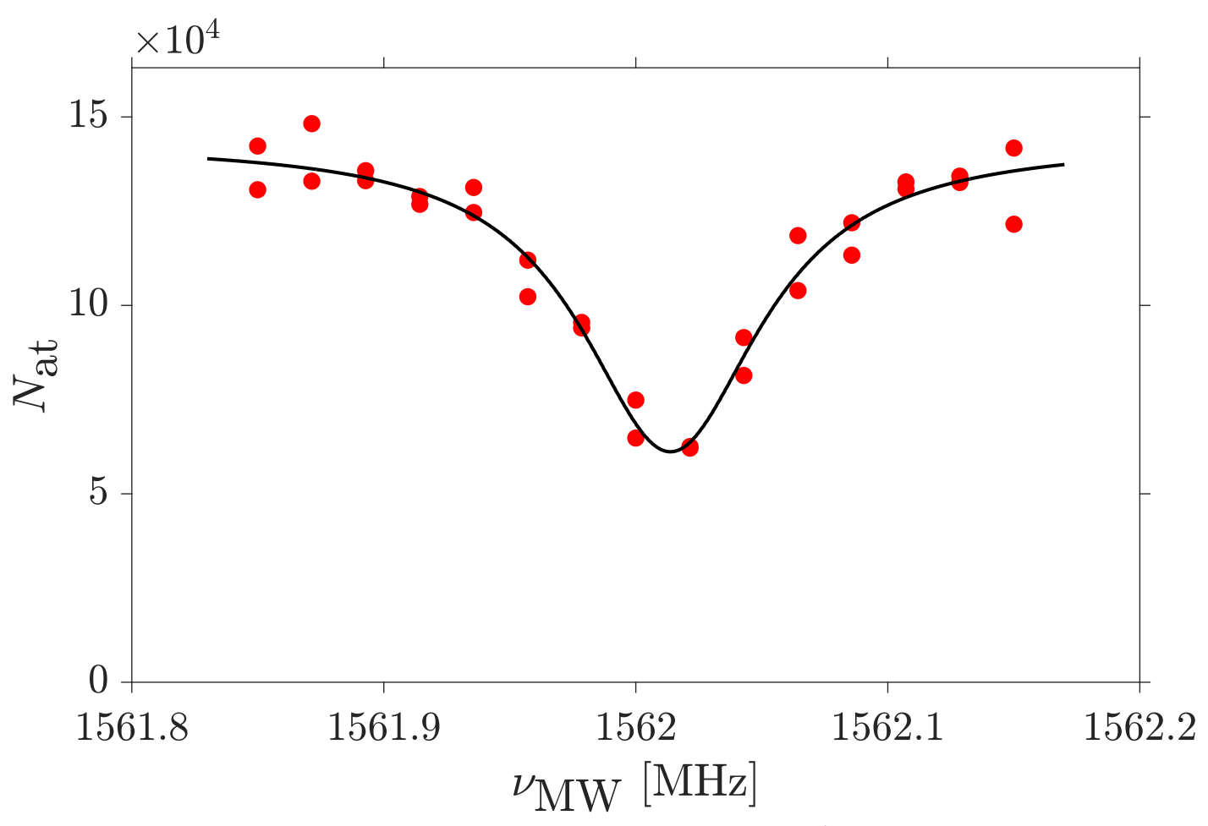
- **Optical spectroscopy** of the vibrational levels of sodium molecules has been realized [4]. Resonance for the 15th vibrational level (highest) of the triplet potential expected at 1568 GHz.
- Atom loss spectroscopy realized for atoms magnetically trapped in $|f=1, m_f=-1\rangle$.
- Observation of a first **resonance close to 1562 GHz** for a static magnetic field of 1G, containing 4 different lines. Observation of a **second, broad resonance** around 1280 GHz.



(a) Atom loss spectroscopy showing the broad and the narrow resonances.

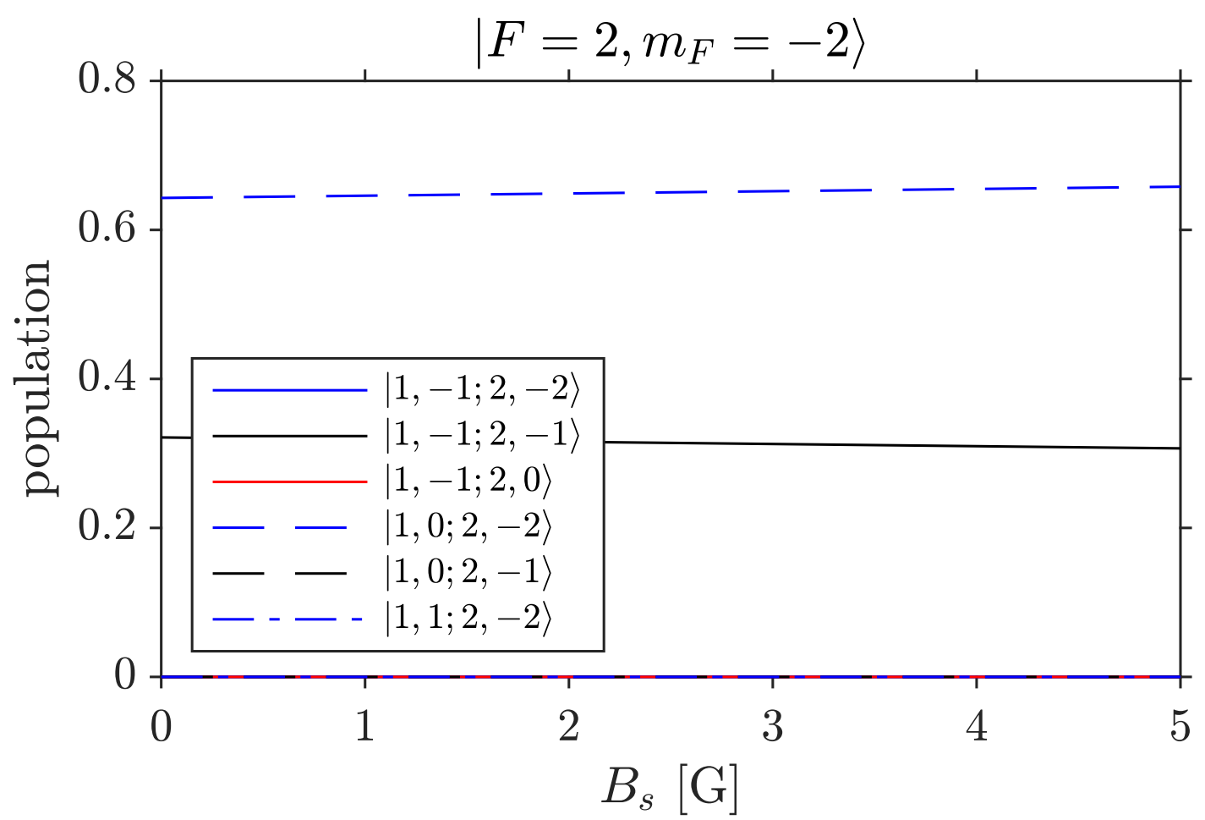


(b) Resonance frequency of the 4 lines part of the narrow resonance.



Atom loss spectroscopy of the $|F=3, m_F=-1\rangle$ resonance.

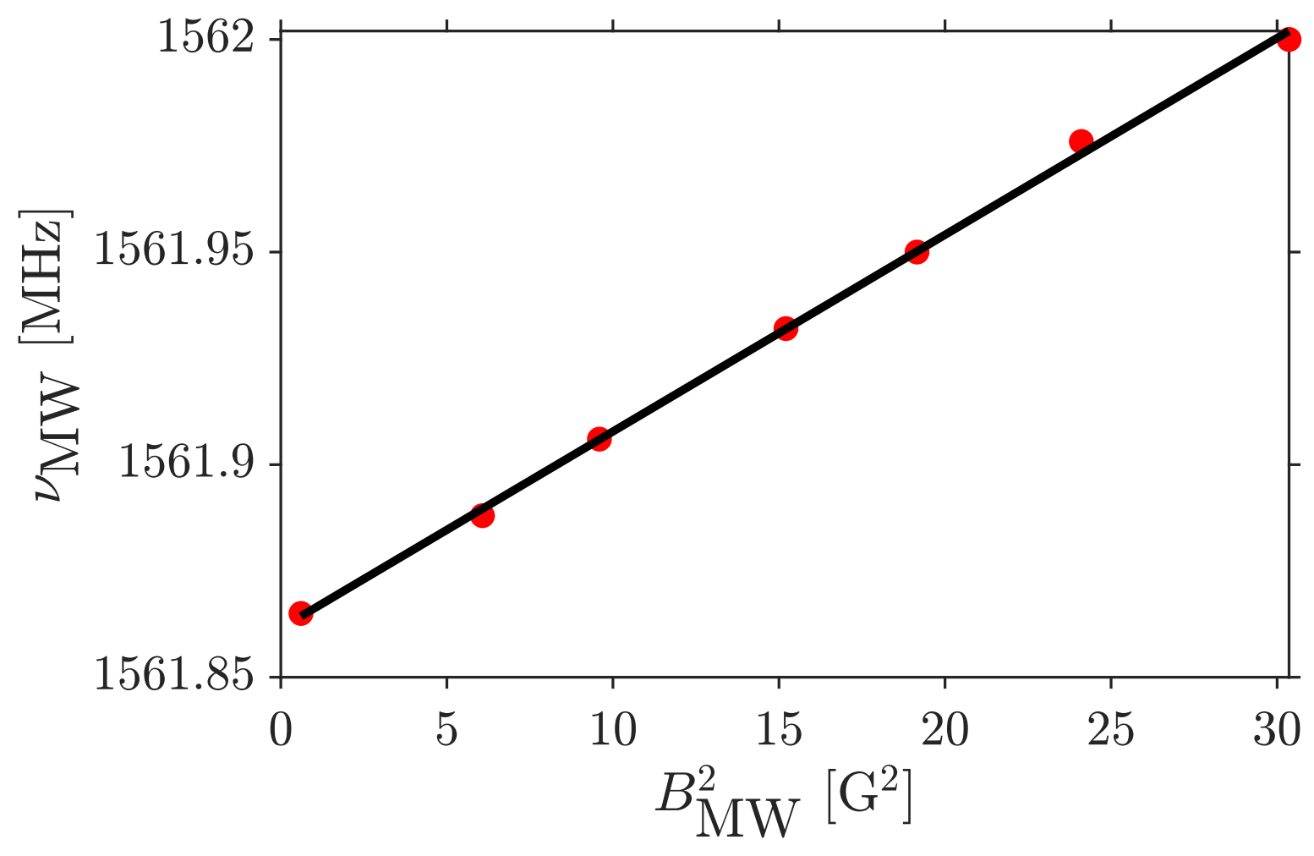
- **Selection rules** limit the number of accessible spin states.



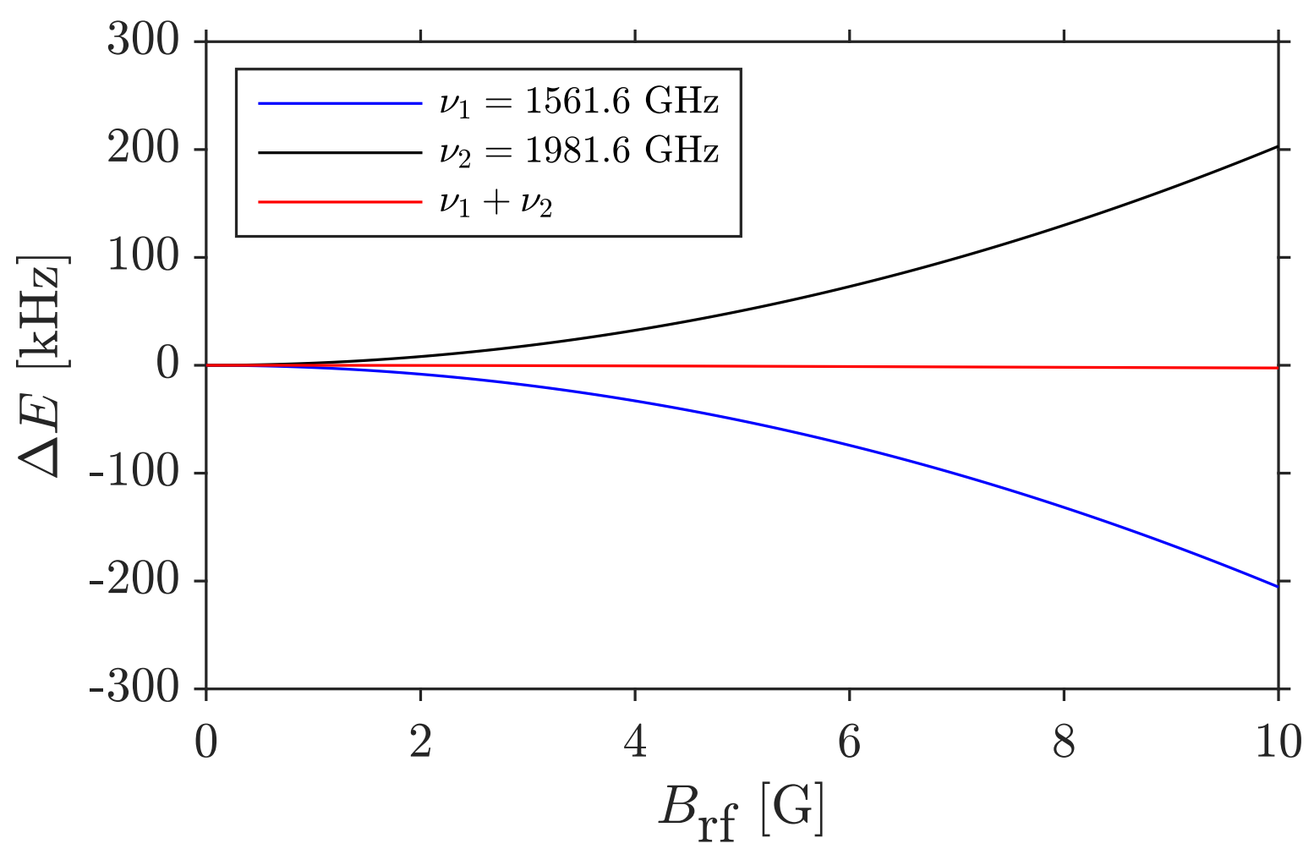
Decomposition in the $|f, m_f; f', m_{f'}\rangle$ basis.

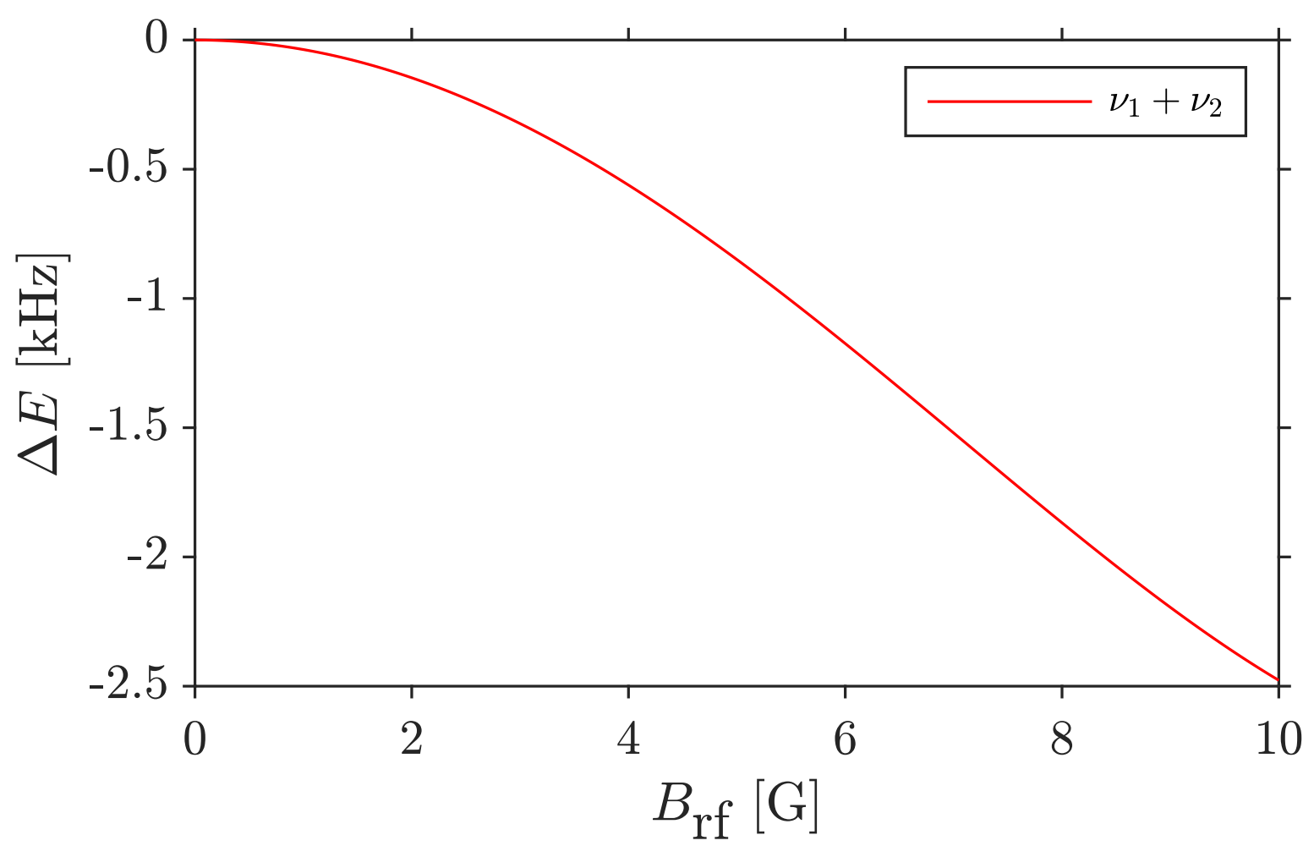
- Observations compatible with exchange interaction **U=hx680 MHz**. Much larger than rubidium [3].
- F=2 states have very short lifetime (few ns) due to **predissociation.** Extremely large resonance width.
- Dependence of the resonance frequency with the **microwave field amplitude** compatible with [1].

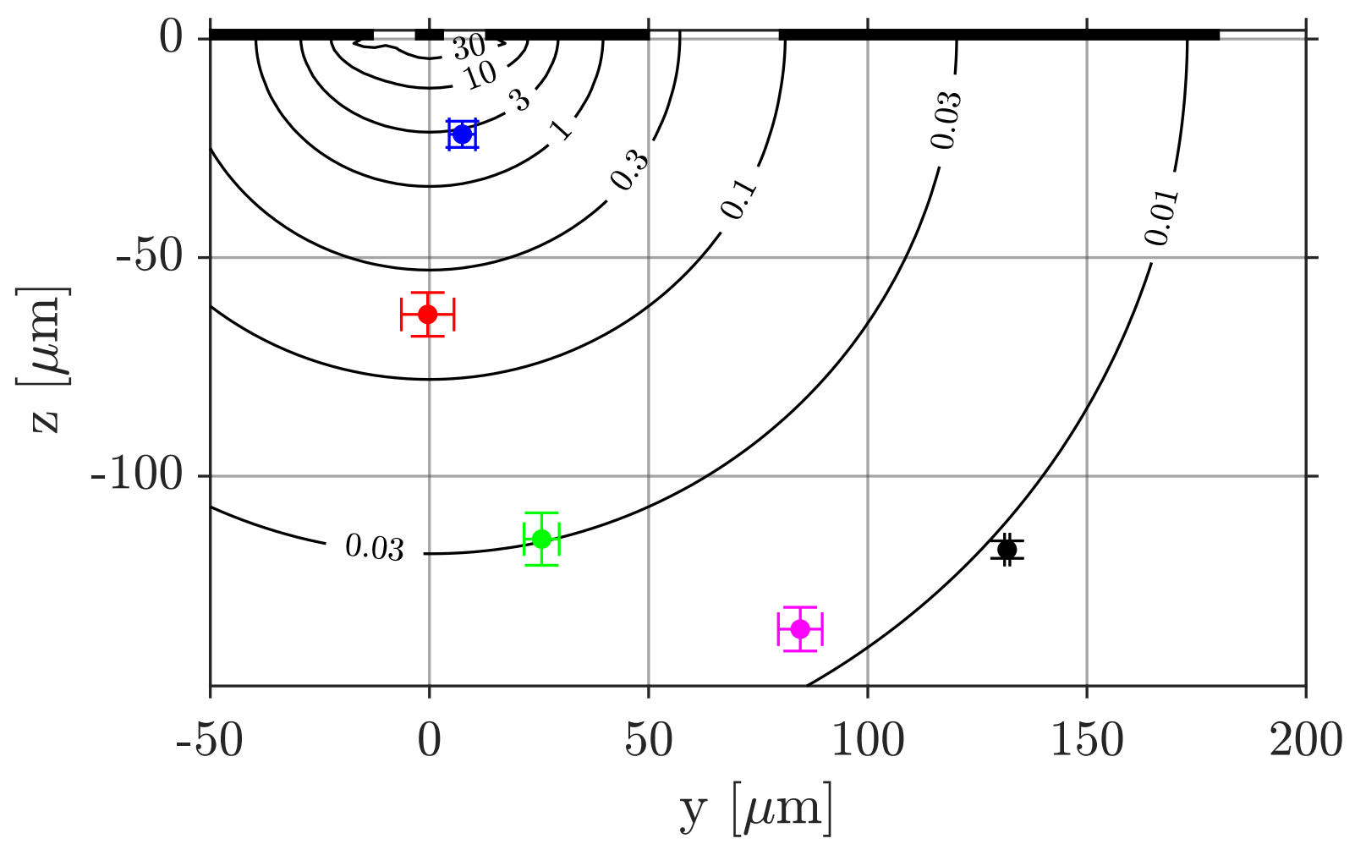
$$\hbar\omega_{\rm res} = \Delta E_{\rm hfs} - |E_T| + \alpha B^2$$



Light shift compensation

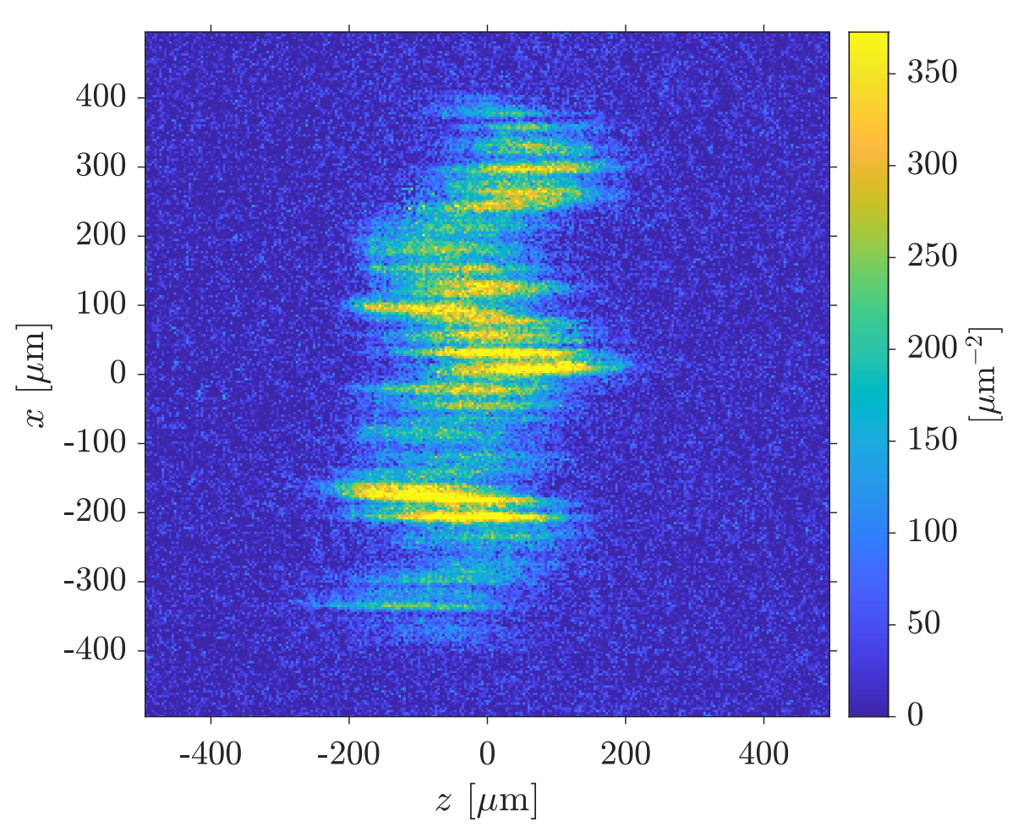






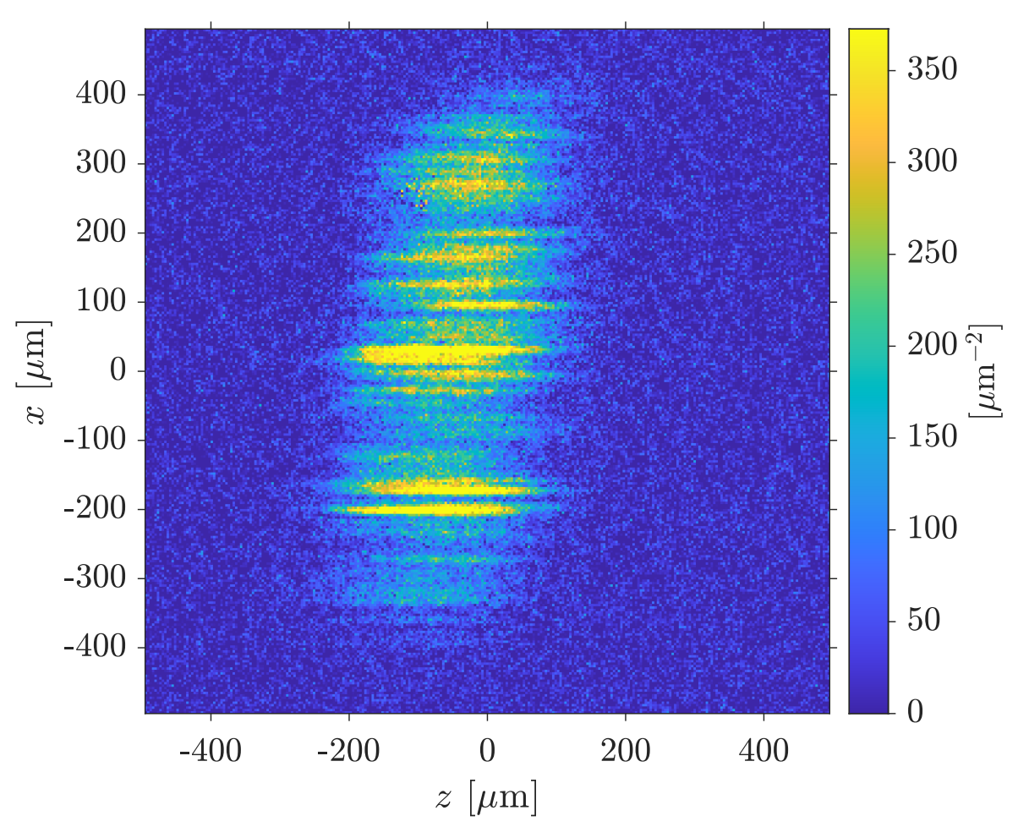
- Dressed atomic state energy shifted due to **light shift** from the hyperfine transition.
- Deforms the trapping potential due to amplitude gradients with the distance to the waveguide.
- **Compensate** light shift with a second **blue detuned** microwave field, at a symmetric frequency, feeding the same microwave guide.
- Small residual light shift cannot be compensated.
- Experimentally : minimize **dipole excitations** to optimize relative amplitude of the microwave fields.

Uncompensated



Time of flight : 10ms.

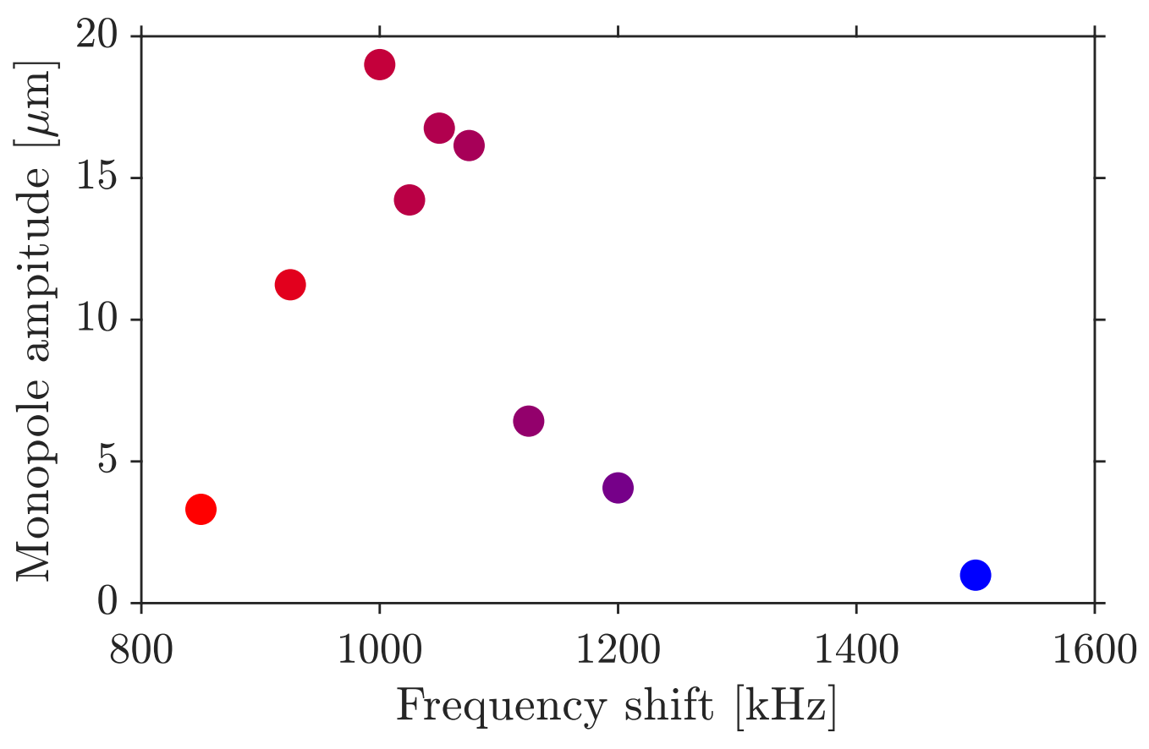
Compensated

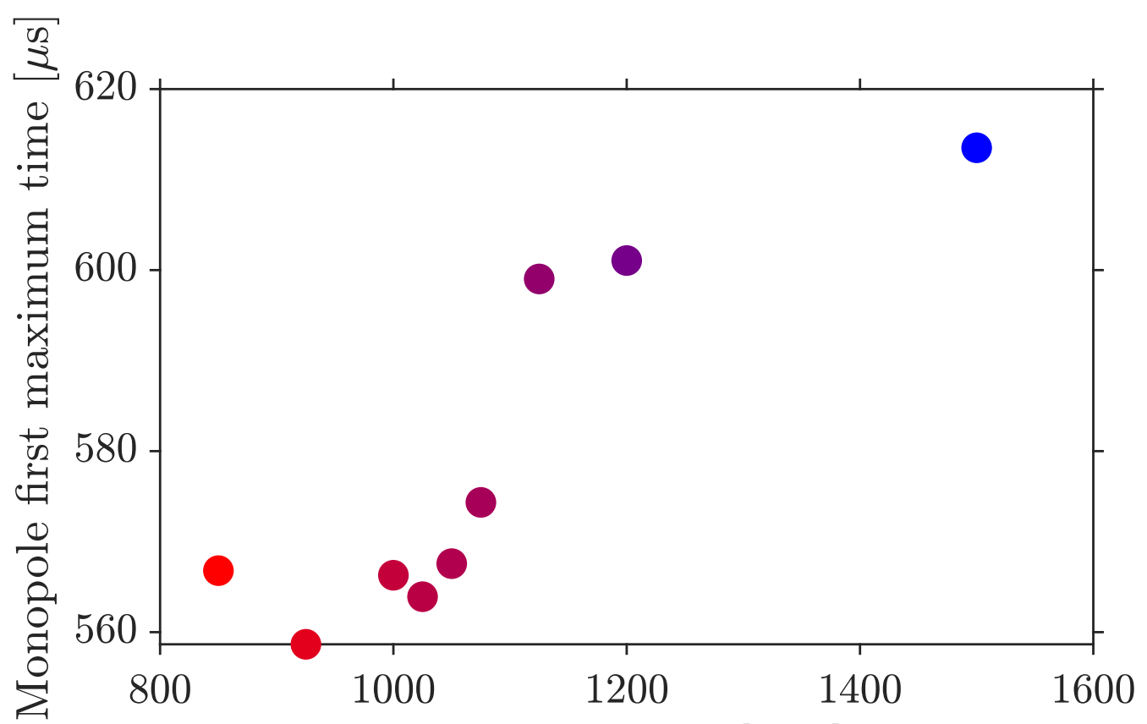


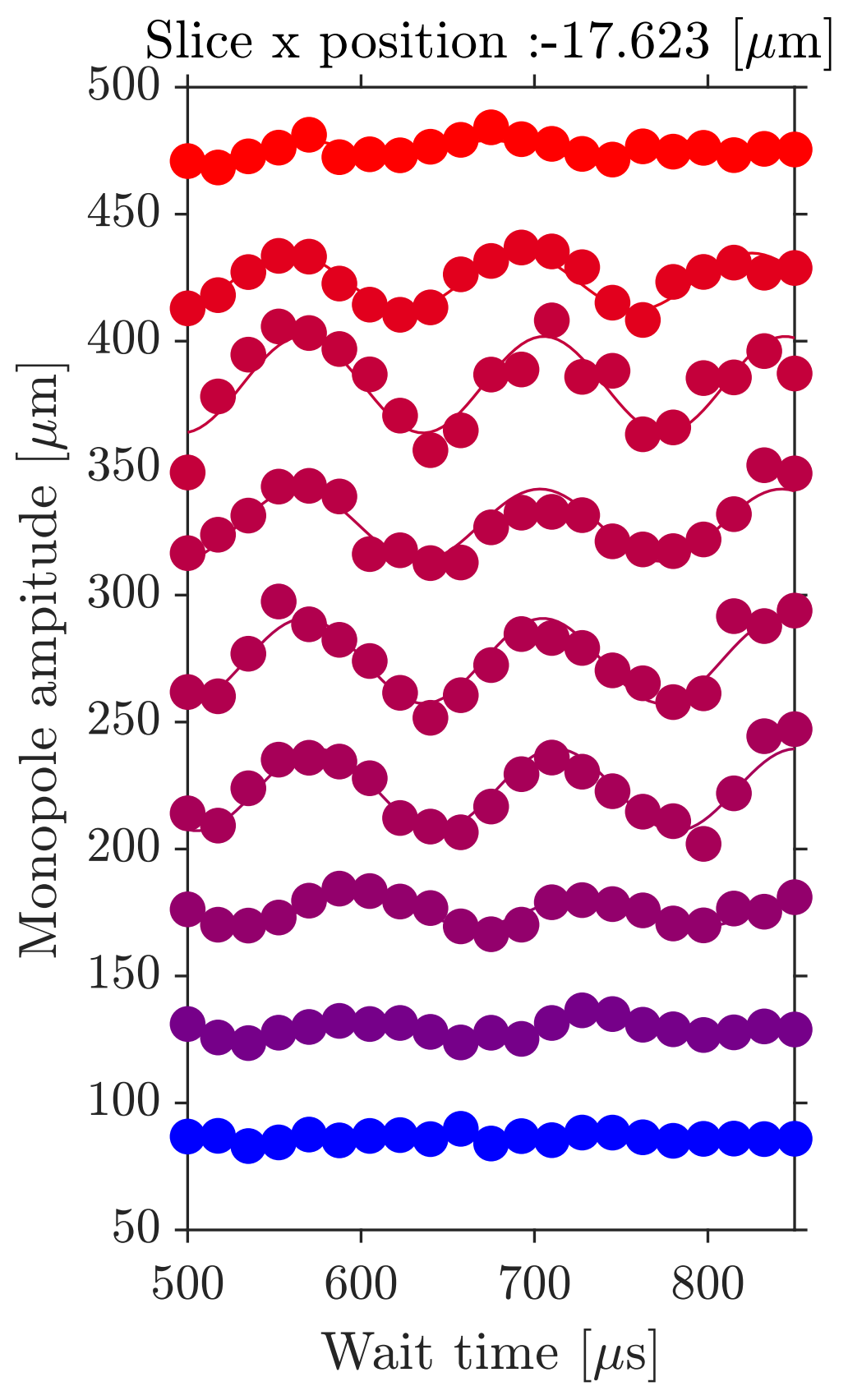
Time of flight : 10ms.

- Microwave waveguide on an atom chip induces **strong microwave field**.
- Amplitude decreases with the **square of the distance** to the center of the waveguide (gradients).
- Move the center of the trapping potential to the high amplitude region.

Radial breathing mode excitations (preliminary)







Experimental protocol

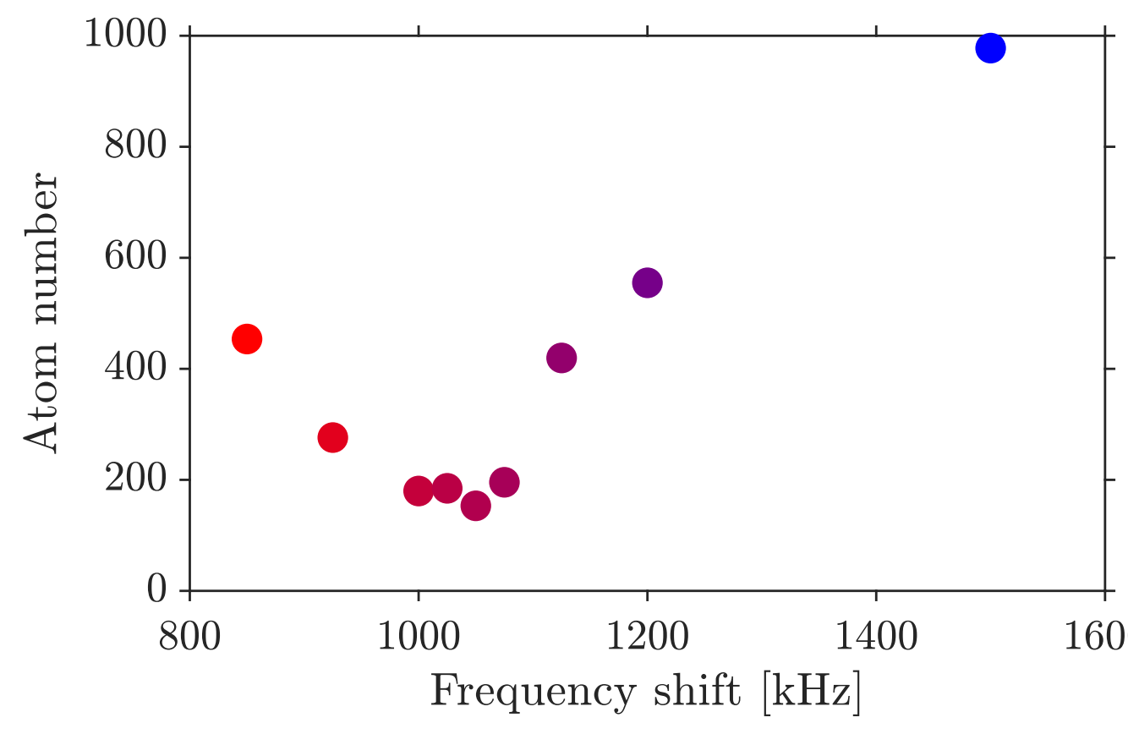
- Prepare **condensate at rest**.
- Switch on microwave fields in 1ms :
  - **large amplitudes** (>14MHz coupling).
  - Light shift compensated (1561 GHz and 1981 GHz).
  - Negative detuning compare to molecular resonance : -1MHz.
- Rapid positive frequency shift close to resonance (<10µs).
- Switch off microwave fields after 100µs.
- Switch off magnetic trap after a varying wait time.
- Absorption imaging after 10ms time of flight.

Observations

- Excitation of the **transverse breathing mode** close to the molecular resonance.
- Maximum of amplitude at resonance.
- **Phase jump** (1/4 of a period) near the resonance.
- Atom losses around resonance.

Thomas-Fermi radius $R_\perp \propto (Na)^{1/5}$

Need clear signal to be able to distinguish between **losses** and **change in scattering length**.



Bibliography

[1] D. Papoular *et al.*, Phys. Rev. A **81** 041603 (2010)
[2] D. Papoular, PhD thesis (2011)
[3] C. Maury *et al.*, Phys. Rev. Research **5** L012020 (2023)
[4] L. De Araujo *et al.*, J. Chem. Phys. **119** 2062 (2003)