

Oh

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Tous les fichiers svg :

# Dedication

For those who hate looking at a template with 500 lines of code and an extra 300 lines commented out.

# Declaration

# Acknowledgements

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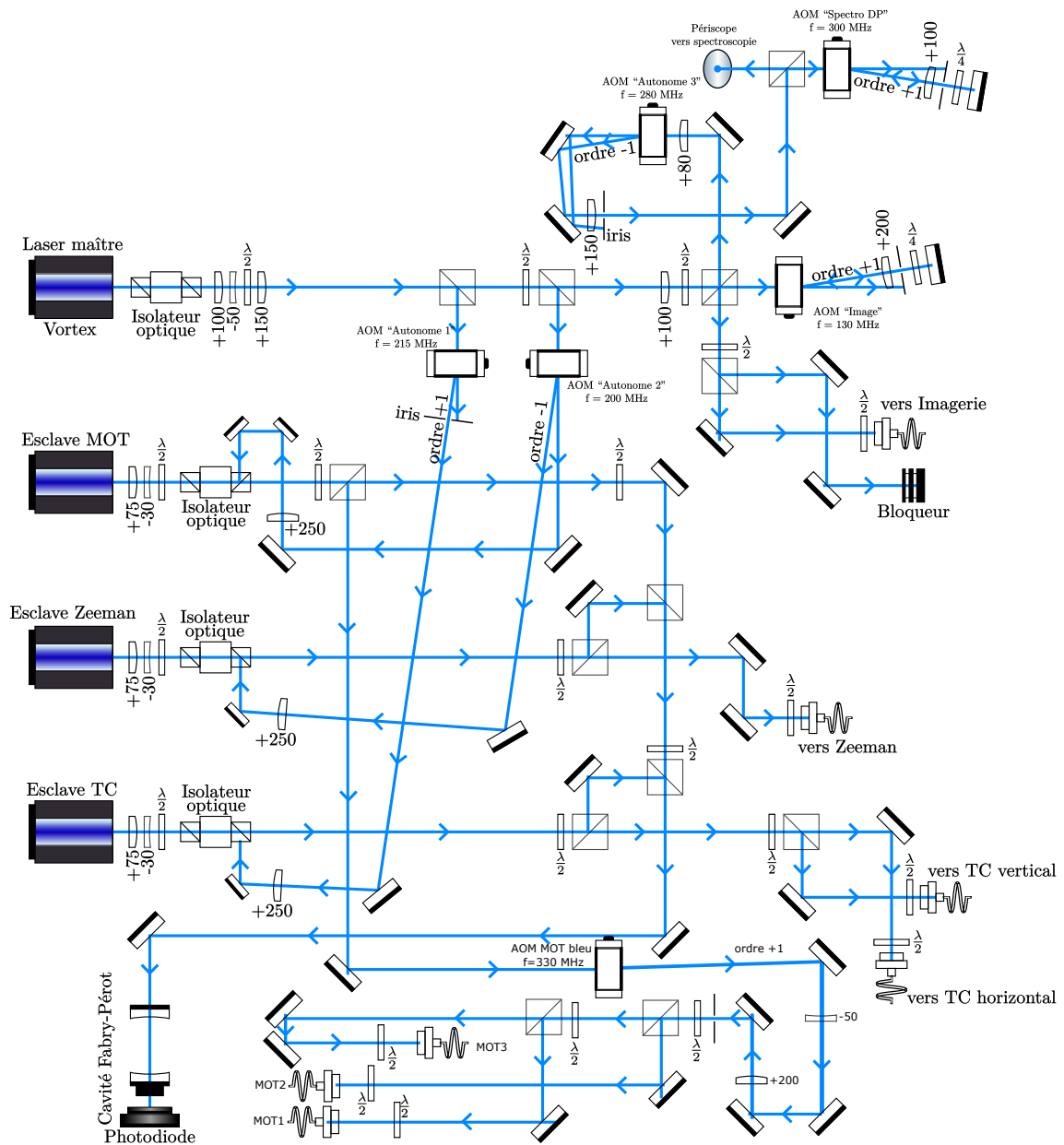


Figure 1.2: Caption

### 1.1.4 Repumper

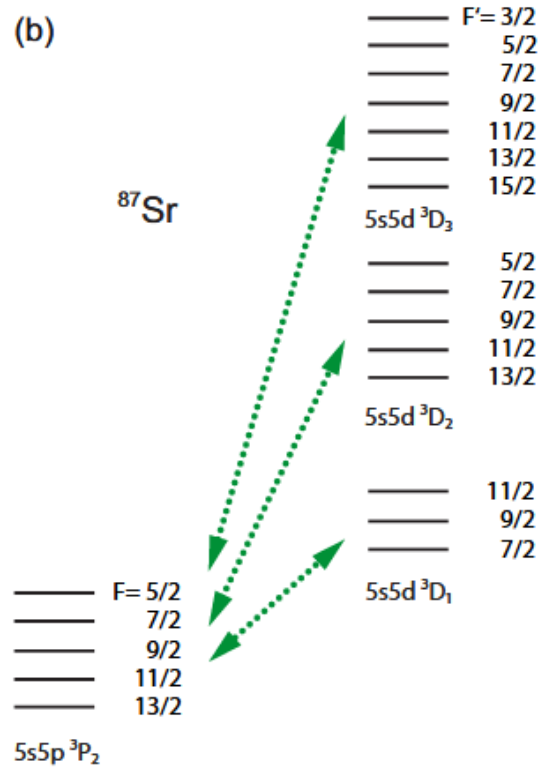


Figure 1.3: Caption

### 1.1.5 BB MOT

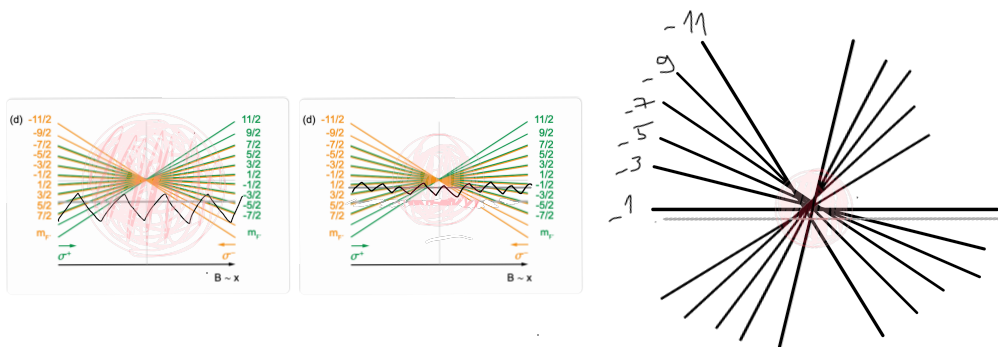


Figure 1.4: Caption

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Need a stir because :



Figure 1.5: Caption



Figure 1.6: Caption

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cf p.43 S.Stellmer thesis

##### 1.1.7.1 Optimization of the narrow MOT (intensity, frequency, effect on the size of the cloud)

Include images of the cloud for different I and detuning ?

### 1.1.7.2 Optical setup

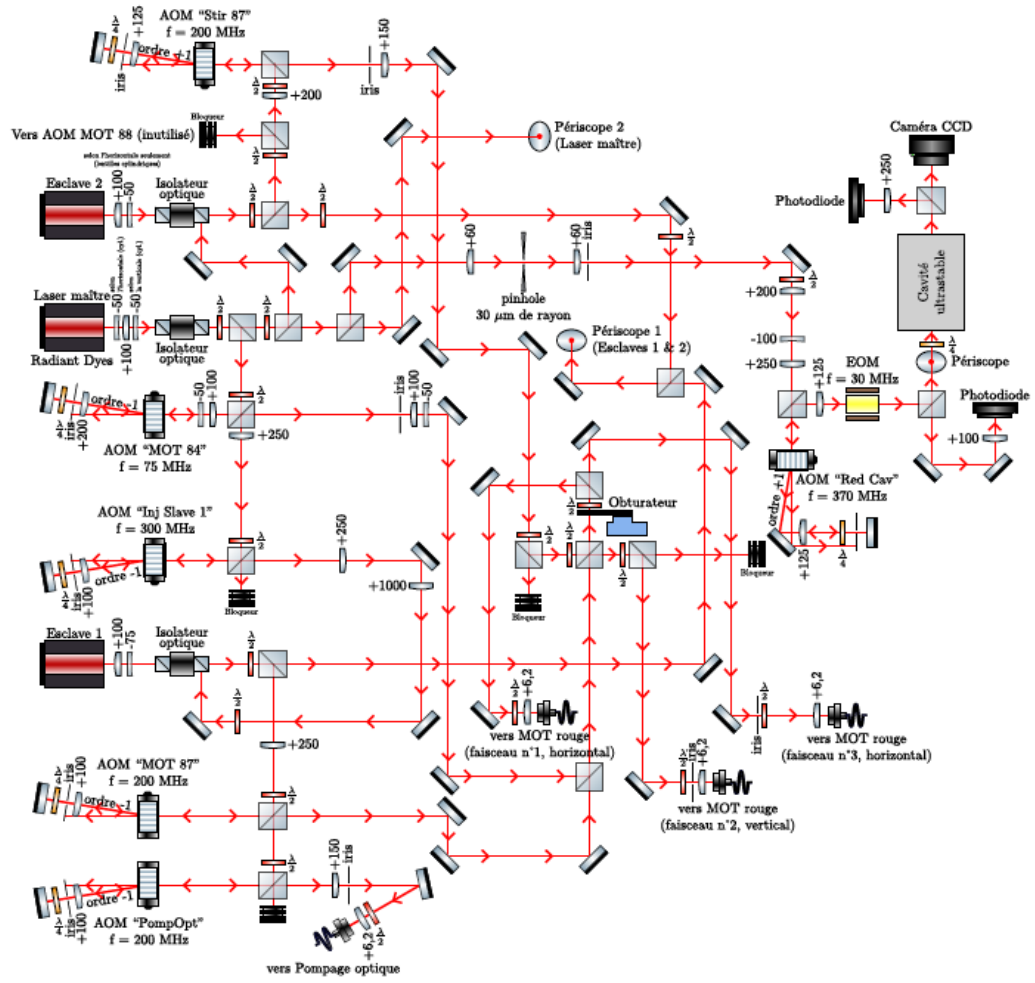


FIGURE 14 – Préparation des différents lasers rouges

Figure 1.7: Caption

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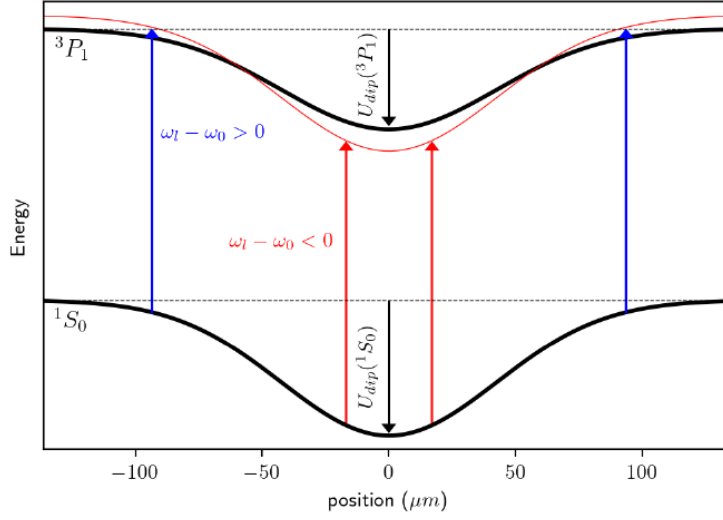


Figure 1.8: Caption

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Comment on the LS it does to each state

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Figure 1.10: Caption



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## Ramsey interferometers on qudit

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blablablagtg

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##### 2.2.1.1 Rabi oscillations

Comment on what the FP could add as a longer coherence time of the qubit

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ment faire mieux que les chiffres actuels)

# Chapter 3

## Engineering highly entangled system of photoassociated $^{87}\text{Sr}$ atoms

Engineering Dicke states

### 3.1 Introduction on photoassociation

#### 3.1.1 Preamble on scattering theory

It is convenient in the case of the  $^{87}\text{Sr}$  to approximate the electrons following the movement of the nuclei because of the mass ratio. In a Born-Oppenheimer picture we neglect the coupled terms between the kinetic energy of the electrons and the kinetic energy of the nuclei. In this manner we can study separately the radial and the angular part of the electronic movement.

As in the LANDAU-ZENER we will find the solutions of the 1D radial Schrödinger equation of the electrons

$$-\frac{\hbar^2}{2\mu} \left( \frac{1}{r^2} \frac{d^2 \Psi_l}{dr^2} r^2 - \frac{l(l+1)}{r^2} + \hat{V}(r) \right) \Psi = E \Psi \quad (3.1)$$

-  $\Psi$  the eigenfunction - by approximating the scattering of the atoms as a sum of an incoming plane wave with a spherical scattered one - considered as plane wave at long distance [3.1](#)

$$\Psi = e^{i\mathbf{k}\cdot\mathbf{z}} + f(\theta) \frac{e^{ikr}}{r} \quad (3.2)$$

$f(\theta)$  a function that will tell the absorption of the scattered wave if the collision is elastic or inelastic.  $\theta$  is the angle between the vector wore by the incoming wave with the vector worn by the scattered wave.

The solution at asymptotes contains the scattering part of the phenomenon studied on this subsection. To solve this hamiltonian we will take the results of [\[1\]](#) that changes the solution basis to find a general solution of the hamiltonian [3.1](#).

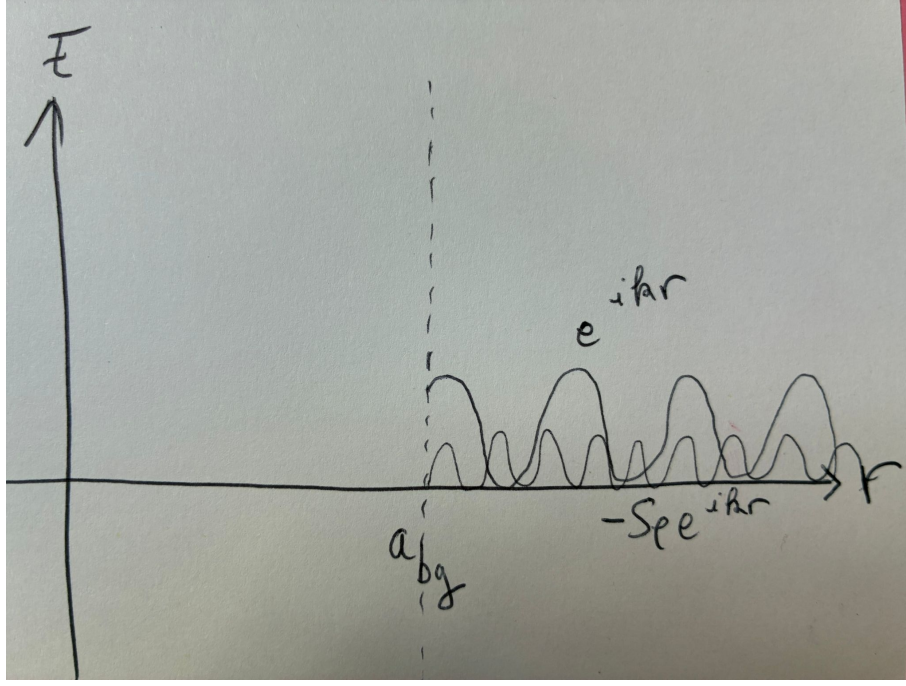


Figure 3.1: Caption

$$\Psi = \frac{a_l}{r} \sin(kr - \frac{l\pi}{2} + \delta_l) \quad (3.3)$$

with  $a_l$  a normalization factor and  $\delta_l$  the phase acquired by the atoms at the distance at which they scatter.

Continuity of the wavefunction in every region should be respected. It gives

$$\delta_l \propto k^{2l+1} \quad (3.4)$$

For s-waves ( $l = 0$ ), this express as

$$a = -\lim_{k \rightarrow 0} \delta_0/k \quad (3.5)$$

To understand how the atoms scatter we are going to express the scattered part of 3.2 as  $\Psi - e^{ikz}$  in a spherical basis where the solutions are a sum on all the partial waves.

$$\Psi \simeq \frac{i}{2kr} \sum_{l=0}^{\infty} (2l+1) ((-1)^l e^{-ikr} - S_l e^{ikr}) \quad (3.6)$$

with  $S_l = e^{2i\delta_l}$  the scattering amplitude.

For a **conservative hamiltonian**  $|S_l| = 1$  meaning  $\delta_l \in \mathbb{R}$ . In this case the wavefunction is well a sum of incoming and outcoming waves of same amplitude.

The elastic cross section representing the surface where the scope of the potential is effective writes as

$$\sigma_{el} = \frac{\pi}{k^2} \sum_{l=0}^{\infty} (2l+1) |1 - S_l|^2 \quad (3.7)$$

But we see in equation 3.6 that  $|S_l|$  needs to be  $< 1$  to allow dissipation of the wavefunction. Defining  $\delta_l$  as a complex number satisfies this condition.

In this case the inelastic collisions cross section reads as

$$\sigma_{inel} = \frac{\pi}{k^2} \sum_{l=0}^{\infty} (2l+1) (1 - |S_l|^2) \quad (3.8)$$

In ultracold gases, only s-wave atoms can collide because they do not have enough kinetic energy to pass the potential barrier of higher angular momentum states so  $l = 0$  and the scattering amplitude is

$$S_0 = e^{2i\delta_0} \simeq 1 + 2i\delta_0 \quad (3.9)$$

By using the result of 3.5

$$1 + 2i\delta_0 \simeq 1 - 2ika \quad (3.10)$$

Because  $\delta_0$  is complex, a direct result of these equations is that we can write a general scattering length as

$$a = a_{bg} + ia'' \quad (3.11)$$

At low temperatures we can re-express equations 3.7 and 3.8 as

$$\sigma_{el} = 4\pi |a|^2 \quad (3.12)$$

$$\sigma_{inel} = 4\pi |a''|^2 \quad (3.13)$$

A usual case of the elastic collisions is atoms in the ground state. For inelasticity photoassociation is a good example of dissipative process where two atoms in the ground state are coupled to a molecular state by a laser.

### 3.1.2 What is photoassociation

Photoassociating two atoms consists in bounding two colliding atoms with light that occurs mostly with two-body and three body losses : it means adding a dissipative part on the interaction.

In a first step we can express the equation evolution of a pair of atoms without dissipation in the basis  $\{|\psi_g\rangle, |\psi_e\rangle\}$  of a non coupled closed channel of free atoms  $\psi_g = |g, g\rangle$  and their first molecular state virtual channel  $\psi_e = |g, e\rangle$

$$i\hbar \frac{d}{dt} \begin{pmatrix} \psi_g \\ \psi_e \end{pmatrix} = \begin{pmatrix} -\frac{\hbar^2}{2\mu} \nabla + V_g & 0 \\ 0 & -\frac{\hbar^2}{2\mu} \nabla + V_e \end{pmatrix} \begin{pmatrix} \psi_g \\ \psi_e \end{pmatrix}. \quad (3.14)$$

In the virtual channel we see in 3.2 the presence of the internal states of the molecule. It is clear that the atoms get more bounded with the increase of the potential amplitude.

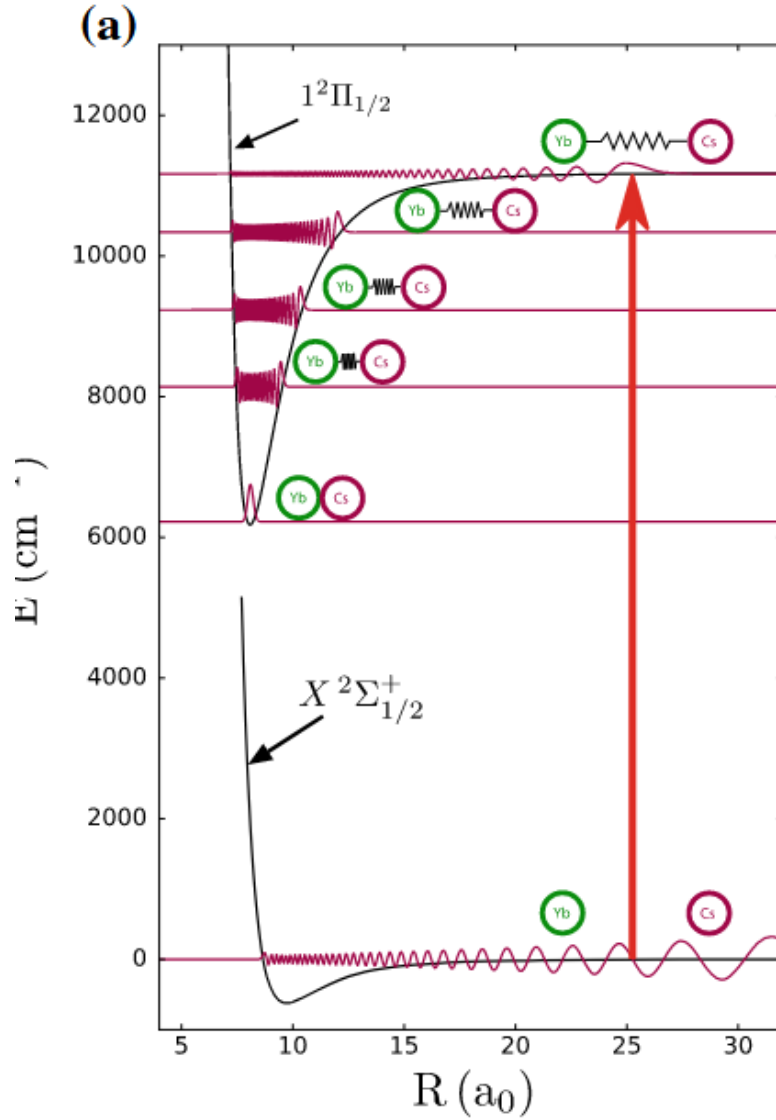


Figure 3.2: Caption

Then at resonance  $\Delta = \omega_{at} - \omega_L = 0$  with a bounded molecular state a dissipative term appears on the evolution of the system because of the molecular spontaneous emission linewidth  $\gamma_{mol}$ .

The evolution of the atom number evolves

$$\frac{dN}{dt} = -\beta N^2 - \Gamma N \quad (3.15)$$

where the 2-body losses express as  $\beta \propto \gamma_{mol}$  (we are going to comment more in the next section). In comparison with [2],  $\beta = \frac{K_2 V_e}{2}$ , where  $V_e$  is the effective volume of the cloud  $(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z$  for a density Gaussian distribution and  $\Gamma$  the one-body losses rate. This latter is limited by the vacuum quality and the lifetime of the atoms in the trap.

Adding the inelastic collisions of the PA process gives the following effective evolution equation

$$i\hbar \frac{d}{dt} \begin{pmatrix} \psi_g \\ \psi_e \end{pmatrix} = \begin{pmatrix} -\frac{\hbar^2}{2\mu} \nabla + V_g & \Omega/2 \\ \Omega/2 & -\frac{\hbar^2}{2\mu} \nabla + V_e + \hbar\Delta - i\frac{\gamma_{mol}}{2} \end{pmatrix} \begin{pmatrix} \psi_g \\ \psi_e \end{pmatrix}. \quad (3.16)$$

The eigenvector of the ground state  $|\psi_g\rangle$  is then modified by this coupling. It also means that the phase  $\delta_l$  (see 3.3) of the free state wavefunction is modified so the scattering length. The real part of  $a$  encodes two-body losses rate whereas its imaginary part changes the collisions properties. In this case we can write an effective scattering length enclosing the background scattering length  $a_{bg}$  standing for elastic collisions without any coupling,  $\delta a$  a modification of it because of the coupling and still the inelastic part of it

$$a = a_{bg} + \delta a + ia'' \quad (3.17)$$

In the case of spectroscopy we usually start with the least bounded state to have the atomic state reference. From that we sweep the atom frequency to adress the molecular states red detuned from the atomic line. The quantity that will testify there is two-body losses is the atom number remaining in the trap after a photoassociation pulse. The molecule leaves the trap by acquiring kinetic energy from the binding energy.

PA is mostly used in Feshbach resonance field because determining the exact position of the vibrational states enables by changing the magnetic field to tune the scattering length of the atoms and thus the interactions in the system.

### 3.1.3 Parameters for PA study

In this subsection we are going to admit the expression of the two-body losses rate we introduced above but we will take a look on its dependencies.

This rate writes as

$$K_2 = \frac{\pi \hbar^2}{k} n \frac{\gamma_{stim} \gamma_{mol}}{\Delta^2 + (\gamma_{stim} + \gamma_{mol})^2} \quad (3.18)$$

$\gamma_{stim}$  is linear with the intensity of the PA laser, proportionnal to the 3D density  $n$ , and the probability to transit from  $\psi_g$  to  $\psi_e$  that we call **Franck-Condon factor**

$$F_{FC} = \left| \int_0^\infty \psi_g(r) \psi_e(r) dr \right|^2 \quad (3.19)$$

It depends directly with the overlap of the wavefunctions of the initial and final states. **The Condon radius** is the distance between the atoms for which this factor is maximum which also means that in a classical approach the atoms spend the most time at this position.

In the molecular community it is conventional to characterize the strength of the photoassociation rate with the **optical length**

$$K_2(I) = \frac{4\pi\hbar}{\mu} n l_{opt}(I) \quad (3.20)$$

$\mu$  the reduced mass of the two atoms. From this formula we can say that the major experimental changes enabling the increase of the PA rate is the density of the cloud and the intensity if the. PA beam as we are going to test in the experimental results.

Exciting an atom from a ground state to a single excited state is straightforward and quite easy to do precisely. It is not as easy for molecules because there exist a big number molecular potentials and internal states for each potential. These internal and external accesible states of the molecule are presented in the following via the introduction of the molecular quantum numbers.

### The good quantum numbers

We write the total angular momentum of the molecule  $T = R + F = R + I + J$ ,  $F$  being the total spin of the two atoms  $f_1 + f_2$ ,  $J = j_1 + j_2$  is the angular momentum of the molecule that describes the spin-orbit coupling, and  $R$  the rotational angular momentum of the molecule.

We define the projection of the different angular momentum on the inter-nuclear axis as

$$\Omega = \Lambda + \Sigma \quad (3.21)$$

with  $\Lambda$  the projection of the orbital momentum of the molecule on the internuclear axis and  $\Sigma$  the projection of the momentum spin.

$M_T$  is the projection of the total angular momentum  $T$  onto a defined quantization axis.

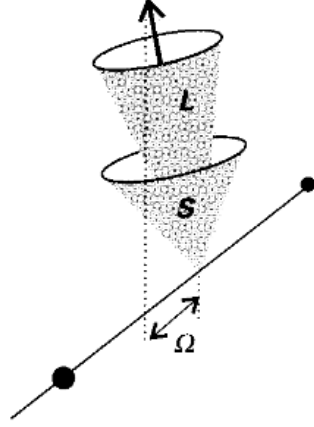
For the rotational quantum number there is a parity of the total wavefunction that needs to be fulfilled. In addition there are only s-wave collisions in cold gases then the part of the wavefunction should be odd the spin one antisymmetric

$$|\Psi\rangle = (|\phi_e\rangle_A |\phi_g\rangle_B + (-1)^R |\phi_e\rangle_B |\phi_g\rangle_A) \otimes |\chi\rangle \quad (3.22)$$

$|\phi_e\rangle$  and  $|\phi_g\rangle$  are the electronic wavefunctions of the two atoms A and B in ground and excited state respectively,  $|\chi\rangle$  is the spin wavefunction. It gives accessible values  $R = 0, 2$  or  $4...$



For  $^1S_0 - ^3P_1$  molecular state there is a strong spin-orbit coupling that couples its related momentum to the internuclear axis (3.3), quantified by  $\Omega$  and described as Hund's case (c)



**Fig. 11.4** A vector diagram for Hund's case (c), in which the spin-orbit coupling is very strong.

Figure 3.3: hund

The experiment presented in the following section is photoassociation in the  $F = 11/2$  hyperfine state. We will focus in this state to simplify the discussion.

Say we have one atom in the  $^1S_0$  state and one in the  $^3P_1$  state: we can have a total spin of  $J = 0, 1$  or  $2$ . It gives possible values of total atomic angular momentum  $F$ :

$$\text{For } J = 0, \quad F = \frac{9}{2} \quad (3.23)$$

$$\text{For } J = 1, \quad F = \frac{7}{2}, \frac{9}{2}, \frac{11}{2} \quad (3.24)$$

$$\text{For } J = 2, \quad F = \frac{5}{2}, \frac{7}{2}, \frac{9}{2}, \frac{11}{2}, \frac{13}{2} \quad (3.25)$$

We have one atom with  $f_1 = 9/2$  from the  $^1S_0$  state and one in the  $^3P_1$  state with  $f_2 = 11/2$ . The possible values of total angular momentum of the molecule are

$$\text{For } R = 0, \quad T = 1, 2, 3 \dots 10 \quad (3.26)$$

$$\text{For } R = 2, \quad T = 1, 2 \dots 12 \quad (3.27)$$

$$\text{For } R = 4, \quad T = 1, 2 \dots 14 \quad (3.28)$$

The initial  $T^i = i_1 + i_2$  with  $R = 0$  because we are in s-wave collisions. In respect with the parity  $p = +1$  the possible values of  $T^i$  are  $T^i = 0, 2, 4, \dots$

As for atoms there are selection rules for transitions from a free state to a molecular state fixed by the angular momentum of the electrons.  $\Delta J = 0, 1$  gives  $\Delta T = 0, 1$  with  $T = 0 \rightarrow T = 0$  forbidden.

In the end the accessible transitions in the first molecular excited state of the  $f_1 = 11/2$  are

$$\text{For } R = 0, \quad T^f = 1, 2, 3 \dots 11 \quad (3.29)$$

$$\text{For } R = 2, \quad T^f = 1, 2 \dots 13 \quad (3.30)$$

$$\text{For } R = 4, \quad T^f = 1, 2 \dots 15 \quad (3.31)$$

$$\dots \quad (3.32)$$

There are 981 combinations of accessible  $(R, T^f)$  molecular states

Another element to describe the molecule is the symmetry of the orbital wavefunction. For an even wavefunction the exchange of the two atoms  $A$  and  $B$  does not change the sign of the wavefunction, as in left figures 3.4. We say the potential is **gerade**. The probability of finding electrons in between the two atoms is high compared to the **ungerade** potential where the odd wavefunction cancels the probability of finding electrons in between.

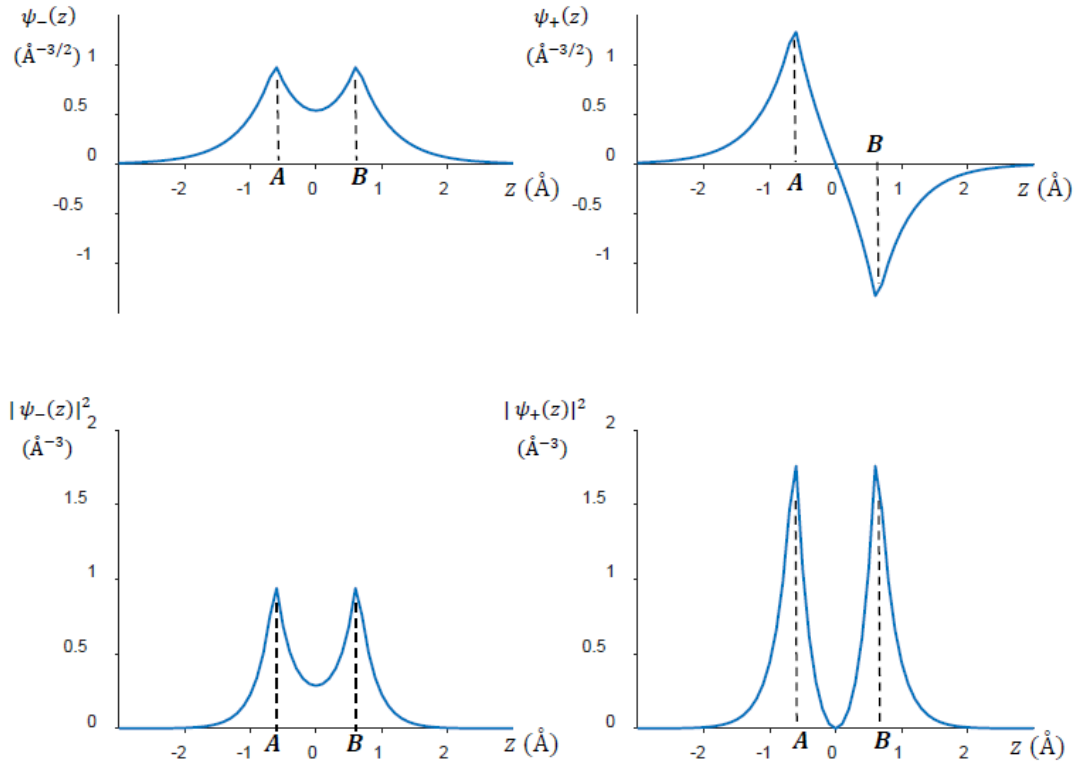


Figure 8.5 : Evolution le long de l'axe internucléaire  $Oz$  ( $x=0, y=0$ ) des fonctions d'onde liante  $|\psi_{-}\rangle$  et antiliante  $|\psi_{+}\rangle$  et des densités de probabilité de présence de l'électron associées  $|\psi_{-}|^2$  et  $|\psi_{+}|^2$ . La distance internucléaire est fixée à  $R = 1,25 \text{ \AA}$  (minimum de  $E_{-}$ ).

Figure 3.4: u-g symmetry

### 3.1.4 External energy states

As seen in the subsection 3.1.1 in a molecular picture the hamiltonian express as in [2] by

$$\hat{H} = \frac{\hat{p}_r^2}{2\mu} + \frac{\hbar^2}{2\mu r^2} R(R+1) + \hat{V}_{BO} + \hat{H}_{HF} \quad (3.33)$$

with

$$\hat{V}_{BO} = \frac{-C_6}{r^6} \left( 1 - \frac{\sigma^6}{r^6} \right) - s \frac{C_3^\Omega}{r^3} \quad (3.34)$$

$$\hat{H}_{hf} = A(\mathbf{i}_1 \cdot \mathbf{j}_1) + B \frac{3(\mathbf{i}_1 \cdot \mathbf{j}_1)^2 + \frac{3}{2}(\mathbf{i}_1 \cdot \mathbf{j}_1) - i_1(i_1+1)j_1(j_1+1)}{2i_1(2i_1-1)2j_1(2j_1-1)} \quad (3.35)$$

$s = \pm 1$  for gerade and ungerade potentials respectively. The hyperfine term of the atom in  $^1S_0$  is zero because its electronic angular momentum is zero. Only the hyperfine interaction of the atom with  $i_1, j_1$  in  $^3P_1$  counts.

#### 3.1.4.1 WKB approximation

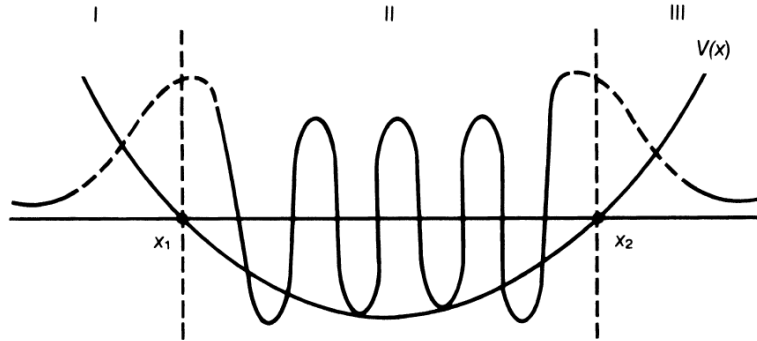


FIGURE 2.1. Schematic diagram for behavior of wave function  $u_E(x)$  in potential well  $V(x)$  with turning points  $x_1$  and  $x_2$ .

Figure 3.5: Caption

#### 3.1.4.2

### 3.1.5 Internal energy states

Leroy-Bernstein approx

## 3.2 About photoassociation on other species

### 3.2.1 Mass scaling ( $^{88}\text{Sr}$ )

$^{88}\text{Sr}$  is a bosonic isotope of strontium with no hyperfine structure. The photoassociation spectrum is then simpler than the fermionic ones : only two potentials in

the first excited molecular state  $0_u$  and  $1_u$ . Results have been presented in [3] where their fitting model gives the following potential expression

$$\hat{V}_{BO} \sim \frac{-C_{6,\Lambda}}{r^6} - \frac{C_3}{r^3} + \frac{C_J}{r^2} \quad (3.36)$$

for the two accessible potentials  $\Lambda = 0, 1$ .

Mass scaling method presented in [4] enables to predict the position of the vibrational states of the different isotopes of strontium.

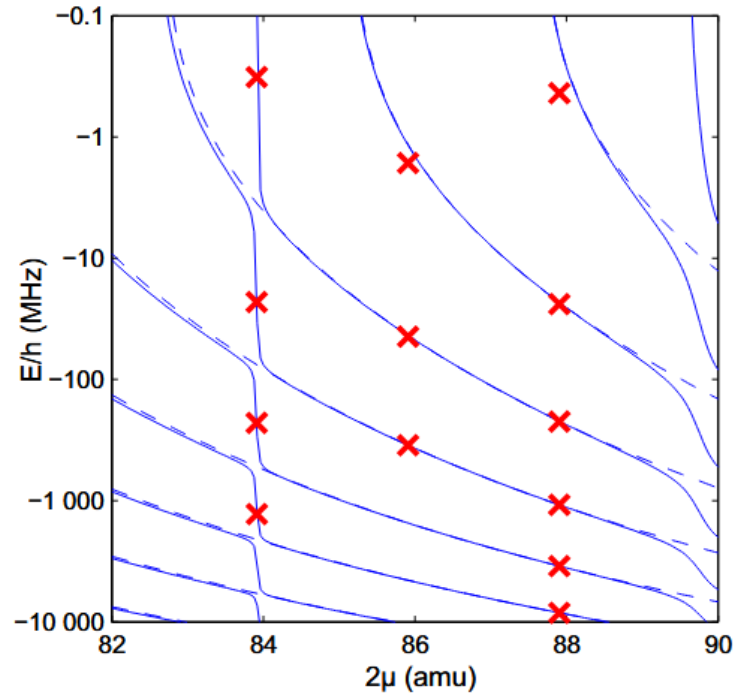


Figure 3.6: Caption

### 3.2.2 Ytterbium: hfs

As the  $^{87}\text{Sr}$  the fermionic  $^{173}\text{Yb}$  has a hyperfine structure that makes its molecular potential landscape more complex than many known species.

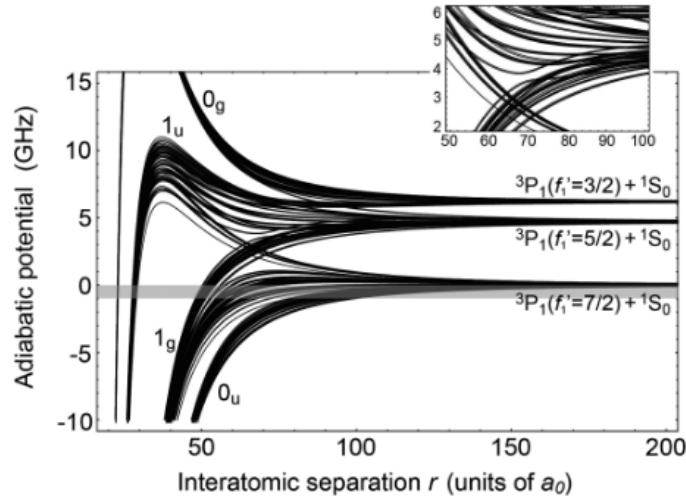


FIG. 2. Adiabatic molecular potentials for a  $^{173}\text{Yb}_2$  dimer in the  $^1S_0 + ^3P_1$  channel as functions of the interatomic separation  $r$ . The molecular potentials for 205 different  $(T, F, R)$  configurations are displayed, which are accessible via PA from the initial  $s$ -wave colliding atoms in the  $^1S_0 + ^1S_0$  channel. At large  $r$ , the potentials converge to three asymptotic branches which correspond to excited atomic states with hyperfine numbers of  $f'_1 = 3/2, 5/2$ , and  $7/2$ . Some of the potentials have a local minimum (inset), possibly hosting purely long-range bound states [14]. The energy offset is adjusted to the  $f'_1 = 7/2$  asymptote. The shaded region indicates the spectral range of our measurements.

Figure 3.7: Caption

$^{171}\text{Yb}$  In their fitting model they consider the same interactions as in our case (expressed in equation 3.33) but without the hyperfine term.

### 3.3 Experimental setup

### 3.4 $^{88}\text{Sr}$ Results

The  $s$ -wave collisions imposes that for fermions -by parity of the total wavefunction being antisymmetric- only atoms with even angular momentum can collide meaning their spin is in a singlet state as in the case of  $^{87}\text{Sr}$ . For bosons it is the contrary : from an even orbital wavefunction, the spin wavefunction should be antisymmetric to collide. Lopt, power broadening, thermal broadening...

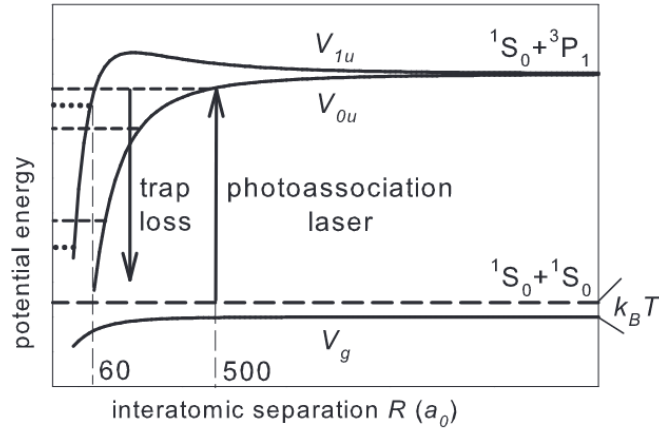


Figure 3.8: Caption

### 3.4.1 Technical issues of inhabitation of photoassociation

#### 3.4.1.1 Laser width

## 3.5 $^{87}\text{Sr}$ molecules

The s-wave collisions imposes that for fermions -by parity of the total wavefunction being antisymmetric- only atoms with even angular momentum can collide meaning their spin is in a singlet state as in the case of  $^{87}\text{Sr}$ . Lopt questions sur nb quantique / choix de pompage optique

### 3.5.1 Physical sources of inhabitation of photoassociation

#### 3.5.1.1 On $F = 9/2$ : predissociation

#### 3.5.1.2 Coupling to more energetic state from the IR

#### 3.5.1.3 Node of wavefunction for some vibrational states

### 3.5.2 Energy landscape of $^{87}\text{Sr}$ - $^{87}\text{Sr}$ molecules

# Conclusion

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# Appendix A

## Algorithms