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Ultracold Atoms in Nonlinear Optical Traps

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Avoided Crossings in Two-level Systems

The two-level system with a general coupling is described by the Hamiltonian:

$$H = \begin{pmatrix} E_1 & W \\ W^* & E_2 \end{pmatrix} = \begin{pmatrix} \bar{E}+\Delta & W \\ W^* & \bar{E}-\Delta \end{pmatrix}$$

Its **eigenenergies** with respect the varying parameter Δ contains two types of states:

- **Adiabatics:** Blue lines in Fig. 1, have avoided crossings. $W \neq 0$.
- **Diabatics**: Red lines in Fig. 1, they cross each other. $W = 0$.

The evolution of the states with respect the velocity of the variations of the Hamiltonian is governed by the

Adiabatic theorem:

There exists a non-zero probability of take the diabatic path and pass from one level to the other for quick changes in the Hamiltonian.

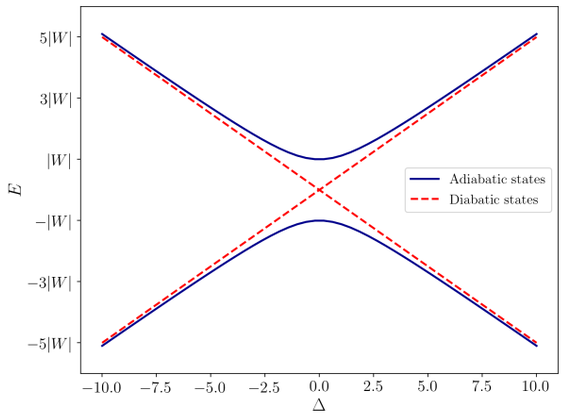

Fig. 1. Eigenenergies with respect a varying parameter of the two-level coupled system.

Scan this QR code to see the animation of the transition

This transitions are the so called **Inelastic Confinement-Induced Resonances** in systems of two ultracold atoms in optical traps.

The System

Our system consist of two ultracold atoms (UCA) that are confined with lasers. The magnetic field is tuned in order to **change the effective interaction** between them, i.e. the s-wave scattering length. Here, we present the needed ingredients to solve the Schrödinger equation: the trapping and the interatomic potential.

Anharmonic Traps

The traps are not perfectly harmonic. For this reason, the inclusion of **anharmonic terms** further the second order Taylor expansion is needed. The following potential in rm-CM coordinates are expanded to 6th order:

$$V_{rm}(r) = 2\sum_{j=x,y,z} V_j \sin^2(k_j r_j/2)$$

$$V_{CM}(r) = 2\sum_{j=x,y,z} V_j \sin^2(k_j R_j)$$

$$W_{rm-CM}(r) = -4\sum_{j=x,y,z} V_j \sin^2(k_j R_j)\sin^2(k_j r_j/2)$$

Coupling term

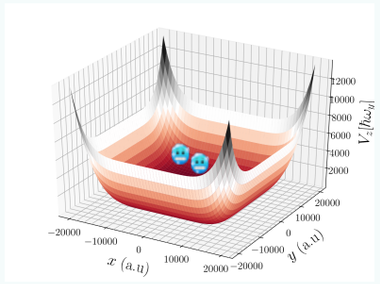

Fig. 2. Coupled potential.

Interatomic Interaction

Theoretically, this is usually modeled as a point-like Huang Yang potential. Nevertheless, a **Born-Oppenheimer potential** is more realistic to describe the interaction between the atoms

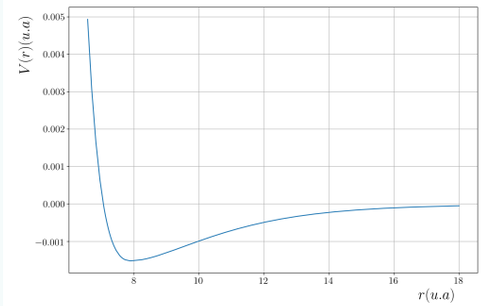

Fig. 3. Interatomic potential.

Results

Solving the Schrödinger equation for two ^{7}Li in a mixed (quasi-1D + 3D) optical trap for several values of the scattering length a_s leads to the results shown in Fig. 4. Two different states can be differentiated:

- **Molecular states**: All states bending down to -∞ corresponds to $^7Li_2$ molecules. They wavefunction are formed by bounded level in the rm coordinate and CM excitations.
- **Trap states:** The energy levels that remain almost constant for every a_s corresponds to states where the atoms are free. They wavefunction are formed by different rm excitations and the CM ground state.

In the figure below avoided crossings due to the rm-CM coupling of the potential are present. Thus, for fast changes of a_s there is a probability of creating a coherent molecule. Physically, the energy of the relative motion of the lowest trap state is transferred to the CM coordinate (see Fig. 5)

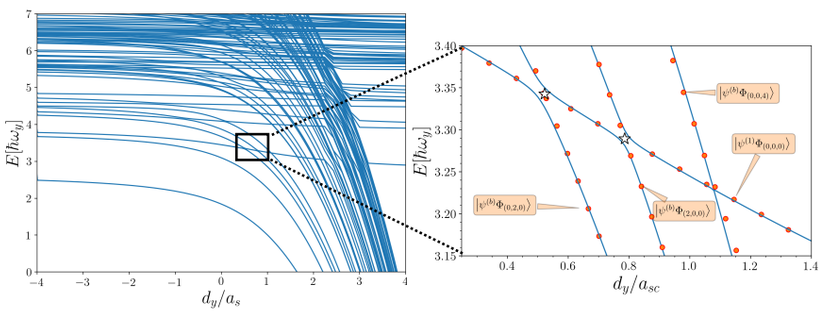

Fig. 4. Energy spectrum as a function of the normalized s-wave scattering length (left) and its corresponding zoom (right). The diabatic states (orange dots) are marked by kets and the inelastic confinement-induced resonances with white stars.

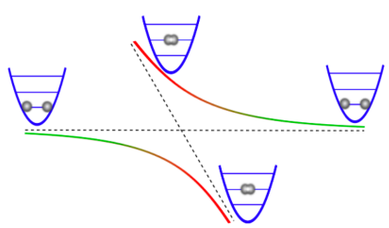

Fig. 5. Coherent molecule formation due to the Inelastic Confinement-Induced Resonances.

To Keep in Mind

Here we report the main conclusions of this communication:

- The **couplings** are placed in the **off-diagonal** positions of the quantum Hamiltonian operator.
- **Couplings** are responsible of having **avoided crossings** in the eigenernergies spectrum. Furthermore, the Adiabatic Theorem of quantum mechanics dictates that quickly varying Hamiltonians leads to non-adiabatic transitions.
- The transitions occur in systems of two ultracold atoms trapped in nonlinear optical traps. **Nonlinearities** have its origin on the **anharmonicities** of the **trapping potential**. They arise as coupling terms between the relative motion and center-of-mass coordinates.
- Non-adiabatic transitions due to the **rm-CM coupling** are **observed** in the spectrum, using as varying parameter the s-wave scattering length a_s. It occurs between a molecular level and a trap state. They are the so-called **Inelastic Confinement-Induced Resonances** (ICIR).
- **ICIR** can be used to **create coherent molecules** simply by tuning the confinement anisotropy.

Part of our results will be reported in the publication T. Sánchez-Pastor, A. Saenz, and F. Revuelta. *On the limits of the theoretical calculation of inelastic confinement-induced resonances.*