



THE STUDY OF COHERENT ATOM MOLECULE IN LINEAR APPROXIMATION OF JOSEPHSON FREQUENCY

Deepak Kumar
Department Of Physics
B. S. College, Simraha
(Saharsha) Bihar

Abstract

This imaging technique is sensitive to a specific absorption line of the atoms it does not measure the number of molecules. One also expects to observe oscillations in the number of condensate atoms. Moreover, if the situation is such that the detuning between the pulses is relatively large the effect of the coupling can be neglected and the frequency of the observed oscillations corresponds to the energy difference between the atoms and the molecules i.e. the molecular binding energy. This is indeed what is observed, thereby providing compelling evidence for the existence of coherence between atoms and molecules.

Introduction

We have studied the coherent atom- molecules oscillations. The experimental observation of atom- molecule coherence in Bose-Einstein condensate has been made^{1,2} and its theoretical description has been derived in terms of mean field theory. In the experiments^{1,2} performed both in Wieman's group at JILA, one makes use of Feshbach resonance³ at $B_0 = (55.04)$ Gauss in the ($f=2$; $m_f = -2$) hyperfine state of ^{85}Rb . The width of the in the U Thesis Physics resonance is equal to ΔB 11.04 G and the off resonant background scattering length is given by $a_{bg} = - 443$ where a_0 is the Bohr radius. The difference in the magnetic moment between the open channel and the closed channel is given by $\Delta\mu = - 2.23$ where s the Bohr magneton. In both experiments, one starts from a stable and essentially pure condensate of about N_c 10,000 atoms at a magnetic field such that the effective scattering length is close to zero. This implies that,

since the condensate is in the noninteracting limit, its density profile is detuned by the harmonic oscillator ground state wave function. The harmonic external trapping potential is axially symmetric with trapping frequencies ν_r - 17.4 and ν_z - 6.8 Hz in the radial and axial direction respectively. Starting from this situation, one quickly ramps the magnetic field to a value B_{hold} close to the resonant value and keeps it there for a short time t_{hold} before ramping to a value B_{evolve} . The magnetic field is kept at this last value for a time t_{evolve} before performing a similar pulse to go back to the initial situation. The duration of all four magnetic field ramps is given by time t_{ramp} and the hold time t_{hold} are kept fixed, ramp t_{ramp} Both the t_{ramp} , fixed at values of 10-15 μs . The time t_{evolve} between the pulses is variable.

Such a double pulse experiment is generally called a Ramsey experiment. Its significance is most easily understood from single system of two coupled harmonic oscillator. The atomic condensate corresponding to oscillator 'a' and the molecular condensate to oscillator 'b'. Therefore, after performing the double- pulse sequence in the magnetic field one makes a light absorption image of the atomic density from which one extracts the number of condensate and noncondensed atoms. The parameters of the inter-atomic potentials are fit to the experimental results for the frequency. Clearly, the frequency of the coherent atom-molecule oscillations agrees very well with the molecular binding energy in vacuum over a large range of magnetic field. Moreover in the magnetic field range $B_{\text{evolve}} \cong 157$ -159 G the frequency of the oscillations. Close to resonance, the measured frequency deviates from the two body result.

Although some of the physics of these coherent atom- molecule oscillations can be understood by a simple two-level picture. First of all, during Rabi oscillation in a single two level system one quantum in a state oscillates to the other state. In case of Feshbach resonance pairs of atoms oscillate back and forth between the dressed molecular condensate and a atomic condensate. Therefore the Hamiltonian is not quadratic in the annihilation and creation operators and physics is more complicated. In particular the dressed molecule may decay into two noncondensed atoms instead of forming two condensate atoms. Second, the observed atom molecule oscillations are oscillations between an atomic condensate and a dressed molecular condensate.

The exact solution is found easily by diagonalizing the hamiltonian. One assumes that initially there are only quanta in oscillator a and none in b, so that one has that $\langle b|b \rangle(0) = 0$, The number of quanta in oscillator a as a function of time is then given by with the frequency ω given by one sees that the number of quanta in the oscillator a oscillates in time with frequency ω . Such oscillations are called Rabi oscillations. Note that the number of quanta in oscillator b is determined by so that the total number of quanta is indeed conserved.

Theory

The Josephson frequency in the absence of the fractional derivative term given by which reduces to $\hbar\omega = 6(B)$ sufficiently far off resonance where the coupling may be neglected. This result does not agree with the experimental result because, by neglecting the fractional derivative, which corresponds to the molecular self-energy, one is describing Josephson oscillations between an atomic condensate and a condensate of bare molecules instead of dressed molecules.

In first approximation one takes the dressing of the molecules into account as follows. If one is in the magnetic field range where the Josephson frequency deviates not too much from the molecular binding energy, one is allowed to expand the propagator of the molecules around the pole at the bound state energy. This corresponds to introducing the dressed molecular field and leads to the Heisenberg equations of motion. The linearized meanfield equations that describe the Josephson oscillations of a atomic and a dressed-molecular condensate are therefore given by and lead to the Josephson frequency .

which reduces to $\hbar\omega = e(B)$ in the situation where the coupling is much smaller than the binding energy. This result agrees with the experimental fact that the measured frequency is, sufficiently far from resonance, equal to the molecular binding energy. Moreover, the initial deviation from the two-body result in the measured frequency is approximately described by the equation for the Josephson frequency in Eq. (5.12). The amplitude of the oscillations is in this case given by which close to resonance is much larger than the result.

With the meanfield theory derived one now calculates the magnetic field and density dependence of the Josephson frequency of the coherent atom-molecule oscillations, in a linear approximation. The only parameter that has not been determined yet is the effective range of the inter-atomic interactions r_{bg} . The effective range is determined by calculating the molecular binding energy in vacuum and comparing the result with the experimental data. One has seen that far off resonance the Josephson frequency is essentially equal to the molecular binding energy. Since the effect of a nonzero effective range only plays a role for large energies, and thus is important far off resonance, this comparison uniquely determines the effective range. As explained, the molecular binding energy.

Discussion of Results

The result are shown in table 5T₁ by the use of linearized version of the time dependent meanfield equation. This has been developed by Drummond et. al.¹¹ pue Timmermans et. al.^{12,13} Actually linearized time dependent field equation are coupled equation and these equations describe exactly the Rabi oscillation as the coupled harmonic equation with the coupling constant $A=4g_0$, . In the context of particle number oscillations between condensates, Rabi oscillations are referred to as Josephson oscillat and the associated frequency is called the Josephson frequency. The Jossephson frequency in the absence of fractional derivative is given by this is Josephson oscillation between and atomic condensate and a condensate of bare molecule instead of dressed molecules. Now if one expand the propagation of the molecules around the pole at the bound state energy then one obtains the Josephson oscillates of a atomic and a dressed molecular condensate and the Josephson frequency is given by This result agrees well with the experimental fact. In table 5T₁ we have given the Josephson frequency hw , in KH, as a function of magnetic field B(G). We have compared our theoretical result with the work of J.M. Gerton et.al. ¹⁴ Our theoretical result are in good agreement with that of the experimental data.

Table 5T₁

**Evaluated result of Josephson frequency of the coherent atom molecule oscillation
as a function of the magnetic field**

Magnetic field B(G)	Frequency of the coherent atom – molecule oscillation (Josephson frequency) KHz		
	Our's Cal.	Other's Cal.	Expl.
150	10.2	9.82	12.6
155	15.3	14.68	18.9
156	58.5	55.34	60.6
157	62.6	60.25	65.2
158	69.7	70.56	72.8
159	76.8	76.59	79.5
160	120.5	121.8	122.8
161	460.6	465.6	472.8
162	960.7	970.8	1000.2

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