

Journal of Chemical, Biological and Physical Sciences



An International Peer Review E-3 Journal of Sciences

Available online at www.jcbps.org

Section C: Physical Sciences

CODEN (USA): JCBPAT

Research Article

An evaluation of magnetic field and density dependence of the Josephson frequency in atom-Molecule Coherence in Bose gases and study of emergence of molecular Bose-Einstein condensate from a Fermi gas,

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Received: 02 December 2017; **Revised:** 25 December 2017; **Accepted:** 05 January 2018

Abstract: Using the theoretical formalism of R A Duine and H T C Stoof (arXiv: cond-mat/0303230v) 22 March 2003), we have theoretically evaluated magnetic field and density dependence of the Josephson frequency in coherence atom-molecule oscillation in Bose-Einstein condensed gas. Our theoretically obtained results show that Josephson frequency increases with both magnetic field for constant condensate density and also with condensate density for fixed magnetic field. Our theoretically evaluated results are in good agreement with the experimental data and also with other theoretical workers. Using the theoretical formalism of Markes Greiner et al (Nature, 26 Nov (2005)), we have studied the emergence of molecular Bose-Einstein condensate from a Fermi gas of ⁶Li atoms. The study has been performed with the help of Feshbach resonance. We have evaluated molecular condensate fraction N_0/N as a function of (T/T_c) and as a function of (T/T_F) . We have also evaluated scattering length 'a' in unit of a_0 , of mixture of two lowest hyperfine states of ⁶Li atom, temperature (μ K) all as a function of magnetic field (mT) near the crossing of the

scattering length. Our theoretically evaluated results are in good agreement with the other theoretical workers.

Keywords: Josephson frequency of atom-molecule oscillation, molecular Bose-Einstein condensate, Condensate density, Zero-crossing in the scattering length, Feshbach resonance, Ramsey experiment, coherent atom-molecule oscillation, atomic condensate and dressed molecular condensate.

INTRODUCTION

After successful series of experiments¹⁻⁵ with atomic gases Bose-Einstein condensation has emerged very exciting as well very challenging field in the condensed matter physics. The particular reason of this progress is the unprecedented experimental control over the atomic gases of interest⁶. This experimentally control between interaction of atoms of the gases were achieved with the help of Feshbach resonance⁷. Feshbach resonances were introduced in nuclear physics to describe the narrow resonances observed in the total cross-section for a neutron scattering of a nucleus⁸. The defining feature of a Feshbach resonance is that the bound state responsible for the resonance exists in another part of the quantum mechanical Hilbert space. Due to low temperatures of these gases, their effective interatomic interactions are completely determined by the s-wave scattering length. The detuning is experimentally adjustable by tuning the magnetic field. This implies that the s-wave scattering length and hence the magnitude and sign of inter atomic interactions is also adjustable to any desirable.

With this experimental degree of freedom it is possible to study very interesting new regimes in the many-body physics of ultra-cold atomic gases. One studies the coherent atom-molecules oscillations. In the experiments^{9,10} performed both in Wieman's group at JILA, one makes use of Feshbach resonance¹¹ at $B_0 = 55.04 \text{ Gauss}$ in the ($f=2$; $m_f = -2$) hyperfine state of ^{87}Rb . The width of the resonance is equal to $\Delta B = 11.04 \text{ G}$ and the off resonant background scattering length given by $a_{bg} = 443a_0$ where a_0 is the Bohr radius. The difference of magnetic moment between the open channel and closed channel is given by $\Delta\mu = -2.23\mu_B$ where μ_B is Bohr magnetron. In the experiment, one starts from a stable and essentially pure condensate at 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 non-interacting limit, its density profile is detuned by the harmonic oscillator ground state wave function. The harmonic oscillator trapping potential is axially symmetric with trapping frequencies $\nu_r = 17.4 \text{ Hz}$ and $\nu_z = 6.8 \text{ Hz}$ in the radial and axial direction respectively. Starting from this situation, one quickly ramps the magnetic field to a value B_{hold} close to 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 t_{ramp} . Both the ramp time t_{ramp} and hold time t_{hold} are kept fixed at values of $10\text{-}15\mu\text{s}$. The time t_{evolve} between the pulses is variable.

Such a double pulse experiment is generally called a Ramsey experiment¹². Its significance is most easily understood from single system of two coupled harmonic oscillator. The atomic condensate corresponds 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 non-condensed atoms. Since 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. The parameters of the inter-atomic potentials are fit to the experimental results of the frequency. 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. In the magnetic field range $B_{\text{evolve}} = 157\text{--}159\text{G}$ the frequency of oscillations is well described by the formulae $[\varepsilon_m(\mathbf{B})] = \frac{\hbar^2}{m a^2(\mathbf{B})}$ for the binding energy. 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 state oscillates to the other state. In case of Feshbach resonance pairs of atoms oscillate back and forth between the dressed molecular condensate and an 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 non-condensed atoms instead of forming two condensate atoms. Second, the observed atom-molecule oscillations are oscillations between an atomic condensate and a dressed molecular condensate.¹³⁻¹⁶

In this paper, using the theoretical formalism of R A Duine and H T C Stoof¹⁷, we have theoretically evaluated magnetic field and density dependence of Josephson frequency of coherent atom-molecule oscillation in Bose condensed gas. Magnetic field dependence of Josephson frequency is evaluated for fixed condensate density and density dependence for fixed magnetic field. In both cases, Josephson frequency increases with magnetic field and condensate density. Our theoretically evaluated results are in good agreement with experimental data¹⁸ and also with other theoretical workers^{19, 20}. Using the theoretical formalism of Markes Geiner *et al.*²¹, we have theoretically studied emergence of molecular Bose-Einstein condensate from Fermi gas of ^6Li atoms. In these studies, we have evaluated molecular condensate fraction N_0/N as a function of scaled temperature (T/T_C) and as a function of (T/T_F). We have also calculated scattering length 'a' in the unit of a_0 of mixture of the two lowest hyperfine states of ^6Li atoms, temperature $T(\mu\text{K})$ of the mixture all as a function of magnetic field (mT). Our theoretically evaluated results are in good agreement with the other theoretical workers^{22, 23}.

MATHEMATICAL FORMULAE USED IN THE EVALUATION

One considers the Hamiltonian of two coupled harmonic oscillators²⁴

$$H = \frac{1}{2} (\hat{a}^* \hat{b}^*) \begin{pmatrix} \delta(t) & \Delta \\ \Delta & -\delta(t) \end{pmatrix} \begin{Bmatrix} \hat{a} \\ \hat{b} \end{Bmatrix} \quad \dots(1)$$

Where \hat{a}^* and \hat{b}^* create a quantum in the oscillators a and b respectively and Δ denotes the coupling between the two oscillators. One considers first the situation that the detuning $\delta(t)$ is time independent. 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 $\langle \hat{b}^* \hat{b} \rangle(0) = 0$. The number of quanta in oscillator a as a function of time is then given by

$$\langle \hat{a}^* \hat{a} \rangle(t) = [1 - \frac{\Delta^2}{(\hbar\varpi)^2} \sin^2(\varpi t / 2)] \langle \hat{a}^* \hat{a} \rangle(0) \quad \dots (2)$$

With the frequency given by

$$\hbar\varpi = \sqrt{\delta^2 - \Delta^2} \quad \dots (3)$$

One sees that the number of quanta in the oscillator a oscillates in time with frequency ϖ . Such oscillations are called Rabi oscillations. The number of quanta in oscillator b is determined by

$$\langle \hat{b}^* \hat{b} \rangle(t) = -\frac{\Delta^2}{(\hbar\varpi)^2} \sin^2(\varpi t / 2) \langle \hat{a}^* \hat{a} \rangle(0) \quad \dots (4)$$

The hold time quanta in oscillator a will go to oscillator b is given by $t_{\text{hold}} = \frac{\pi \hbar}{2 \Delta}$ on average half of the quanta in oscillator a will go to oscillator b. Such a pulse is called a $\frac{\pi}{2}$ pulse. The number of atoms in the condensate is given by the formula

$$N_c(t) = N_{\text{average}} - \alpha t + A \exp(-\beta t) \sin(\omega_c + \phi) \quad \dots (5)$$

Where N_{average} is the average number of condensate atoms, A and ϕ are the oscillation amplitude and phase respectively, and β is the damping rate of the oscillation. The overall atom loss is characterized by rate constant α . The experimentally observed frequency is equal to $\omega_c = 2\pi\sqrt{v_e^2 - [\beta/2\pi]^2}$. By defining the frequency of the coherent atom-molecule collision in this way one compensates for the effects of the damping on the frequency.

This is seen most easily by considering the linearized version of the time –dependent mean-field equation. Writing $\phi_a(t) = \phi_a e^{-\mu t/\hbar} + \delta\phi_a(t)$ and $\phi_m(t) = \phi_m e^{-2\mu t/\hbar} + \delta\phi_m(t)$, one has

$$i\hbar \frac{\partial \delta\phi_m(t)}{\partial t} = [\delta(B) - g^2 \frac{m^{\frac{3}{2}}}{2\pi\hbar^3} i \sqrt{i\hbar \frac{\partial}{\partial t} - 2\hbar\Sigma^{\text{HF}}}] \delta\phi_m(t) + 2g\phi_a \delta\phi_a(t) \quad \dots (6)$$

$$\text{And} \quad i\hbar \frac{\partial \delta\phi_a(t)}{\partial t} = 2g\phi_a^* \delta\phi_m(t) \quad \dots (7)$$

Here, we have neglected the off-resonant part of the inter-atomic interactions. This is justified sufficiently close to resonance, where one is also allowed to neglect the energy dependence of the atom-molecule coupling constant. In the context of particle-number oscillations between condensates, Rabi oscillations are referred to as Josephson oscillations and the associated frequency is called the Josephson frequency. The Josephson frequency in the absence of the fractional derivative term in equation (7) is given by

$$\hbar\omega_J^{\text{bare}} = \sqrt{\delta^2(B) + 16g^2 n_a} \quad \dots (8)$$

which reduces to $\hbar\omega_J^{\text{bare}} \ll |\delta(B)|$ 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 of dressed molecules. The amplitude of Josephson oscillation is given by

$$A_J^{\text{bare}} = \frac{16g^2 n_a}{[\delta^2(B)]^2} \quad \dots (9)$$

In first approximation, one takes the dressing of the molecules into account as follows. If one is in the magnetic field range where 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 equation of motion. The linearized mean field equations that describe the Josephson oscillations of an atomic and a dressed-molecular condensate are given by

$$i\hbar \frac{\partial \delta\phi_m(t)}{\partial t} = \varepsilon_m(B) \delta\phi_m(t) + 2g\sqrt{Z(B)} \phi_a \delta\phi_a(t) \quad \dots (10)$$

$$i\hbar \frac{\partial \delta\phi_a(t)}{\partial t} = 2g\sqrt{Z(B)} \phi_a^* \delta\phi_m(t) \quad \dots (11)$$

which leads to the Josephson frequency

$$\hbar\omega_J = \sqrt{\varepsilon_m^2(B) + 16g^2 Z(B) n_a} \quad \dots (12)$$

which reduces to $\hbar\omega_J = |\varepsilon_m(B)|$ 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 the 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 equation (12). The amplitude of the oscillations in this case is given by

$$A_J = \frac{16g^2 Z(B) n_a}{[\varepsilon_m(B)]^2} \quad \dots (13)$$

which close to resonance is much larger than the result in equation (9). With the mean field 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 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. The molecular binding energy is determined by solving for E in the equation

$$E - \delta(B) - \hbar \Sigma_m^{(+)}(E) = 0 \quad \dots (14)$$

The retarded molecular self-energy is given by

$$\hbar \Sigma_m^{(+)}(E) = - \frac{g^2 m}{2\pi \hbar^2 \sqrt{1 - 2 \frac{r_{bg}}{a_{bg}}}} \frac{i \sqrt{1 - 2(r_{bg}/a_{bg})mE/\hbar^2} - (r_{bg}mE/2\hbar^2)}{1 + ia_{bg} \sqrt{1 - 2(r_{bg}/a_{bg})mE/\hbar^2} - (r_{bg}a_{bg}mE/2\hbar^2)} \quad \dots (15)$$

STUDY OF EMERGENCE OF MOLECULAR BOSE-EINSTEIN CONDENSATE FROM FERMI GAS AND EVALUATION OF MOLECULAR CONDENSATE FRACTION N_0/N AS A FUNCTION OF SCALED TEMPERATURE T/T_c

Molecular Bose-Einstein condensate arises from a mixture of two lowest hyperfine states of ^6Li atoms which is a Fermion atom. This is done with the help of Feshbach resonance in a colliding two-atom system. Here, the energy of the incoming open elastic channel is magnetically tuned into resonance with bound molecular state of an energetically closed channel. The tunability dependence arises from the difference in the magnetic moments of the open and closed channels²⁵. In the vicinity of Feshbach resonance, the s-wave scattering length is described by T Lufford *et al*²⁶.

$$a(B) = a_{bg} \left[1 - \frac{\Delta B}{B - B_0} \right] \quad \dots (16)$$

Where B is applied field, B_0 is the field at which the resonance occurs, a_{bg} is the background scattering length and ΔB is proportional to the strength of the coupling between the open and closed channels.

DISCUSSION OF THE RESULTS

Using the theoretical formalism of R A Duine and H T C Stoof¹⁷, we have theoretically evaluated magnetic field and density dependence of Josephson frequency in atom-molecule oscillation in Bose-Einstein condensed gas. In **Table T1**, we have presented an evaluated results of Josephson frequency of the coherent atom-molecule oscillation as a function of magnetic field for fixed value of condensate density. Our theoretically obtained results show that Josephson frequency (KHz) increases with magnetic field $B(G)$. Our theoretically evaluated results are in good agreement with the experimental data¹⁸ and also with other theoretical workers^{19,20}. In **table T2**, we have shown the evaluated results of Josephson frequency as a function of condensate density for three different values of the magnetic field $B=156G$, $156.5G$ and $157G$. We observed that Josephson frequency increases with condensate density for each fixed magnetic field. The increase is large for $B=156G$ and small for $B=157G$. In **table T3**, we have presented the evaluated results of molecular condensate fraction N_0/N as a function of scaled temperature T/T_c . Here N is the total number of molecules when there is n change of magnetic field for expansion and T_c is determined by the formulae

$$T_c = 0.94 (N v_F^2 v_z)^{\frac{1}{3}} \frac{\hbar}{K_\beta}$$

$$T_F = (6Nv_F^2 v_z)^{\frac{1}{3}} \frac{\hbar}{K_\beta}$$

Here N is the particle number in each spin state. v_F and v_z are axial and radial trap frequencies having values 430MHz and 250 MHz respectively. Our theoretically obtained results are in good agreement with experimental data²⁷. **In Table T4**, we have shown the expt. result of dependence of condensate fraction as a function of time (ms) in which the magnetic field is ramped across the Feshbach resonance. This is the dependence of condensate fraction on magnetic field sweep rate and measurement of condensate life time. **In table T5**, we have presented the results of analytic model of the scattering length in unit of a_0 for mixture of two lowest hyperfine states of ^6Li atoms as a function of magnetic field (mT). The results show that the scattering length has zero crossing. **In table T6**, we have shown the evaluated results of temperature T (μK) of the condensate near the zero crossing of the magnetic field. Our theoretical results show that temperature increases and attains maximum value and then decreases. **In TableT7**, we have shown the evaluated results of number of atoms (trapped population $\times 10^3$) as a function of magnetic field (mT) near the zero crossing of the scattering length. We observed that there is decrease in the trapped population as the magnetic field is increased. We also observe that there is rise of the trap population near 65mT and this type of magnetic field dependence of trap population was observed by Dieckmann *et al.*²⁸. **In table T8**, we have presented the results of dependence of the condensate fraction N_0/N of the atom-molecule mixture as a function of scaled temperature T/T_F . The results show that the BEC is formed when the initial temperature is below $0.17T_F$. **In table T9**, we have shown the evaluated results of total expansion energy per particle for the molecular condensate as a function of the scattering length ' a ' in the unit of a_0 . Our theoretically evaluated results show that the energy (nK) increases with scattering length. The results also indicate that the energy dependence is proportional to scattering length ' a '. This linear dependence of energy suggests that molecule-molecule scattering length is proportional to atom-atom scattering length²⁹. There is some recent calculations³⁰⁻³⁶ which reveals the similar behaviour.

Table T1: An 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 ^{19,20} .	Expt ¹⁸ .
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	76.9	76.59	79.5
160	120.5	121.8	122.4
161	460.6	465.6	472.8
162	960.7	970.8	1000.2

Table T2: An evaluated result of Josephson frequency of the coherent atom-molecule oscillation as a function of condensate density n_a (cm^{-3}) for fixed magnetic field B(G)

n_a (cm^{-3})	Josephson frequency KHz		
	B=156G	B=156.5G	B=157G
1.1×10^{11}	1.25	0.97	0.80
1.5×10^{11}	1.37	1.08	0.85
2.0×10^{11}	1.86	1.18	0.89
3.0×10^{11}	2.54	1.76	1.05
5.0×10^{11}	2.77	2.10	1.24
6.0×10^{12}	3.58	3.86	1.86
8.0×10^{12}	5.69	4.12	2.65
1.0×10^{13}	6.72	5.87	3.22
5.0×10^{13}	7.86	6.10	4.16
8.0×10^{13}	9.12	8.25	5.75
10×10^{13}	10.68	9.16	6.98
15×10^{13}	12.59	10.25	7.26

Table T3: An evaluated result of molecular condensate fraction N_0/N as a function of scaled temperature T/T_C , N is the total number of molecules when there is no change of magnetic field.

T/T_C	$(N_0/N)_{\text{theory}}$	$(N_0/N)_{\text{expt}}$
0.40	0.186	0.205
0.45	0.174	0.188
0.50	0.162	0.165
0.55	0.150	0.158
0.60	0.142	0.140
0.65	0.134	0.137
0.70	0.105	0.112
0.75	0.086	0.095
0.80	0.052	0.067
0.85	0.045	0.053
0.90	0.042	0.046
0.95	0.037	0.041
1.00	0.035	0.038
1.10	0.027	0.030
1.20	0.018	0.021

Table T4: Experimental result of dependence of condensate fraction N_0/N as a function of magnetic sweep rate . Here fraction of condensed molecule is evaluated as a function of time in which the magnetic field is ramped across the Feshbach resonance.

Ramp time (ms)	← N_0/N →
0.0	0.000
1.0	0.022
2.0	0.045
3.0	0.053
4.0	0.065
5.0	0.087
6.0	0.107
7.0	0.115
8.0	0.127
9.0	0.135
10.0	0.142
12.0	0.137
14.0	0.165
15.0	0.127

Table T5: A theoretical result of the analytical model of the scattering length ‘a’ of mixture of the two lowest hyperfine states of ^6Li atom as a function of magnetic field (mT)

Magnetic field (mT)	Scattering length (unit of a_0)
0.0	0.00
5.0	10.25
10.0	15.87
20.0	121.9
30.0	250.6
40.0	1543.2
50.0	2000.9
60.0	2500.6
80.0	4000.8
100.0	-4725.0
110.0	-4156.0
120.0	-3947.2
130.0	-3540.3
140.0	-2000.5
150.0	-1965.0

Table T6:An evaluated result of temperature T (μK) as a function of magnetic field (mT) near the zero crossing of the scattering length

Magnetic field (mT)	Temperature T(μK)
20	30.7
30	35.9
40	42.6
45	49.5
50	53.4
55	92.8
60	83.2
65	65.4
70	57.6
75	50.3
80	48.6
85	43.2
90	40.0
100	37.5

Table T7:An evaluated result of number of atoms (trapped population) $\times 10^7$ as a function of magnetic field (mT) near the zero crossing of the scattering length

Magnetic field (mT)	Trapped population $\times 10^7$
20	534.8
30	523.7
40	500.4
45	489.0
50	480.8
55	677.6
60	603.2
65	512.4
70	500.5
75	487.8
80	455.5
85	417.8
90	300.2
95	295.5
100	210.9

Table T8:An evaluated result of dependence of condensate fraction N_0/N of the atom-molecule mixture as a function of T/T_F

T/T_F	N_0/N
0.05	0.172
0.06	0.165
0.08	0.162
0.10	0.158
0.12	0.145
0.14	0.137
0.15	0.128
0.18	0.110
0.20	0.095
0.22	0.072
0.25	0.065
0.30	0.050
0.32	0.045
0.34	0.042
0.35	0.040
0.38	0.038
0.40	0.036

Table T9:An evaluated result of total expansion energy per particle (nK) for the molecular condensate as a function of scattering length a (a_0)

Scattering length a (a_0)	Expansion energy (nK)
10	2.76
50	3.87
100	4.24
200	5.56
400	6.92
500	7.68
800	8.14
1000	9.27
1200	10.28
1400	11.39
1500	12.45
1800	13.86
2000	14.29
2500	15.56
3000	18.27

CONCLUSION

From the above theoretical investigations and analysis, we have come across the following conclusions:

- Josephson frequency increases for both as a function of magnetic field and condensate density. The evaluation is performed near Feshbach resonance. Far off the resonance, the frequency is determined by two-body physics.
- Josephson frequency is relatively large and description is made purely in terms of scattering length which turns out to be inadequate. Then, one includes effective range parameter of inter atomic interaction in the calculation.
- Close to the resonance the frequency deviates from two-body result due to various many-body shifts. Considering the many-body effect, there is a good agreement with the experimental data over the entire range of magnetic field.
- We have studied the zero crossing in Feshbach resonance in fermionic atoms. Our theoretical results of trap population as a function of magnetic field confirms this fact that there is zero –crossing in the elastic scattering length of a mixture of two lowest hyperfine states of ^6Li atoms.
- We have also studied the emergence of molecular Bose-Einstein condensate from a Fermi gas. Our theoretically evaluated results show that the dependence of condensate fraction of the atom-molecule mixture on scaled temperature. The results also show that the BEC is formed when the initial temperature is below $0.17T_F$.

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Online publication Date: 05.01.2018