A dynamical process of optically trapped singlet ground state $^{85}\text{Rb}^{133}\text{Cs}$ molecules produced via short-range photoassociation

Zhonghao Li, Ting Gong, Zhonghua Ji, Yanting Zhao, Liantuan Xiao and Suotang Jia

We investigate the dynamical process of optically trapped $X^1\Sigma^+\ (\nu'' = 0)$ state $^{85}\text{Rb}^{133}\text{Cs}$ molecules distributed in $J'' = 1$ and $J'' = 3$ rotational states. The considered molecules, formed from short-range photoassociation of mixed cold atoms, are subsequently confined in a crossed optical dipole trap. Based on a phenomenological rate equation, we provide a detailed study of the dynamics of $^{85}\text{Rb}^{133}\text{Cs}$ molecules during the loading and holding processes. The inelastic collisions of $^{85}\text{Rb}^{133}\text{Cs}$ molecules in the $X^1\Sigma^+\ (\nu'' = 0, J'' = 1$ and $J'' = 3$) states with ultracold $^{85}\text{Rb}$ (or $^{133}\text{Cs}$) atoms are measured to be $1.0 (2) \times 10^{-10} \text{ cm}^3 \text{s}^{-1}$ ($1.2 (3) \times 10^{-10} \text{ cm}^3 \text{s}^{-1}$). Our work provides a simple and generic procedure for studying the dynamical process of trapped cold molecules in the singlet ground states.

Introduction

The preparation and manipulation of ultracold molecules have attracted significant interest in the past few years. Due to strong dipole–dipole interactions, ultracold heteronuclear molecules in the absolute ground state are particularly attractive: with permanent electric dipole moments (EDMs) ranging from a half to several Debye, such molecules could interact strongly with external fields, as well as with each other via long-range dipole–dipole forces. These novel molecular properties promise interesting applications in precision measurement, quantum control of cold chemical reactions, and quantum computation.

At present, there exist various proposals on the preparation of ground-state polar molecules, in particular those in the lowest rovibrational ground state. In this context, one of the most promising approaches involves the combination of magnetoassociation (MA) with stimulated Raman adiabatic passage (STIRAP), in sense of achievable temperature and phase space density. This has led to the achievement of $^{40}\text{K}^{87}\text{Rb}, ^{87}\text{Rb}^{133}\text{Cs}, ^{87}\text{Rb}^{135}\text{Cs}, ^{87}\text{Na}^{40}\text{K}$, and $^{23}\text{Na}^{87}\text{Rb}$. However, this scheme is only suitable for atomic species where the MA is available and requires the initial cold atomic state to be nearly degenerate. Alternatively, photoassociation (PA) as a simple and universal method has been extensively applied. For example, the combination of PA with “pump–dump” has been applied to $^{85}\text{Rb}^{133}\text{Cs}$. Nevertheless, the transfer efficiency is low due to the large branching ratio to other electronic states and complicated optical pathways. The PA has also been combined with STIRAP in $^{41}\text{K}^{85}\text{Rb}$. This while gives rise to a transfer process that is highly efficient and state-selective, the ground-state molecules can only be formed once per experimental cycle, thus limiting the accumulation of molecules. A third approach uses direct short-range PA, where the direct spontaneous emission after PA allows creation of molecules with a simple and generic procedure for studying the dynamical process of trapped cold molecules in the singlet ground states.

$^{a}$ Shanxi University, State Key Laboratory of Quantum Optics and Quantum Quantum Devices, Institute of Laser Spectroscopy, Wucheng Rd. 92, 030006 Taiyuan, China. E-mail: zhaoyt@sxu.edu.cn
$^{b}$ Shanxi University, Collaborative Innovation Center of Extreme Optics, Wucheng Rd. 92, 030006 Taiyuan, China.
Experimental setup

Fig. 1(a) shows a diagram illustrating the formation and detection mechanism of ultracold $^{85}\text{Rb}^{133}\text{Cs}$ molecules in the lowest vibrational ground state. (i) PA. Pairs of colliding $^{85}\text{Rb}$ and $^{133}\text{Cs}$ atoms are excited to a deeply bound state in a short range. (ii) Decay. After the two-photon-cascade spontaneous emission process, the stable molecule states are distributed in different vibrational states. (iii) Detection. The molecules are detected using the PI technology.

As shown in Fig. 1(b), the ultracold $^{85}\text{Rb}$ and $^{133}\text{Cs}$ atoms are initially cooled and trapped in overlapped dual species magneto-optical traps (MOTs). The MOTs are operated in the dark spontaneous force optical traps (dark-S MOTs) configuration, which provides the atomic sample with a high atomic density and a low collision rate. The vacuum background pressure in the chamber is kept at about $3 \times 10^{-7}$ Pa. A pair of anti-Helmholtz coils generates a magnetic gradient of about 15 G cm$^{-1}$. Four Littrow external-cavity diode lasers (Toptica, DL100) locked via a saturation absorption spectroscopy technique provide the trapping and repumping beams for $^{85}\text{Rb}$ and $^{133}\text{Cs}$. All of these beams are 15 mm in diameter.

The total power of the trapping laser is around 36 mW, and the total power of the repumping laser is around 8 mW, respectively. The dark-SPOTs are achieved by filling the depumping beams in the dark region of the repumping beams. The dark region is created by a black dot in the center of the mixed repumping beams. Both depumping beams have a power of about 80 $\mu$W with 3 mm diameter. The overlap of atomic clouds is verified using two charge-coupled device (CCD) cameras placed along the horizontal and vertical directions, respectively.

In this way, about $1 \times 10^{7}$ of $^{85}\text{Rb}$ atoms are formed in the $5S_{1/2}$ ($F = 2$) state with a density of $8 \times 10^{10}$ cm$^{-3}$, and about $2 \times 10^{7}$ $^{133}\text{Cs}$ atoms are formed in the $6S_{1/2}$ ($F = 3$) state with a density of $1.5 \times 10^{11}$ cm$^{-3}$.

The PA process is achieved by employing a tunable Ti:sapphire laser system (M Squared, Sols Ti:sapphire) with a typical linewidth of 100 kHz and an output power of up to 1.5 W. We focus the PA beam on the center of the overlapped dark-SPOTs with the Gaussian radius of 150 $\mu$m. The PA laser is locked via the transfer cavity technique based on an ultrastable He–Ne laser as a reference laser. The produced molecules will subsequently decay to the ground state. The frequency is monitored using a commercial wavelength meter (High Finesse-Angstrom, WS-7R) with an absolute accuracy of 0.002 cm$^{-1}$ (about 60 MHz), which is calibrated with the Rb atomic transition line.

The PI laser pathways as shown in Fig. 1(a) are chosen to observe the produced ground state molecules. The PI laser is a tunable dye laser (CBR-G-18EG, Spectra physics, wavelength is about 651.8 nm, pulse duration of 7 ns, diameter is about 3 mm, pulse energy is about 1 mJ, and repetition rate of 10 Hz). The dye laser is pumped by the second harmonic of an Nd:YAG laser (Spectra physics, INDIE-40-10-HG, wavelength of 532 nm) and operated on DCM dissolved in dimethyl sulfoxide (DMSO). The ions formed in this process are accelerated by a pulsed electric field with a duration time of 20 $\mu$s. After the acceleration procedure, these moving ions will fly freely with a length of 68 mm. Finally, the ions are detected using a pair of microchannel plates (MCPs). The electric signals are detected, amplified, monitored on a digital oscilloscope, and recorded using an NI PCI-1714 card following a boxcar (Boxcar, SRS-250) with 10 averages.

An ODT is built to trap the formed molecules. The simplest configuration of ODT is a single focused beam, which creates a highly anisotropic trap with relatively weak confinement along the propagation axis and tight confinement in the perpendicular direction. By crossing two focused beams, one can create a nearly isotropic and tight confinement in all dimensions, allowing formation of denser samples. In our experiment, the ODT is realized with a linearly polarized broadband fiber laser (IPG Photonics, YLR-300-AC) with a central wavelength of 1070 nm and a linewidth of 2 nm. The IPG laser is divided...
into two beams with orthogonal linear polarization. As shown in Fig. 1(b), two ODT beams are crossed on the center of the dark-SPOTs with an angle of 45°. The waists of these two beams are both 76 (2) μm. The frequencies are shifted oppositely by 110 MHz by using two acousto-optic modulators (AOMs) to prevent DC interference effects and allow rapid control of the ODT (τ = 1 μs). The AC Stark shift produces a conservative potential with a minimum at the focus, where the ultracold atomic and molecular sample can be trapped. We find that it is advantageous to move the point of the crossed ODT below the center of dark-SPOTs by 0.5 mm along the direction of gravity.

The total power of ODT beams is normally around 5 W. About 8 × 10^5 of ^85Rb atoms at the 5S_{1/2} (F = 2) state with a density of 2 × 10^{11} cm^3 and about 1.5 × 10^6 ^133Cs atoms at the 6S_{1/2} (F = 3) state with a density of 4 × 10^{11} cm^3 are transferred from the dark-SPOTs.

The time sequence of the experiment is shown in Fig. 1(c), which is divided into five stages. (1) The loading procedure of dark-SPOTs. The PA procedure occurs simultaneously and the duration time is about 6 s. All the dark-SPOTs lasers are turned on in the presence of a magnetic field to trap cold atoms. The cooling and repumping lasers are chosen at the optimized
value for the largest loading rate. (2) The loading procedure of ODT. (3) The expansion procedure of untrapped atoms and molecules with a duration time of 20 ms. In this procedure, the depumping and repumping lasers can be selected to keep on as the pushing lasers to remove the mixed atoms in ODT or are turned off for the investigation of atom–molecule collisions. (4) The holding procedure of trapped samples in ODT. In this period, only the dipole laser is kept on. (5) Detection. The trapped molecules are detected via PI through resonance-enhanced two-photon ionization (RETPI).

Experimental results and analysis

Optical trapping of $X^1\Sigma^+$ ($v' = 0$) state molecules distributed in $J'' = 1$ and $J'' = 3$ rotational states

Fig. 2(a) shows the rotational structure of the excited $2^3\Pi_0^+$ ($v = 10$, $J = 1$) state, which agrees with the measured results in ref. 18. Because this state has large free-to-bound and bound-to-bound Franck–Condon factors (FCFs), it can be used for the preparation of molecules in the $X^1\Sigma^+$ ($v'' = 0$) state with the ratio of about 30% efficiently. In the following experiments, the frequency of the PA laser is fixed at $J = 1$. The rotational distributions of molecules in the $X^1\Sigma^+$ ($v'' = 0$) state are $J'' = 1$ and $J'' = 3$ according to ref. 41 and also have been confirmed in our measurement using depletion spectroscopy. To be concise, $X^1\Sigma^+$ ($v'' = 0$) represents the $X^1\Sigma^+$ ($v'' = 0$, $J'' = 1$ and $J'' = 3$) states in the following contexts.

The $X^1\Sigma^+$ ($v'' = 0$) state molecules could be state-selectively detected via RETPI. The PI spectra have been measured using the scanning PI laser (frequency of about 630–680 nm) while keeping the PA laser fixed at the $2^3\Pi_0^+$ ($v = 10$, $J = 1$) level. Here we show a part of PI spectra of the $X^1\Sigma^+$ ($v'' = 0$) state in Fig. 2(b). Since the frequency bandwidth of the PI laser (about 0.2 cm$^{-1}$) is larger than the energy spacing of the rotational level, it is impossible to distinguish rotational levels. The spectra allow for straightforward assignment of the observed transitions between vibrational states based on ref. 18 and 43. We assign the $\sim 15278.31$ cm$^{-1}$ peak to the $2^3\Pi_0^+ (v' = 10) \rightarrow X^1\Sigma^+ (v'' = 0)$ transition and the $\sim 15341.41$ cm$^{-1}$ peak to the $2^3\Pi_1 (v' = 12) \rightarrow X^1\Sigma^+ (v'' = 0)$ transition. The red line is the Lorentzian fitting. In following work, the PI laser frequency is fixed at about 15341.41 cm$^{-1}$.

Based on the sensitive PI technology, the molecules in the $X^1\Sigma^+$ ($v'' = 0$) state can be compared directly with the time of flight (TOF) mass spectrometer can be found as 185. We assign the $\sim 15278.31$ cm$^{-1}$ peak to the $2^3\Pi_0^+ (v' = 10) \rightarrow X^1\Sigma^+ (v'' = 0)$ transition and the $\sim 15341.41$ cm$^{-1}$ peak to the $2^3\Pi_1 (v' = 12) \rightarrow X^1\Sigma^+ (v'' = 0)$ transition. The red line is the Lorentzian fitting. In following work, the PI laser frequency is fixed at about 15341.41 cm$^{-1}$.

Loading procedure of optical trapped molecules

The dynamical processes of $^{85}$Rb$^{133}$Cs molecules in the ODT will be analyzed in two different procedures: loading and holding. The loading procedure of molecules in the $X^1\Sigma^+$ ($v'' = 0$) trapped in the ODT. In addition, the $\Delta m/z$ value is 1.18 by fitting the data with the Lorentzian function. Considering the $m/z$ value of $^{85}$Rb$^{133}$Cs$^+$ is 218, the resolution of the TOF mass spectrometer can be found as 185.
state is observed [see Fig. 3(a)]. As we can see, the number of molecules in the $X^1\Sigma^+ (v^\prime = 0)$ state loaded into the ODT increases rapidly until reaching a maximum value, which is followed by a number decrease due to a loss process.

A phenomenological rate equation is introduced to describe dynamical processes of molecules in the loading procedure. The molecule number $N_{\text{mol}}(t)$ in the loading procedure can be described as

$$\frac{dN_{\text{mol}}(t)}{dt} = R_L \cdot e^{-\gamma t} - \Gamma_L N_{\text{mol}}(t) - \int v^2(r,t) dr. \tag{1}$$

Here $R_L$ is the maximum loading rate when the molecules are loaded into ODT at the initial time, $\gamma$ represents the loss rate of molecules, $\Gamma_L$ denotes the single molecular collision with both background gas and co-trapped cold samples ($^{85}\text{Rb}$ atoms and $^{133}\text{Cs}$ atoms) in the dark-SPOTs, and $\beta_L$ is the loss rate of molecule–molecule cold collisions. The subscript $L$ is used to distinguish the loss rates during the loading process from the holding process in the ODT. Since the number of trapped molecules is much smaller (see the text below) than the trapped atoms, their volumes are nearly the same, the molecular density is much lower than the atomic density. Considering the universal inelastic rates for $\text{Rb–Rb}$Cs, $\text{Cs–Rb}$Cs, and $\text{Rb–Cs}$Cs inelastic collisions are at the same order, the $\beta_L$ is ignorable compared to the $\text{Rb–Rb}$Cs and $\text{Cs–Rb}$Cs inelastic loss rates. Thus eqn (1) can be reduced as

$$\frac{dN_{\text{mol}}(t)}{dt} = R_L \cdot e^{-\gamma t} - \Gamma_L N_{\text{mol}}(t) \tag{2}$$

The analytical solution to this equation is

$$N_{\text{mol}}(t) = \frac{e^{-\Gamma_L t} (\Gamma_L N_0 - R_L + e^{(\Gamma_L - \gamma) t} R_L - N_0 \gamma)}{\Gamma_L - \gamma} \tag{3}$$

Here, $N_0$ is the number of molecules loaded into ODT when the ODT beams are turned on. Based on this solution, it is expected that the number of molecules increases linearly with the initial loading time, $N_{\text{mol}}(t) = R_L t$. This is consistent with our observation. We choose the initial 15 ms to fit the maximum loading rate of $R_L = 47 (\pm 2) \text{ s}^{-1}$ ions per pulse while the other parameters in the loading procedure are determined by fitting the measured ion signal to eqn (3) (shown in the inset of Fig. 3(a)).

Based on eqn (3), if $\gamma$ is zero, the number of molecules will gradually increase to a maximum value. The $\Gamma_L$ and $\gamma$ are fitted to be $75 (4) \text{ s}^{-1}$ and $1.4 (2) \text{ s}^{-1}$ ions per pulse with the experimental data. The presence of $\gamma$ causes the decrease of the molecule number in the loading procedure. The measured number of $^{85}\text{Rb}$ and $^{133}\text{Cs}$ atoms in the PA region, respectively, is not affected by the presence of ODT, which can exclude the possibility that the loss rate is induced by the decrease of atom number in the PA region. We then measure the number of trapped Rb and Cs atoms in the ODT during the loading procedure as both atoms and molecules are loaded into the ODT simultaneously. The results are shown in Fig. 3(b) and (c). The fitting curves are also based on eqn (1), now modified for atom number $N_{\text{atom}}$. The number of atoms increases until reaching a maximum value. This is because the $\gamma_{\text{atom}}$, which represents the loss rate of the MOT atoms, is zero for that there is no operation for dark-SPOT lasers in our experiment. We observe that the number of trapped molecules and atoms reached the maximum values at nearly the same time, although their dynamics subsequently are quite different. Thus we attribute the loss rate $\gamma_{\text{atom}}$ to the loss rate of RbCs molecules in dark-SPOTs, as induced by the trapped atoms in ODT.

### Holding procedure of optical trapped molecules

First, we compare the time evolution of the molecule number in “ODT off” and “ODT on”. As shown in Fig. 4(a), the molecule number decreases quickly and has a shorter lifetime in “ODT off” compared to the “ODT on” case. The starting point in “ODT off” is the beginning of the release procedure and the one in
Here, $\Gamma_{\text{BG}}$ is the loss rate of molecules due to their collision with the background gas, $\Gamma_{\text{atom}}$ is the loss rate of inelastic coretrapped atom–molecule collisions, and $\beta_H$ is the loss rate of molecule–molecule cold collisions. The factor $\sqrt{1 + q_s^2}$ takes into account of the different trap sizes for atoms and molecules, where $q_s$ is the ratio between the atomic and molecular polarizabilities. In the following analysis, the atomic polarizabilities are experimental values ($^{85}\text{Rb}$ is 318.4 a.u. and $^{133}\text{Cs}$ is 401.2 a.u.). The molecular polarizability in the $X^1\Sigma^+$ ($v^\prime = 0$) state is 597.6 a.u., which is supported by explicit ab initio calculations. As mentioned before, the $\beta_H$ can be ignored. So eqn (4) is simplified as

$$\frac{dN_{\text{mol}}(t)}{dt} = -\left(\Gamma_{\text{BG}} + \frac{1}{\sqrt{1 + q_s^2}}\Gamma_{\text{atom}}\right)N_{\text{mol}}(t) = -\Gamma N_{\text{mol}}(t).$$

This equation can be solved as

$$N_{\text{mol}}(t) = N_0 e^{-\Gamma t}.$$  

Here, $\tau$ is the typical lifetime and $\tau^{-1} = \Gamma$. The typical lifetime $\tau_{\text{off}}$ is 10 (5) ms and the molecules almost disappear after the release time, while $\tau_{\text{on}}$ is 19 (4) ms after the release time. Under “ODT on” conditions, the molecules are not trapped and surrounded by atoms prepared in dark-SPOTs, so the $\Gamma_{\text{off}}$ comes from processes involving the molecule–background gas collisions, atom–molecule inelastic collisions and the dissipation process of thermal motion. Under “ODT on” conditions, the molecules have been confined in the ODT, and have longer lifetime. But, the molecular lifetime and number are still limited by the collisions, including the atom–molecule inelastic collisions.

To remove influences of atom–molecule inelastic collisions, pushing lasers are adopted in our experiment. By selectively turning on the pushing laser, the molecules or the molecules with chosen atoms could be prepared in ODT. Fig. 4(b) shows the time evolution of the $^{85}\text{Rb}^{133}\text{Cs}$ molecules, the molecules with $^{85}\text{Rb}$ atoms in the $F = 2$ state and $^{133}\text{Cs}$ atoms in the $F = 3$ state in the holding procedure. As we can see, the absence of cold atoms in the ODT significantly increases the number and lifetime of the trapped molecules.

The introduction of pushing lasers allows us to observe the atom–molecule collisions. In the molecular sample in the $X^1\Sigma^+$ ($v^\prime = 0$) state in the trap, the typical lifetime is 97 (20) ms, which is consistent with the background gas-limited lifetime for isolated $^{133}\text{Cs}$ atomic clouds in our measurement. These results also mean that the molecular lifetime is limited by collisions with the background gas. Under these conditions, $\Gamma_{\text{atom}} = 0$ and $\tau_1^{-1} = \Gamma_{\text{BG}} = 10 (3)$ s$^{-1}$ by fitting with eqn (6). So, the $\Gamma_{\text{RbCs}}$ value is deduced to be 19 (4) s$^{-1}$ from the data of molecules trapped with $^{85}\text{Rb}$ atoms, and the $\Gamma_{\text{Cs}}$ value is deduced to be 50 (12) s$^{-1}$ from the data of molecules trapped with $^{133}\text{Cs}$ atoms. The sum of $\Gamma_{\text{RbCs}}$, $\Gamma_{\text{Rb}}$ and $\Gamma_{\text{Cs}}$ is 79 (8) s$^{-1}$, agreeing with the value of $\Gamma_L$. $\Gamma_{\text{atom}}$ is related to the inelastic collision...
rate $K$ and $\Gamma_{\text{atom}} = K n_{\text{atom}}$. Assuming that the atomic density is a constant, we extract $K n_{\text{RB}}$ as $1.0 \times 10^{-10}$ cm$^{-3}$ s$^{-1}$ and $K n_{\text{Cs}}$ as $1.2 \times 10^{-10}$ cm$^{-3}$ s$^{-1}$ from our data. The released energy from the rovibrational quenching will remove the reactive atoms and molecules from the trap, thus the inelastic collisions of $^{85}\text{Rb}^{133}\text{Cs}$ molecules in the $X^1 \Sigma^+ (v'' = 0)$ state with $^{85}\text{Rb}$ ($^{133}\text{Cs}$) atoms are not affected by the inelastic collisions of $^{85}\text{Rb}^{133}\text{Cs}$ molecules in $X^1 \Sigma^+ (v'' > 0)$ states with $^{85}\text{Rb}$ ($^{133}\text{Cs}$) atoms. These values are on the same order as those reported in other experiments performed with trapped molecules in a $3 \Sigma^+$ states and high lying level of $X^1 \Sigma^+$ states, such as the $^{85}\text{Rb}^{133}\text{Cs}$ molecules in a $3 \Sigma^+$ states, $^7\text{Li}^{133}\text{Cs}$ molecules in a $3 \Sigma^+$ states and high lying level of $X^1 \Sigma^+$ states. Besides, our inelastic rate is still higher than the computed one, which indicates that partial waves higher than the s-wave have to be involved in the collision under our experimental conditions. We notice that although the produced molecules populate in several vibrational states, the measured results should be the same as the case for pure $X^1 \Sigma^+ (v'' = 0)$ state ones, due to ignorable vibrational redistribution and molecule–molecule cold collisions.

### Conclusion

We have shown that ultracold $^{85}\text{Rb}^{133}\text{Cs}$ molecules in the lowest vibrational $X^1 \Sigma^+ (v'' = 0)$ ground state (to be precise, the $J'' = 1$ and $J'' = 3$ states of $X^1 \Sigma^+ (v'' = 0)$) produced via short-range PA have been confined in a crossed ODT. The loading and holding procedures of $X^1 \Sigma^+ (v'' = 0)$ state molecules in ODT are analyzed based on a phenomenological rate equation. The inelastic collisions of $^{85}\text{Rb}^{133}\text{Cs}$ molecules in the $X^1 \Sigma^+ (v'' = 0, J'' = 1$ and $J'' = 3$) states with ultracold $^{85}\text{Rb}$ (or $^{133}\text{Cs}$) atoms are measured. We note that ref. 51 has suggested that the $2^3 \Pi_0$ state may have vibrational levels that permit efficient $X^1 \Sigma^+ (v'' = 0)$ state production in LiK, LiRb, LiCs, NaK, NaRb, NaCs and KCs systems. So, our demonstration provides a simple and generic procedure for studying the dynamical process of trapped cold molecules in singlet ground states.

### Conflicts of interest

There are no conflicts to declare.

### Acknowledgements

We thank Y. Hu, Y. Yang and C. Li for the meaningful discussions. The work was supported by the National Key Research and Development program (2017YFA0304203), the National Natural Science Foundation of China (No. 61675120, 11434007 and 61378015), the NSFC Project for Excellent Research Team (No. 61121064), the Shanxi Scholarship Council of China, “1331 KSC”, PCSIRT (No. IRT 13076), and the Applied Basic Research Project of Shanxi Province (No. 201601D202008).

### References

47 Although the trapped RbCs molecules populate in a series of vibrational distributions, the vibrational redistribution can be neglected as the lifetimes of RbCs in the lowest vibrational states are on the order of $10^4$ s (see J. Chem. Phys., 2004, 120, 88 and J. Chem. Phys., 2005, 123, 174304), which are much larger than the measured lifetime of trapped molecules. The time evolutions of RbCs molecules in $X^1\Sigma^+$ ($v^\pi = 1$) and $X^1\Sigma^+$ ($v^\pi = 2$) states also express simple exponential decay functions with trapped lifetimes of 98 (15) ms and 96 (11) ms. These values are consistent with the $X^1\Sigma^+$ ($v^\pi = 0$) state, confirming the reasonability of neglecting vibrational redistribution. Furthermore, it is expected that the populations of molecules in the other vibrational states in the optical trap are the same as the dark-SPOTs in ref. 18. 