Collisional loss rates of sodium Bose-Einstein condensates in the $F = 2$ state in a one-dimensional optical lattice

Hiromitsu Imai,* Tomoya Akatsuka, Takashi Ode, and Atsuo Morinaga
[1] *Faculty of Science and Technology, Tokyo University of Science, 2641 Yamazaki, Noda-shi, Chiba 278-8510, Japan*
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We have created stable sodium Bose-Einstein condensates in the $|F = 1, m_F = -1\rangle$ state in a one-dimensional optical lattice with a lifetime of 102 ± 42 s, which is limited by the photon scattering rate. The condensates were transferred to the upper hyperfine $F = 2$ state and the one-body and two-body loss rates were examined. Condensates in the $|2,1\rangle$ state were transferred in the optical lattice from the initially prepared condensates using a two-photon microwave–radio-frequency pulse. The two-body loss coefficients in the $|2,0\rangle$ and $|2,1\rangle$ states were found to be $(2.1 \pm 1.4) \times 10^{-12}$ and $(7.7 \pm 1.0) \times 10^{-13}$ cm^3 s^{-1}, respectively. The lifetime of the $|2,1\rangle$ state was 15 ms at the initial density of 5×10^{14} atoms/cm^3. We constructed a Ramsey atom interferometer using BECs in the $|1,-1\rangle$, and $|2,1\rangle$ states with an interrogation time of 2 ms in the optical lattice.

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I. INTRODUCTION

In recent years, optical lattices [1], by which neutral atoms can be trapped at the intensity maxima (or minima) of a standing-wave light field due to the optical dipole force, are one of the most important tools for the realization of optical clocks [2,3] and quantum information processing [4]. In particular, Bose-Einstein condensates (BECs) trapped in an optical lattice have been developed for studies in condensed matter physics [5,6], suggesting the possibility of new applications [7]. In principle, the optical dipole force confines atoms in all hyperfine states, independent of the internal spin states of the atoms, for a long duration of more than a second, therefore enabling the study of a rich variety of spinor BEC physics [8]. On the other hand, a magnetic trap confines only the weak-field–seeking state, although it can condense a comparatively large number of atoms by forced evaporative cooling [9–11]. Therefore the best strategy to produce large spinor BECs is to load a BEC in the weak-field–seeking state created in a magnetic trap into an optical lattice and transfer it to other hyperfine or spin states [12,13].

For the study of spinor BECs, spin-2 BECs are more attractive than spin-1 BECs since the number of spin degrees of freedom of the atoms is larger. Condensates of alkaline atoms in the $F = 2$ ground hyperfine state are widely used. However, the ^{85}Rb $F = 2$ BEC has a negative scattering length and the $F = 2$ states in ^{7}Li, ^{23}Na, ^{39}K, and ^{87}Rb are in the upper hyperfine manifold, meaning that they decay to the lower hyperfine state. Therefore it is important to measure the collisional rates of condensates in the $F = 2$ state. Görlitz *et al.* studied the loss rates of sodium BECs confined in a dipole trap, and they found that the condensate in the $|2,0\rangle$ state at a density on the order of 10^{14} atoms/cm^3 decays within milliseconds by rapid inelastic losses [13], although the condensates in the $F = 1$ state were trapped in a dipole trap for more than 10 s [8]. In an optical lattice which we study here, the axial potential is several thousand times larger than that in a dipole trap, so that the density of atoms becomes higher. Recently, spin-dependent two-body inelastic collisions in $F = 2$ ^{87}Rb BECs were studied in detail by Tojo *et al.* [14], and it was found that ^{87}Rb has a two-body loss rate on the order of 10^{-14} cm^3 s^{-1}. The two-body loss rate of ^{23}Na is known to be much larger than that of ^{87}Rb; however, the collisional rates of sodium BECs in the $F = 2$ state have not yet been measured in detail.

We have demonstrated Ramsey interference fringes with a visibility of close to 100% for an interrogation time of 10 ms using released sodium BECs in the clock transition between the $|F = 1, m_F = 0\rangle$, and $|2,0\rangle$ states and two two-photon stimulated Raman pulses [15]. However, the interrogation time was limited to 10 ms at a time of 30 ms after the release from the magnetic trap, since BECs fell under gravity to outside the Raman pulse. For the realization of an atom interferometer or atom clock using BECs, a longer interrogation time is desired. The fact that the sodium $|2,0\rangle$ state has a short trapped time in an optical trap shows that it is very difficult to observe the Ramsey interference fringes between the two states of sodium BECs confined in an optical trap.

Instead of the clock transition of $|1,0\rangle \rightarrow |2,0\rangle$, two-photon microwave-radio frequency (MW-rf) transitions between the ground hyperfine levels $|1,-1\rangle$ and $|2,1\rangle$ of Rb atoms have often been used as an ideal "qubit" [16] or "clock transition" [17]. This is because there is a "magic" magnetic field of 323 μT at which the transition frequency is insensitive to the magnetic field. In the case of sodium atoms, the transition of $|1,-1\rangle \rightarrow |2,1\rangle$ (see Fig. 1) is insensitive to the magnetic field when the strength of the magnetic field is 67.7 μT, which is easy to produce [18]. Using this transition and released sodium BECs, we have expanded the interrogation time of Ramsey interference to 40 ms at a time of 40 ms after the release from the magnetic trap. The width of the two-photon MW-rf pulse was 0.5 ms and the pulse separation was 39.5 ms. We then obtained Ramsey fringes with a fringe period of 25.00 ± 0.24 Hz and a visibility of 65%. This interrogation time was still limited by the freefall of BECs due to gravity. To overcome the problem of gravity, one method is to trap BECs spatially and subject them to interference in an optical

*Present address: NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi-shi, Kanagawa, 243-0198, Japan.

trap. However, the lifetime is limited by trap losses due to interatomic collisions at high density. Therefore it is desirable to determine the collisional loss rate of sodium condensates in the $|2,1\rangle$ state trapped in an optical lattice.

In this paper, first we report our strategy used to stably trap a large number of sodium BECs in the $|1,-1\rangle$ state in an optical lattice. Next we describe the measurement of the lifetime of sodium BECs in the $|2,1\rangle$ state confined in an optical lattice, which is transferred from the $|1,-1\rangle$ state using a two-photon MW-rf pulse. Finally, we report the construction of a Ramsey atom interferometer using BECs in an optical lattice based on the transition between the $|1,-1\rangle$ and $|2,1\rangle$ states, which is insensitive to the magnetic field.

II. SODIUM HYPERFINE STATES

Figure 1 shows a diagram of the well-known ground hyperfine states of ^{23}Na. The ground-state hyperfine splitting between the $F = 1$ and $F = 2$ states is 1.771 626 GHz [19], and these states split into submagnetic states due to Zeeman splitting in the presence of a magnetic field [20]. The g factors of the $F = 1$ and $F = 2$ states are -1/2 and 1/2, respectively; thus the Zeeman splitting for each state is essentially identical at the first-order approximation. The $|1,-1\rangle$, $|2,2\rangle$ and $|2,1\rangle$ states are weak-field seeking states, but only the $|1,-1\rangle$ state can be condensed in a magnetic trap by rf-induced forced evaporative cooling [21].

The so-called clock transition occurs between the $|1,0\rangle$ and $|2,0\rangle$ states by applying a one-photon microwave pulse with the frequency of hyperfine splitting or a two-photon Raman pulse whose frequency difference corresponds to the frequency of hyperfine splitting. On the other hand, the two-photon MW-rf transition between the $|1,-1\rangle$ and $|2,1\rangle$ states also is magnetic-field insensitive.

The resonance frequency $\nu_{-1,1}$ between the $|1,-1\rangle$ and $|2,1\rangle$ states is minimum at $B_0 = 67.7\ \mu$T, which is called the magic value, and it is 762 Hz lower than the frequency of the clock transition in a zero magnetic field [18]. As a result, even if the magnetic field is varied by about 10% around B_0, the frequency shift $\nu_{-1,1}$ is only 7 Hz. We use two-photon MW-rf excitation to drive this clock transition. At the magic magnetic field, the Zeeman splitting frequency is 474 kHz. We apply a pulse of microwave radiation, whose frequency is 420 kHz less than that corresponding to the ground-state hyperfine splitting of ^{23}Na, along with an rf magnetic field of around 420 kHz. This connects the $|1,-1\rangle$ state to the $|2,1\rangle$ state via an intermediate virtual state with a detuning of 54 kHz from the $|2,0\rangle$ state by σ^+-σ^+ polarized fields.

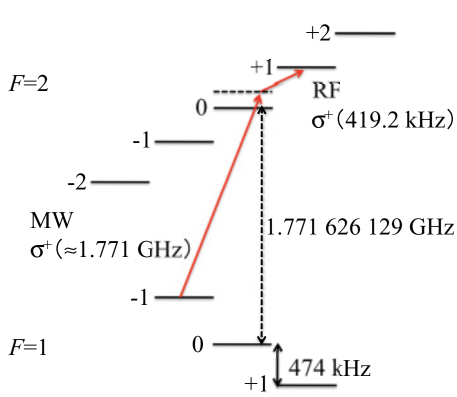

FIG. 1. (Color online) Energy diagram of sodium ground hyperfine states ($F = 1,2$) due to the presence of a magnetic field of 67.7 μT, together with a two-photon microwave (MW)–radio-frequency (rf) transition between the $F = 1$, $m_F = -1$ and $F = 2$, $m_F = 1$ states (solid allows). σ^+: σ^+ circular polarization.

III. EXPERIMENT

The experimental setup we used for creating BECs was similar to that in our previous work [15]. Thermal sodium atoms were decelerated by a Zeeman slower and trapped by a dual-operation magneto-optical trap (MOT) [22], a temporal dark MOT, and by polarization gradient cooling (PGC). Next, the spin of the trapped atoms was polarized in the $|1,-1\rangle$ state using the spin polarization technique developed by van der Stam *et al.* [23], and cold atoms were captured in a directly compressed magnetic trap (direct MT), where the typical radial and axial trap angular frequencies were $\omega_{x,y} = 2\pi \times 148$ Hz and $\omega_z = 2\pi \times 21$ Hz, respectively. Finally, rf-induced forced evaporative cooling was applied to the trapped atoms for 30 s using an optimized evaporative cooling method [11]. The atoms were condensed at the phase transition temperature of 1 μK. We were able to produce BECs in the $|1,-1\rangle$ state, typically with 3×10^7 atoms and a density of 5×10^{14} atoms/cm^3, every 2 min. The atom clouds were cigar-shaped, with the long axis horizontal and a typical aspect ratio of 7.

A one-dimensional lattice potential was then superimposed on the BECs. The optical lattice was formed by focusing a Nd:YAG (yttrium aluminum garnet) laser beam ($\lambda = 1.064\ \mu$m) into the center of the magnetic trap along the axial z direction. The laser beam was retroreflected by a curved mirror and overlapped by carefully adjusting the position and alignment of the mirror. The beam waist parameter w_0 ($1/e^2$ radius for intensity) was about 40 μm, which was smaller than the size of the BECs. The confocal length was $2\pi {w_0}^2/\lambda = 9.5$ mm. The depth of the optical-trapping potential at a power of 0.11 W was 9.2 μK, and ac Stark frequency shifts of transitions between $F = 1$ and $F = 2$ sublevels were less than 200 Hz. The axial and radial trap frequencies were $\nu_z = 77$ kHz and $\nu_{x,y} = 0.46$ kHz, respectively. The trapped atoms in the magnetic potential were irradiated with the optical lattice beam, and the magnetic potential was shut down after creating the BECs. A quantization magnetic field of 67.7 μT was applied parallel to the axial direction. During the application of the optical lattice beam, the vacuum pressure of the chamber was about 6.3×10^{-9} Pa. The ac Stark shift of the transition frequency between the $|1,-1\rangle$ and $|2,1\rangle$ states in the present optical lattice was estimated to be less than 10 Hz and is disregarded.

Absorption images of the optical trapped condensates were taken *in situ* with a charge-coupled device (CCD) camera by irradiating a probe pulse with a width of 100 μs parallel to the y axis, which is in the direction of gravity. Before irradiating the probe pulse, the atoms were optically pumped into the $|F = 2\rangle$ hyperfine state using a pulse resonant with the $|F = 1\rangle \rightarrow |F = 2\rangle$ transition. The probe pulse was resonant with the

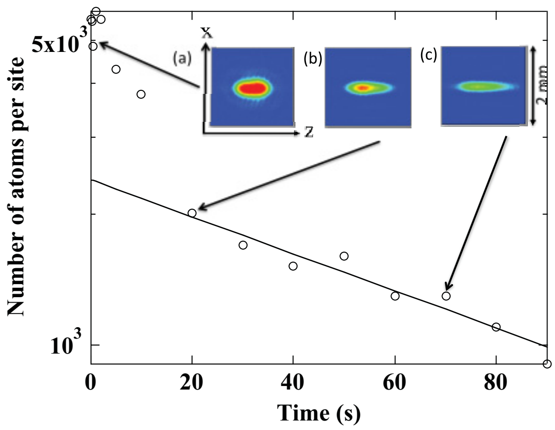

FIG. 2. (Color online) Number of atoms per site in the $F = 1$, $m_F = -1$ state in an optical lattice as a function of storage time. Lattice potential is 10 μK. Inset (a), (b), and (c) are *in situ* absorption images of atoms trapped at storage times of 0.1 s, 20 s, and 70 s, respectively. Solid line is an exponential fit to data points with $t \geqq 40$ s, which yielded a one-body loss rate of $0.0098 \pm 0.0040\ \text{s}^{-1}$.

$|F = 2\rangle \rightarrow |F\prime = 2\rangle$ cycling transition for the condensates. A typical absorption image of BECs at a time of 0.1 s after optical trapping is shown in Fig. 2. From the image we estimated the total number of trapped atoms to be 2×10^7 and the number of sites in the optical lattice to be $(1.65 \pm 0.10) \times 10^3$. The mean number of trapped atoms per site was about 6×10^3 and the density was estimated to be 1×10^{15} atoms/cm^3. The highest transfer efficiency of the BECs from the MT to the optical lattice was about 70%.

IV. RESULTS AND DISCUSSION

A. $F = 1$ state in the optical lattice

To evaluate the intrinsic stability of the optical lattice, the lifetime of atoms in the $|1,-1\rangle$ state was studied by measuring the number of trapped atoms as a function of storage time in the optical lattice. Results obtained at a trapping power of 0.11 W are shown in Fig. 2. Although the number of atoms initially rapidly decreased due to the two- or three-body losses, the rate of reduction decreased after 20 s. Absorption images taken at 0.1 s, 20 s, and 70 s are shown in Fig. 2. At 20 s the density of atoms was about 7×10^{14} atoms/cm^3. A fit to the data for $t \geqq 40$ s yielded a one-body loss rate of $k_1 = 0.0098 \pm 0.0040\ \text{s}^{-1}$, corresponding to a lifetime of 102 ± 42 s. This value is longer than the value of 35 s reported previously [8] and is in good agreement with the calculated photon scattering loss rate of $0.010\ \text{s}^{-1}$ at a laser power of 0.11 W [24]. In fact, since the density increases with the power of the laser beam, the number of atoms decreased more rapidly due to the three-body loss with a coefficient K_3. The long lifetimes observed at the low power of the trapping beam were explained by its limited trap depth, similarly to "rf shielding" in a magnetic trap. [12] The loss also depended on the alignment of the lattice beam and the pressure of the vacuum in the chamber. In the present experiment we did not precisely examine the two- and three-body loss coefficients because the uncertainty of the density was relatively large in the *in situ* measurement at the high density of 10^{15} atoms/cm^3.

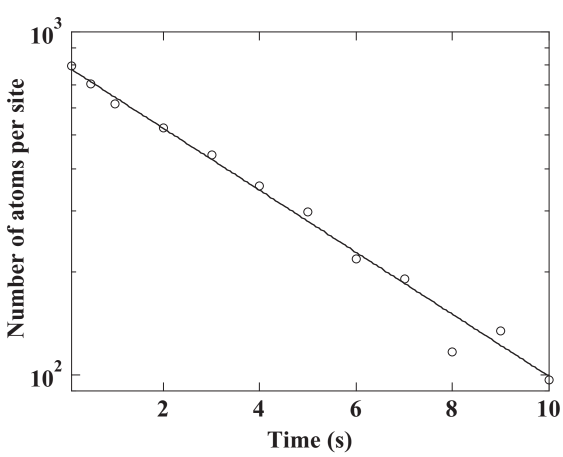

FIG. 3. Number of atoms per site in the $F = 2$, $m_F = -2$ state in an optical lattice as a function of storage time. Solid line is an exponential fit to data points with $0.21 \pm 0.01\ \text{s}^{-1}$.

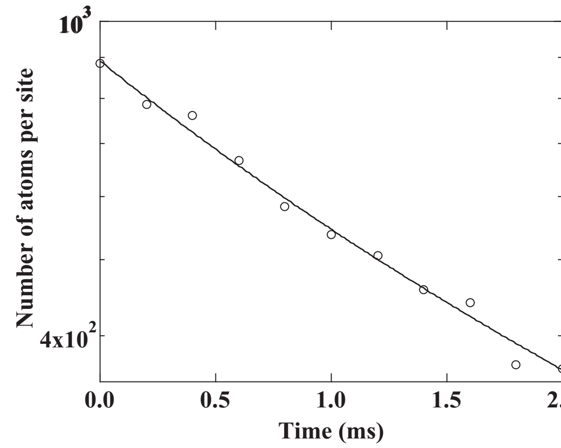

FIG. 4. Number of atoms per site in the $F = 2$, $m_F = 0$ state in an optical lattice as a function of storage time. Solid line is a fitted two-body loss curve with $(2.1 \pm 1.4) \times 10^{-12}\ \text{cm}^3\ \text{s}^{-1}$.

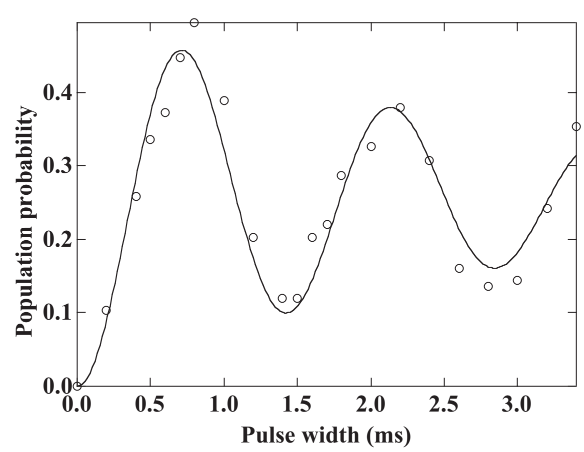

FIG. 5. Rabi oscillation of population probability in the $F = 2$, $m_F = 1$ state excited from the $F = 1$, $m_F = -1$ state as a function of the width of two-photon pulse. Solid curve is a fitted theoretical Rabi oscillation with a relaxation constant.

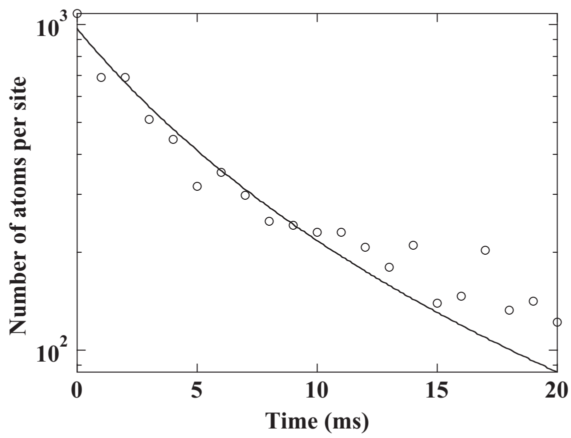

FIG. 6. Number of atoms per site in the $F = 2$, $m_F = 1$ state in an optical lattice as a function of storage time. Solid curve is a fitted two-body loss curve with $(7.7 \pm 1.0) \times 10^{-13}$ cm^3 s^{-1}.

B. $F = 2$ state in the optical lattice

We first transferred the condensates in the $|1,-1\rangle$ state trapped in the optical lattice to the $|2,-2\rangle$ state by applying a σ^--polarized microwave pulse with a frequency of 1.77 GHz. The number of atoms transferred to the $|2,-2\rangle$ state was about 10% of the number of atoms in the $|1,-1\rangle$ state; thus the density of atoms was on the order of 10^{14} atoms/cm^3. Figure 3 shows the number of atoms per site trapped in the lattice as a function of elapsed time. Under our experimental conditions, the two- and three-body loss rates could not be determined clearly. These loss rates have been reported to be 3.1×10^{-15} cm^3 s^{-1} and 1.6×10^{-29} cm^6 s^{-1}, respectively [13]. On the other hand, the one-body loss rate in the $|2,-2\rangle$ state $k_1^{|2,-2\rangle}$ was measured to be 0.21 ± 0.01 s^{-1}, corresponding to a lifetime of 4.8 ± 0.3 s. This value is significantly shorter than the lifetime of a $|1,-1\rangle$ condensate but also is in agreement with the value obtained by Görlitz *et al.* [13]. Thus the condensates in the upper hyperfine $F = 2$ state have a one order shorter lifetime than those in the $F = 1$ state.

Next, to produce optically trapped condensates in the $|2,0\rangle$ state, a σ^+-polarized microwave pulse with a frequency of 1.77 GHz was applied and the loss rate was investigated. As shown in Fig. 4, the number of atoms in the $|2,0\rangle$ state decreased very rapidly in the first few milliseconds, although the density was the same as that of the condensates in the $|2,-2\rangle$ state. This decrease is a result of two-body loss mainly due to spin-dependent inelastic collisions [14]. At the present density of atoms, three- and one-body losses were ignored. The two-body loss coefficient $k_2^{m=0} \equiv k_2^{|2,0\rangle}$ in the $|2,0\rangle$ state was estimated from the time evolution of the number of atoms N_m, described by

$$N_m(t) = \frac{5^{5/2}}{\left[5N_m^{-2/5}(0) + 2\gamma_m k_2^m t\right]^{5/2}}, \tag{1}$$

where γ_m is given by

$$\gamma_m = \frac{15^{2/5}}{14\pi}\left(\frac{M\bar{\omega}}{\hbar\sqrt{a_m}}\right)^{6/5}. \tag{2}$$

M is the mass, $\hbar$ is Planck constant, $\bar{\omega}$ is the average trap frequency, and a_m is the scattering length. $k_2^{|2,0\rangle}$ was found to be $(2.1 \pm 1.4) \times 10^{-12}$ cm^3 s^{-1} at a density of 4.5×10^{14} atoms/cm^3 immediately after transfer to the $|2,0\rangle$ state, where we assumed that the scattering length $a_{m=0} \equiv a_{|2,0\rangle|2,0\rangle}$ was 3.3 nm, which is equivalent to the scattering length $a_{|2,-2\rangle|2,-2\rangle}$ in the $|2,-2\rangle$ state [25]. This is in agreement with the previous value of a few milliseconds [13]. Such agreement verifies that the present optical lattice was optimized experimentally.

Lastly, condensates in the $|2,1\rangle$ state were produced by applying a two-photon MW-rf pulse to optically trapped condensates in the $|1,-1\rangle$ state. A dipole antenna, which generates MW with a frequency of 1.771 206 GHz, was set near the trap so that the polarization direction of the MW was perpendicular to the quantization magnetic field (σ polarization). An rf field was produced by a loop antenna near the MOT and swept at a frequency around 420 kHz. Figure 5 shows the Rabi oscillation as a function of the width of the two-photon pulse. The Rabi frequency was 0.52 ± 0.01 kHz. The width of a π pulse was 0.75 ms and the maximum excitation probability was about 0.5. The value was not 1 due to the reduced atomic number in the upper level and the existence of other spin states when the BECs in the $|1,-1\rangle$ state trapped in the magnetic trap were transferred to the optical lattice. The pulse width of the MW-rf pulse, which corresponded to a spectrum width of 1.3 kHz, was sufficiently narrow to resolve the three magnetic-field-insensitive transitions separated by a few kilohertz.

The number of atoms in the $|2,1\rangle$ state trapped in the optical lattice was measured as a function of elapsed time at the density of 4.9×10^{14} atoms/cm^3 soon after the MW-rf pulse was irradiated, as shown in Fig. 6. The number of atoms in the $|2,1\rangle$ state decreased within a few tens of milliseconds. Thus, the two-body loss rate was obtained to be $(7.7 \pm 1.0) \times 10^{-13}$ cm^3 s^{-1}, where we assumed that the scattering length $a_{|2,1\rangle|2,1\rangle}$ was 3.3 nm. This value is one-third of that in the $|2,0\rangle$ state.

The measured ground hyperfine states in the optical lattice are summarized in Table I, together with known values. We

TABLE I. One-body, two-body, and three-body loss rates of the sodium Bose-Einstein condensates in the ground hyperfine state in the optical lattice. The * indicates values in Ref. [13].

State	$\|1,-1\rangle$	$\|2,-2\rangle$	$\|2,0\rangle$	$\|2,1\rangle$
k_1 (s^{-1})	0.0098 ± 0.004	0.21 ± 0.01		
k_2 (10^{-13} cm^3 s^{-1})	$0.0053 \pm 0.0005^*$	$0.031 \pm 0.003^*$	21 ± 14	7.7 ± 1.0
k_3 (10^{-30} cm^6 s^{-1})	$2.12 \pm 0.16^*$	$16.3 \pm 1.4^*$		

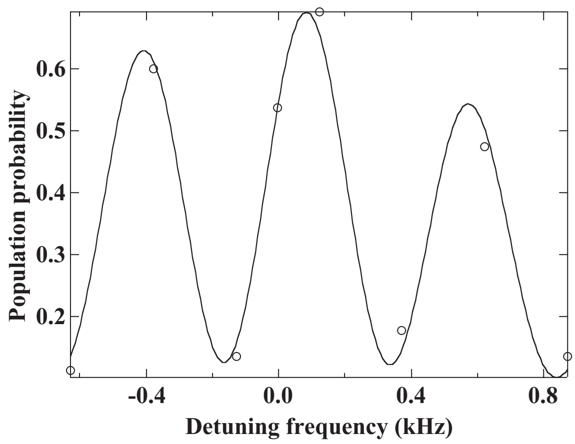

FIG. 7. Ramsey fringes as a function of detuning frequency. Each datum was obtained by single measurement of BECs. The solid curve shows fitted theoretical Ramsey fringes with a fringe period of 500 Hz.

were able to determine the one-body loss rate for the $|2,-2\rangle$ state and the two-body loss rates for the $|2,0\rangle$ and $|2,1\rangle$ states. The values for the $|2,-2\rangle$ and $|2,0\rangle$ states are in agreement with the previous values, but the value for the $|2,1\rangle$ state was newly obtained. If we compare the two-body loss rates of ^{23}Na with those of ^{87}Rb, the loss rate is 20 times higher for the $|2,0\rangle$ state and seven times higher for the $|2,1\rangle$ state.

C. Ramsey atom interferometry

Finally, we constructed a Ramsey atom interferometer composed of the $|1,-1\rangle$ and $|2,1\rangle$ states with two $\pi/2$ MW-rf pulses but a time interval T of less than 5 ms and examined the coherence of the BECs in the optical lattice. After Ramsey excitation, the BECs were irradiated with a probe pulse with a width of 100 μs and the number of atoms $N_{|2,1\rangle}$ in the $F=2$ state was measured. Then the BEC in the $F=2$ state was blown off, an optical pumping beam was used to excite the BECs in the $F=1$ state to the $F=2$ state, and lastly, the number of atoms in the $F=1$ state $N_{|1,-1\rangle}$ was measured with a second probe beam. Thus the population probability of the BEC in the $F=2$ state is given by $N_{|2,1\rangle}/(N_{|1,-1\rangle}+N_{|2,1\rangle})$. Typical interference fringes as a function of the detuning rf are shown in Fig. 7, where each data point was obtained by a single measurement of the BECs. The width of each $\pi/2$ Raman pulse was regulated to be 0.5 ms. For a time interval of 1.5 ms, Ramsey fringes with a fringe period of 500 Hz were obtained in an envelope with a width of 2 kHz. The maximum and minimum population probabilities in the excited state were 0.7 and 0.1, respectively, which correspond to 75% visibility of the Ramsey fringes. The data was well fitted to a function including a cosine function with a period of 500 Hz [26]. Unfortunately, due to the short lifetime of the condensate in the $|2,1\rangle$ state in the optical lattice, we could not examine the performance of long coherent times in the optical lattice.

V. CONCLUSION

We trapped sodium BECs in the $|1,-1\rangle$ state with a lifetime of more than 100 s in an optical lattice, which was close to the value limited by photon scattering loss. We transferred the BECs to the $|2,-2\rangle$ and $|2,0\rangle$ states by irradiation with a one-photon MW pulse. The lifetime of the sodium condensates in the $F=2$ state trapped in the optical lattice was 4.8 ± 0.3 s. The two-body loss rate of the condensates in the $|2,0\rangle$ state was $(2.1 \pm 1.4) \times 10^{-12}$ cm^3 s^{-1} at a density of 4.5×10^{14} atoms/cm^3. This value is about 20 times that for ^{87}Rb. Condensates in the $|2,1\rangle$ state were prepared by irradiation with a two-photon MW-rf pulse. The Rabi oscillation was measured. The condensates in the $|2,1\rangle$ state trapped in the optical lattice decayed within 13 ± 2 ms at a density of 4.9×10^{14} atoms/cm^3. In the future, the two-body loss rates in the $F=2$ state will be investigated for each spin state of colliding atoms [14].

Using BECs in the $|2,1\rangle$ and $|1,-1\rangle$ states trapped in an optical lattice, a Ramsey atom interferometer was constructed with an interrogation time of 2 ms. We obtained interference fringes with a fringe period of 500 Hz and a visibility of 75%. At present, the interrogation time of the interferometer is limited by the two-body loss rate of ^{23}Na in the $|2,1\rangle$ state at a density of 5×10^{14} atoms/cm^3.

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