

Sub-Doppler Cooling, State Preparation, and Optical Trapping of a Triel Atom

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Ultracold gases of atoms from main group III (group 13) of the periodic table, also known as “triel elements,” have great potential for a new generation of quantum matter experiments. The first magneto-optical trap of a triel element (indium) was recently realized, but more progress is needed before a triel is ready for modern ultracold quantum science experiments in optical traps. Reaching this regime typically requires atoms that are cooled to the 10 μ K level or below, prepared in pure quantum states, and confined in a laser field. Here we report the achievement of all three of these milestones in atomic indium. First, we perform polarization gradient cooling of an indium gas to 15 μ K. Second, we spin polarize the gas into a single hyperfine sublevel of either the $5P_{1/2}$ indium ground state or the $5P_{3/2}$ metastable state. Third, we trap indium in a 1064 nm optical lattice, achieving a 3 s trap lifetime. With these results, indium is now a candidate for a next generation quantum research platform.

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I. INTRODUCTION

Each time a new type of atom is cooled to ultralow temperatures, major advances in quantum science have followed. The first atom type to reach the ultracold regime, alkali metals, enabled breakthroughs such as quantum degenerate gases [1,2], spinor condensates [3], and Hubbard model quantum simulations [4,5]. The introduction of the second type, ultracold alkaline earth atoms, opened the door to advances like optical lattice clocks [6,7] and $SU(N)$ interactions [8–10]. Ultracold dipolar atoms [11], with their anisotropic long-range interactions, gave rise to phenomena like emergent structural order [11–15] and dipole-stabilized phases [16,17].

The types of ultracold atoms realized so far lie in polar opposite regimes of angular momentum and magnetic interaction strength, leaving the middle ground largely unexplored. At one extreme, alkali and alkaline earth metals have zero orbital angular momentum ($L = 0$) and few

unpaired electrons, which results in weak magnetic dipole moments. At the other extreme, dipolar atoms exhibit large dipole moments due to high L , many unpaired electrons, or both. Meanwhile the rich intermediate landscape has tremendous potential for novel quantum science.

Among the atoms in this intermediate regime, the triel elements (main group III of the periodic table) stand out for their potential to realize exotic quantum many-body systems. Since these atoms have small dipole moments and $L = 1$, their many-body interactions would be dominated by markedly anisotropic short-range scattering, a property that is novel for ultracold physics. In a Bose-condensed phase, this highly directional contact interaction could give rise to exotic phenomena such as anisotropic spinor physics. Similarly, the $F = 4$ ground state of indium is predicted to support non-Abelian topological excitations under quantum-degenerate conditions [18]. Indium also features both magnetic Feshbach resonances and an ultra-narrow electronic clock transition compatible with stable laser technology. This combination, absent in alkalis and alkaline earths, would allow for an exceptional degree of quantum control, enabling tunable many-body interactions, spatially resolved coherent state manipulation, and probing with atomic clock precision.

These features could support experiments at 10 μ K level temperatures using many-body lattice systems probed with clock lasers, a platform previously explored in

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alkaline-earth atoms [19,20]. An indium-based version of such a system could access a broader range of many-body phenomena given its tunable interactions. At similar temperatures, triel atoms could also be loaded into optical tweezers for quantum simulations with single-particle control, following approaches demonstrated with alkalis and lanthanides. In both contexts, successful implementation typically requires temperatures of order 10 μK , quantum-state purity, and optical trapping.

In this work, we achieve all three of these milestones with indium: cooling two orders of magnitude below the Doppler limit, quantum state preparation with 90% purity, and stable trapping of indium atoms in an optical lattice. Our techniques are broadly applicable to the triel elements, which share similar energy level structure as indium. These accomplishments set the stage for quantum science experiments with ultracold indium in optical lattices or tweezers.

II. SUB-DOPPLER COOLING

We work with the most abundant indium isotope, ^{115}In . Its energy level diagram and the transitions used in this manuscript are shown in Fig. 1. The first stage of our experiment involves collecting indium in a magneto-optical trap (MOT), which proceeds as follows. An indium atomic beam is generated by an effusion cell operating at 800 $^{\circ}\text{C}$. The output is collimated by a microchannel array heated to 900 $^{\circ}\text{C}$ to prevent clogging. The beam is then pumped into the $|5P_{3/2}, F=6\rangle$ metastable cooling state using lasers at 410 and 451 nm [22]. The atoms are then decelerated to 70 m/s with a permanent magnet Zeeman slower. After that, they enter a MOT with a standard six-beam $\sigma^+ - \sigma^-$ configuration. The $|5P_{3/2}, F=6\rangle \rightarrow |5D_{5/2}, F=7\rangle$ transition at 326 nm is used for cooling in the Zeeman slower and MOT. In both of these stages, lasers

driving the $|5P_{3/2}, F=4, 5\rangle \rightarrow |6S_{1/2}, F=5\rangle$ transitions at 451 nm and the $|5P_{1/2}, F=4, 5\rangle \rightarrow |6S_{1/2}, F=5\rangle$ transitions at 410 nm are present for repumping. With this setup, we have observed temperatures of order 1 mK (the Doppler limit is 500 μK) while the atom number was as high as 1×10^9 [21].

To achieve the goal of a 10 μK level temperature, we use polarization gradient cooling (PGC) [24,25], which works well when a cooling transition is in a hyperfine manifold with splittings much larger than the transition linewidth [26,27], as is the case with indium. The primary concern with PGC is to ensure that any residual magnetic fields are well canceled, for nonzero bias fields lift the hyperfine sublevel degeneracy necessary for the PGC mechanism [28]. Therefore, we develop a procedure to measure and compensate the residual magnetic field. We quantify this field by measuring the Zeeman splitting of the ground state hyperfine transition, $|5P_{1/2}, F=4\rangle \rightarrow |5P_{1/2}, F=5\rangle$ (at 11.410 GHz). The hyperfine g -factors for this transition predict that, in a bias magnetic field, it separates into 19 lines split by 93.3 kHz/G (calculated from the standard expressions for the g -factors, with the nuclear g -factor terms neglected).

The sequence for microwave spectroscopy of the 11.410 GHz transition is as follows. After the initial MOT stage, atoms populate the lower-energy cooling state $|5P_{3/2}, F=6\rangle$. Atoms in this state are pumped into the hyperfine ground state $|5P_{1/2}, F=4\rangle$ with four lasers [23]. Three of these lasers have 451 nm wavelengths and drive the $|5P_{3/2}, F=4, 5, 6\rangle \rightarrow |6S_{1/2}, F=5\rangle$ transitions. The fourth laser has a 410 nm wavelength and drives the $|5P_{1/2}, F=5\rangle \rightarrow |6S_{1/2}, F=5\rangle$ transition. Since the MOT randomizes m_F states [29], we expect the population to be distributed across many ground state hyperfine sublevels. We then drive the $|5P_{1/2}, F=4\rangle \rightarrow |5P_{1/2}, F=5\rangle$

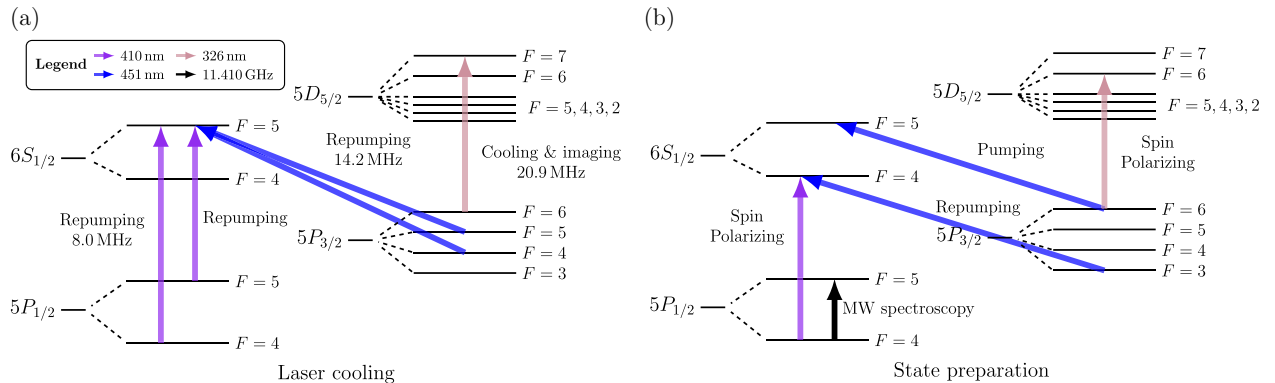


FIG. 1. (a) Indium energy levels used for laser cooling. This scheme is presented in more detail in our previous work [21]. The laser cooling transition is $|5P_{3/2}, F=6\rangle \rightarrow |5D_{5/2}, F=7\rangle$ throughout this manuscript. The frequencies in the figure are the natural linewidths of the respective transitions. (b) Atomic transitions used for spin polarization. Two spin polarization configurations are possible, allowing us to polarize atoms into either $|5P_{1/2}, F=4, m_F=4\rangle$ or $|5P_{3/2}, F=6, m_F=6\rangle$. The purity of spin polarization is determined with microwave spectroscopy.

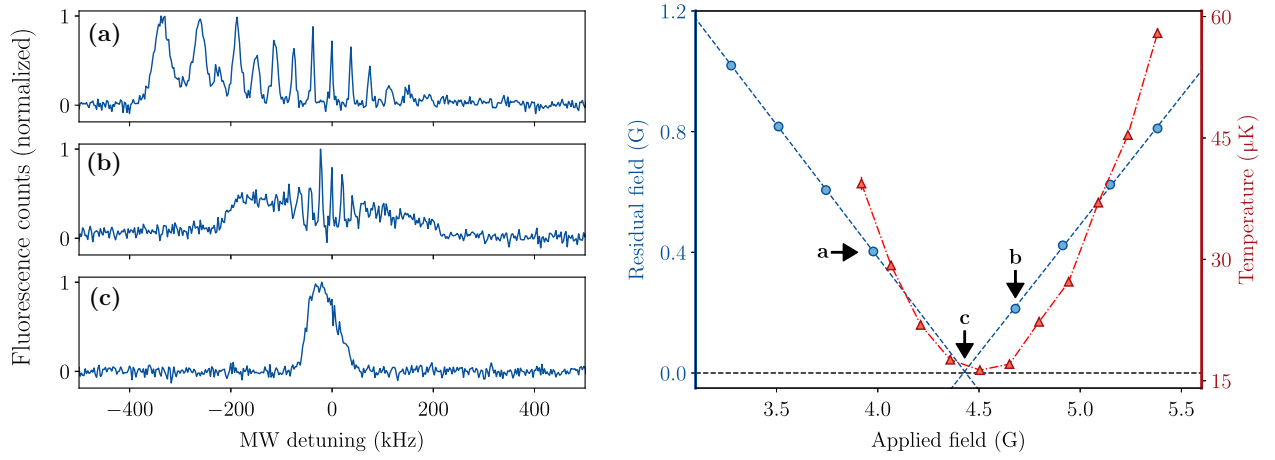


FIG. 2. Left: Typical microwave spectra with decreasing external fields. Panel (c) shows the smallest Zeeman splitting we observed. A theoretical model of the spectrum explains the broadening of lines with larger $|m_F|$ (the features that are farthest detuned from zero) as a result of a dynamic residual field [23]. Right: The residual field (blue circles) and the measured temperature of the atoms (red triangles). The residual field was determined by the frequency difference between microwave resonances. The difference in applied field minima between the residual field and the temperature is because the two curves were measured at different dynamic residual field values [23].

hyperfine transition with a 800 μs microwave pulse. After the pulse is extinguished, we measure the population that completed the transition. To do this, we first apply a single 410 nm laser to drive atoms into $|6S_{1/2}, F = 5\rangle$, which decays into the lower-energy cooling state with a branching ratio of 37%. Then, we drive the cooling transition and collect its fluorescence, which is proportional to the population that made the microwave transition.

Using microwave spectroscopy, we find that the residual field has a static component, originating from magnetized objects in the lab or Earth's field, and a dynamic component due to eddy currents from shutting off the MOT coil. Both the static and dynamic components are large enough that we must compensate for them to obtain efficient PGC. To do this, we first add a delay before PGC to let the eddy currents partially dampen, and then we apply an empirically determined bias field ramp to compensate for the remaining residual field.

Figure 2 illustrates typical microwave spectra for minimizing the residual field. The splitting between the microwave resonances varies as a function of the external magnetic field strength. The residual field is cancelled by measuring these spectra and adjusting the three bias fields until the splitting minimizes and the transitions are unresolved. With this technique, we determine the initial value of the compensating bias field ramp. This value reduces the residual field to below 50 mG.

With this initial residual field cancellation, we implement a PGC sequence [23]. First, the MOT is compressed for 5 ms by ramping up the quadrupole field, at which point the coil current and MOT laser power are shut off. Then we add the delay for dampening eddy currents before we pulse on the MOT lasers for PGC. By measuring the resulting

temperatures, we empirically adjust the delay and compensating bias field ramp parameters during the PGC pulse for optimum cooling [23].

We vary the duration, power, and detuning of the PGC pulse for best cooling (Fig. 3). The PGC pulse duration optimizes at 5 ms, and the power optimizes at the maximum available intensity of $I/I_{\text{sat}} = 1.4$. The observed temperature T is fit to the expected sub-Doppler cooling law of $T = T_0 + T_1(\Gamma/|\Delta|)$, where Δ is detuning, $\Gamma = 2\pi \times 20.9$ MHz is the transition linewidth, and T_0 and T_1 are fit parameters. Although the fitted value of the minimum temperature is $T_0 = 7.0$ μK (and $T_1 = 65.8$ μK), we do not typically achieve this in practice; therefore, we quote 15 μK as our minimum reliable temperature. This temperature, which is 30 times lower than the Doppler limit, is achieved when the detuning exceeds about -150 MHz (or about -7Γ). Roughly half the atoms are lost during the PGC stage.

III. STATE PREPARATION

Many important ultracold experiments require ensembles of atoms to be spin polarized into single hyperfine sublevels (as opposed to spin mixtures) [1,6,7,31]. We are interested in spin polarizing both the $5P_{1/2}$ ground state and the $5P_{3/2}$ metastable state, which has a predicted spontaneous lifetime of 10 s [32]. As previous work has shown, long-lived metastable electronic states have proved useful for studies of exotic interactions and quantum information processing [33–38]. Here we realize spin polarization into the $|5P_{3/2}, F = 6, m_F = 6\rangle$ and $|5P_{1/2}, F = 4, m_F = 4\rangle$ states.

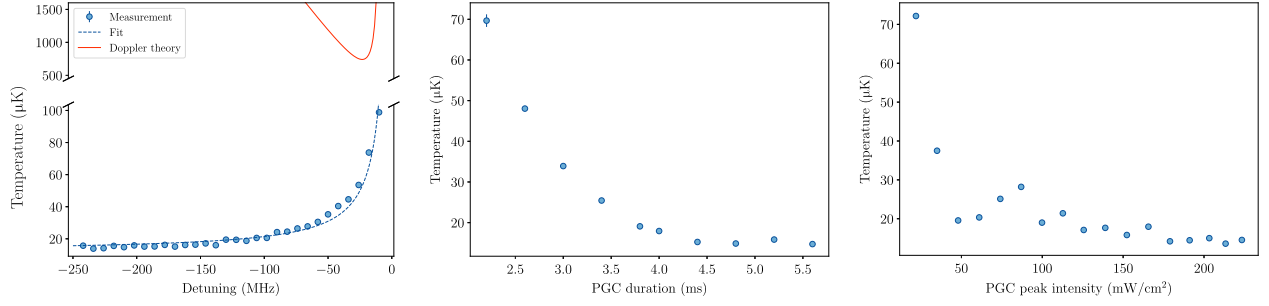


FIG. 3. Characterization of polarization gradient cooling. Left: Temperature vs detuning, indicating sub-Doppler scaling in the temperature. The data is fit to the sub-Doppler cooling law $T = T_0 + T_1(\Gamma/|\Delta|)$, where $T_0 = 7.0 \mu\text{K}$ and $T_1 = 65.8 \mu\text{K}$. In practice, the lowest temperature achieved is $15 \mu\text{K}$. Middle: Temperature vs PGC pulse duration, which optimizes at 5 ms. Right: Temperature vs laser intensity, which shows the best performance at our maximum power.

A. $5P_{3/2}$ state

State preparation schemes often involve using spin-dependent loss mechanisms to remove undesired spin components [1,31] or optical pumping into stretched states [6,7]. We perform state preparation in two phases, first using optical pumping and then with magnetic quadrupole trapping. At the center of a quadrupole field, the z component of the force $\vec{\mathcal{F}}$ on an atom is

$$\mathcal{F}_z = -g_F m_F \mu_B \beta_z \text{sign}(z) - mg, \quad (1)$$

where $g_F = 1/3$ is the g -factor for the $|5P_{3/2}, F=6\rangle$ state, μ_B is the Bohr magneton, the coordinate z is antiparallel to gravity, β_z is the magnitude of the magnetic field

gradient at the center of the quadrupole trap (where $z = 0$), and mg is the gravitational force. The indium gas is loaded into the quadrupole trap after laser cooling, and this causes atoms with $m_F \leq 0$ to be lost (since they are not in trapable states). We then remove specific spin components by decreasing β_z . Note that when β_z is reduced, Eq. (1) shows that all atoms with m_F such that $-g_F \mu_B m_F \beta_z < mg$ will be overpowered by gravity and lost. Therefore, we lower β_z until only atoms in the $m_F = 6$ stretched state remain (Fig. 4).

The purification scheme must be calibrated to determine the coil current at which all $m_F < 6$ spin states are ejected. We perform this measurement by ramping the magnitude of the gradient down to a low value $\beta_{\min}$, waiting for

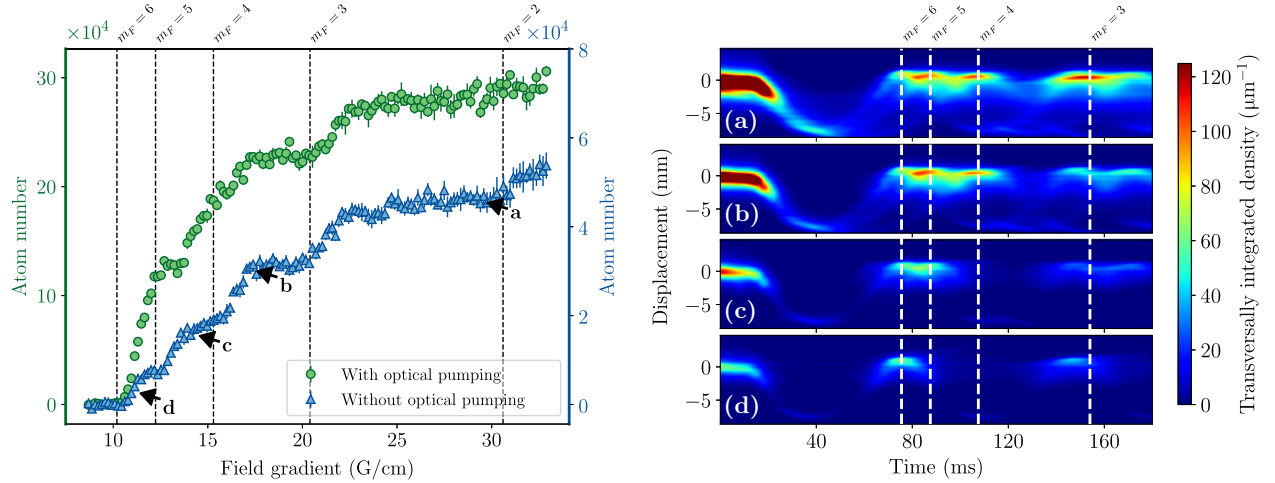


FIG. 4. Left: Atom number as a function of the field gradient magnitude along the direction of gravity. Green data (left y-axis) was taken with optical pumping; blue data (right y-axis) was taken without optical pumping. The step-like features [30] occur when the force of gravity is equal to the confining force of the gradient for a given spin component. The atom number in the polarized component ($m_F = 6$) is 1.3×10^5 (6.8×10^3) with (without) optical pumping, so optical pumping boosts polarized atom number by a factor of 19. The annotations (a) through (d) indicate the points at which we measured the four plots [also labeled (a) through (d)] in the right panel. Right: In (a), several oscillation frequencies are apparent from the $m_F = 3, 4, 5, 6$ spin components. In (d), only one oscillation frequency remains, indicating a spin polarized gas in the $m_F = 6$ state. The figure numbers (a) through (d) correspond to the measurement values (both field gradient and atom number) indicated in the left panel. The color bar represents the atomic density integrated along the x and y directions.

untrappable spin components to drop away, and then ramping back up for strong confinement [23]. Then we trigger a sudden shift of the quadrupole trap center by pulsing on a bias field in the z direction. The shift causes the atoms to oscillate with a frequency related to the trap depth, which is proportional to m_F . With this frequency, we can identify different spin components from their oscillation frequencies (Fig. 4). By varying $\beta_{\min}$, we can identify regimes where different spin components are present. The oscillations are well described by a known classical model [23,39].

This quadrupole trap polarization scheme is lossy since it involves the ejection of many spin components. To mitigate this loss, we add a stage of optical pumping on the $|5P_{3/2}, F=6\rangle \rightarrow |5D_{5/2}, F=6\rangle$ transition with a σ^+ -polarized laser [Fig. 1(b)] before the gradient is ramped. During this pumping stage, we apply a -16 G bias field to define the quantization axis. We find that the application of the spin polarization laser increases the polarized atom number by a factor of 19 (Fig. 4, left).

B. $5P_{1/2}$ state

The g -factor corresponding to $|5P_{1/2}, F=4\rangle$ is five times smaller in magnitude than that of $|5P_{3/2}, F=6\rangle$. Due to this weaker trap depth, our system is not currently capable of spin polarizing $|5P_{1/2}, F=4\rangle$ using the quadrupole trap method employed for the $5P_{3/2}$ state.

Therefore, we perform the following spin polarization sequence [23]. First we polarize the laser cooled atoms using $|5P_{3/2}, F=6\rangle \rightarrow |5D_{5/2}, F=6\rangle$, and then we hold them in the quadrupole trap to remove residual $m_F \leq 0$ spin components. We then apply six lasers. The first of these lasers has a 451 nm wavelength and

drives $|5P_{3/2}, F=6\rangle \rightarrow |6S_{1/2}, F=5\rangle$ to remove atoms from the metastable state. The second laser (at 410 nm and σ^+ polarization) drives $|5P_{1/2}, F=4\rangle \rightarrow |6S_{1/2}, F=4\rangle$, thereby polarizing atoms into $|5P_{1/2}, F=4, m_F=4\rangle$. The third laser (at 451 nm) drives $|5P_{3/2}, F=3\rangle \rightarrow |6S_{1/2}, F=4\rangle$ to control leaks in the 410 nm spin polarizing transition. The remaining lasers are repumpers used in laser cooling, with two at 451 nm driving $|5P_{3/2}, F=4, 5\rangle \rightarrow |6S_{1/2}, F=5\rangle$ and one at 410 nm driving $|5P_{1/2}, F=5\rangle \rightarrow |6S_{1/2}, F=5\rangle$.

The weaker quadrupole trap for $5P_{1/2}$ means we cannot determine the hyperfine sublevel populations with the quenching scheme used in $5P_{3/2}$. Therefore, we infer these populations with microwave spectroscopy of the 11.410 GHz ground state hyperfine transition $|5P_{1/2}, F=4\rangle \rightarrow |5P_{1/2}, F=5\rangle$. To identify which m_F states are populated, we apply a 2.4 G magnetic field to fully split the microwave resonances (Fig. 5). We evaluate different stages of the spin polarization sequence by pumping all atoms into the ground state and performing microwave spectroscopy to investigate the spin purity (Fig. 5). When this sequence is complete, we infer from the spectrum that the atoms are polarized at the 90% level [23].

IV. TRAPPING IN AN OPTICAL LATTICE

With the achievement of low temperatures and spin polarization, we turn our attention to trapping in a one-dimensional (1D) optical lattice. This trapping potential has been used successfully in quantum simulations [4] and precision measurements [6,7,40]. We generate the lattice with a 1064 nm laser since there is a wide variety of high-powered, spectrally narrow sources available

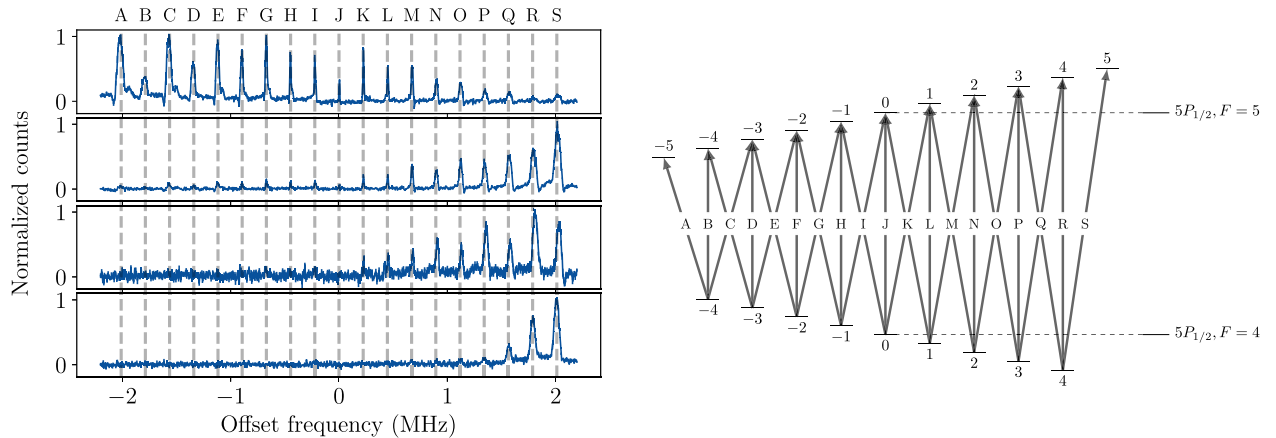


FIG. 5. Left: Microwave spectra at different stages of the $5P_{1/2}$ spin polarization sequence. The top plot shows the microwave spectrum before spin polarization is applied, indicating many spin components. The second plot down shows the $5P_{1/2}$ population after spin polarization using the $|5P_{3/2}, F=6\rangle \rightarrow |5D_{5/2}, F=6\rangle$ transition. The third plot down shows the effect of holding atoms in the quadrupole trap to remove spin components with $m_F \leq 0$. The bottom plot shows the microwave spectrum after spin polarization with a σ^+ -polarized 410 nm laser. The three prominent peaks are expected when the atoms are polarized in the target state, and they imply quantum state purity at the 90% level. Right: The transitions corresponding to those labeled in the observed microwave spectra.

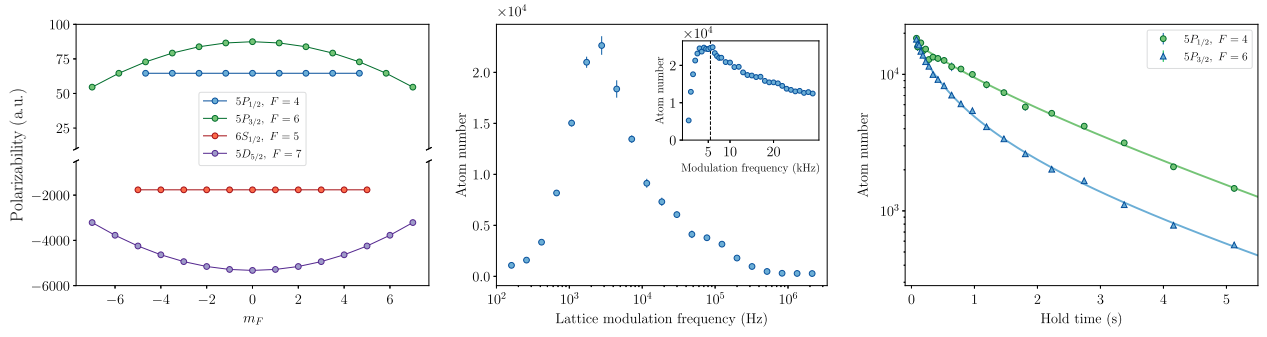


FIG. 6. Optical trapping of indium in an optical lattice. Left: The dynamic polarizability of states relevant to loading indium into a lattice. The calculation is for a 1064 nm laser wavelength. The ground state $|5P_{1/2}, F=4\rangle$ and metastable state $|5P_{3/2}, F=6\rangle$ have positive polarizabilities while the repumping state $|6S_{1/2}, F=5\rangle$ and the cooling state $|5D_{5/2}, F=7\rangle$ have large and negative polarizabilities, causing inefficient trap loading. Middle: Loaded atom number vs intensity modulation frequency. The inset shows the optimum modulation frequency of 5.5 kHz. Right: Atom number vs lattice hold time for different atomic states. A substantial two-body loss feature is apparent for $|5P_{3/2}, F=6\rangle$.

at this wavelength. To confirm good experimental performance at 1064 nm, we calculate the indium polarizability using experimental atomic transition data [41] when it is available and theoretical data [42,43] when it is not.

Considering the case where the optical trap is linearly polarized along the quantization axis, we determine the hyperfine ground state polarizability at 1064 nm to be 65 a.u. (Fig. 6) [23]. This value is small compared to trap wavelength polarizabilities of alkali metals, but it is still amenable to optical trapping with commercial laser sources. We also find that the $|5P_{3/2}, F=6\rangle$ lower-energy cooling state polarizability is similar in magnitude to that of the ground state, and it has a substantial tensor polarizability term, which imparts a non-negligible m_F dependence to the trap depth. For the $|5D_{5/2}, F=7\rangle$ cooling state and the $|6S_{1/2}, F=5\rangle$ repumping state, the polarizability is large in magnitude and negative, resulting in large Stark shifts and anti-trapping at 1064 nm.

These effects cause inefficient trap loading, since the loading phase typically involves overlap between the laser cooling and optical trapping stages of an experimental sequence. To mitigate this inefficiency, trap intensity modulation has been successful [44–47]. In this approach, one rapidly switches the trap intensity off and on, while the cooling light is switched 180° out of phase with the trap [23]. Previous work observed that loading is most efficient when switching frequencies are greater than the trap frequencies [44–47].

Using this modulation technique, we find that the optimal switching frequency for lattice loading is 5.5 kHz (Fig. 6). A lattice potential model accounting for retro-reflection mismatch predicts trap frequencies of 1.9 kHz (247 kHz) for the radial (axial) directions [23]. The switching frequency is well above the radial frequency but considerably less than the axial frequency. We note that while similar anti-trapping concerns arise in tweezer arrays, additional loading challenges beyond

intensity modulation would also be present in such a system.

Loss mechanisms present in optically trapped gases include heating from off-resonant trap light scattering or inelastic collisions [48,49]. To ensure that the atomic population is stable in the trap, we measure the in-trap atom number loss. Fitting this data to a model that contains both one- and two-body loss mechanisms [21], we observe a one-body trap lifetime of 2.7(2) s in the hyperfine ground state. For $|5P_{3/2}, F=6\rangle$, the one-body lifetime is 3.0(1) s, and substantial two-body loss is apparent. Metastable state two-body loss in an optical trap is often caused by state-changing collisions [49,50]. More details on these decay rates and fits can be found within the Supplemental Material [23].

V. CONCLUSION

With the realization of a 15 μ K temperature, quantum state purity at the 90% level, and stable optical lattice trapping, indium is now capable of optically trapped quantum science experiments. Both the $5P_{1/2}$ ground state and $5P_{3/2}$ metastable state can be used in future quantum science experiments. Potential experiments involve utilizing the $5P_{1/2} \rightarrow 5P_{3/2}$ indium clock transition, trapping in tweezers for materials simulations and quantum information [51], evaporative cooling to a novel spinor BEC, and more. Additionally, synthetic spin-orbit coupling without heating is achievable when $L > 0$ [52], suggesting that triel elements could support spin-orbit-coupled spinor gases [53,54].

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