

Isotope-agnostic motional ground-state cooling of neutral Yb atoms

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Efficient high-fidelity ground-state cooling of motional degrees of freedom is crucial for applications in quantum simulation, computing, and metrology. Here, we demonstrate direct ground-state cooling of fermionic ^{171}Yb and bosonic ^{174}Yb atoms in two- and three-dimensional magic-wavelength optical lattices on the ultranarrow clock transition. Its high spectral resolution offers the potential for reaching extremely low temperatures. To ensure efficient cooling, we develop a chirped sideband cooling scheme, where we sweep the clock-laser frequency to mitigate the effects of spatial trap inhomogeneities. We further generalize the theoretical description of sideband spectra to higher-dimensional lattices for precise thermometry. We achieve 2D ground-state fractions of 97% for ^{171}Yb with an average motional occupation of $\bar{n} \simeq 0.015$ and provide a direct comparison with ^{174}Yb , reaching similar cooling performance. Applying the same scheme in 3D results in $\bar{n} \simeq 0.15$ limited by layer-to-layer inhomogeneities in the vertical direction. These results demonstrate efficient motional ground-state cooling in optical lattices, especially for bosonic alkaline-earth(-like) atoms, where other methods are not applicable, opening the door to novel protocols for quantum science applications with neutral atoms.

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Neutral atoms play a central role in quantum science, from quantum simulation [1,2] to computation [3,4] and metrology [5–10]. To achieve optimal performance, ground-state cooling is essential [7,11–13]. Although experimental protocols based on spilling or removal of motional excited states have been developed [5,14–16], fast low-loss cooling to the motional ground state remains a significant challenge. Alkaline-earth(-like) atoms (AELA) are particularly promising for quantum applications given their favorable internal level structure. While subrecoil cooling techniques, such as Raman-sideband cooling, have proven to be effective [17–19], they can only be employed for the fermionic isotopes with nuclear spin $I > 0$, effectively excluding bosonic AELA.

Direct resolved sideband cooling has been demonstrated for Sr atoms on the $^1S_0 \leftrightarrow ^3P_1$ transition, which features a narrow, few-kilohertz linewidth combining high-spectral resolution with large scattering rates [20,21]. In Yb, the equivalent transition is rather broad ($2\pi \times 183$ kHz) and direct sideband cooling is instead realized on the ultranarrow optical clock transition [Fig. 1(a)]. 1D clock sideband cooling (CSC) is a standard technique in fermionic optical lattice clocks to reach record-low temperatures [22–24]. Here, we extend CSC to higher-dimensional 2D and 3D lattices and specifically demonstrate its applicability to bosonic ^{174}Yb . Moreover, we

extend the theoretical model of sideband spectroscopy beyond standard 1D lattices [25] by incorporating potential inhomogeneities, which is essential for benchmarking the cooling performance of the chirped CSC scheme. Our results enable applications in quantum science with optical tweezer arrays and lattices, which require a high absolute ground-state fraction.

All experiments start by loading a laser-cooled cloud of Yb atoms from a magneto-optical trap on the $^1S_0 \leftrightarrow ^3P_1$ transition into a clock-magic optical lattice at $\lambda = 759$ nm [26], formed by two retro-reflected laser beams along x and y and a vertical interfering lattice with $2.2\ \mu\text{m}$ spacing [Fig. 1(b)]. To isolate atoms in the crossing region of the lattices, we first load the atoms into a deep 3D lattice, then turn off the horizontal ones while increasing the vertical confinement before ramping the lattices to the final trap configuration. To perform sideband cooling, we employ three independent clock-laser beams at $\lambda_c = 578$ nm, approximately aligned with each lattice axis, to drive the red sideband connecting $|^1S_0, n\rangle \rightarrow |^3P_0, n-1\rangle$. Resonant repumping is realized on the $^3P_0 \leftrightarrow ^3D_1$ transition at 1388 nm, which after cascaded spontaneous decay via the $^3P_1$ state returns to $^1S_0$, ideally preserving the motional quantum number. A small fraction of atoms (2.5%) decays to $^3P_2$, which is antitrapped and results in atom loss. We opt to use pulsed rather than continuous cooling which avoids differential light shifts on the clock transition due to the resonant repumper. Finally, we detect the atoms via fluorescence imaging with molasses cooling on the $^1S_0 \leftrightarrow ^3P_1$ transition in a deep 3D lattice [27].

Loading a laser-cooled cloud of atoms directly into a higher-dimensional lattice configuration typically results in system sizes that are comparable with the waist of the lattice beams. While this is beneficial for fast loading schemes, the

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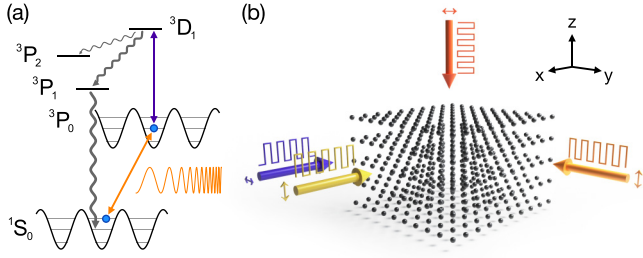


FIG. 1. Schematic of the clock-sideband cooling scheme. (a) Basic internal level structure with optical clock $^1S_0 \leftrightarrow ^3P_0$ and repumping $^3P_0 \leftrightarrow ^3D_1$ transition. Clock-sideband transitions are driven by multiple pulses while sweeping the frequency. The wavy arrows indicate spontaneous decay paths. (b) Illustration of the setup: 3D optical lattice with three independent pulsed clock-laser beams (yellow, orange, and red) and one repumping beam (purple).

atoms experience inhomogeneous trap frequencies challenging efficient cooling. This effect is notably more pronounced than in 1D lattices, as discussed below, and renders cooling at a single, constant sideband frequency ineffective even in magic trapping potentials [Fig. 2(a)], as used in this work. To overcome this challenge, we employ a chirped CSC scheme, where the frequency of the sideband cooling beam is slowly swept following a linear frequency ramp during the pulsed cooling sequence introduced above. Similar schemes have been developed previously for nonmagic trapping potentials [28,29].

We start by demonstrating 2D chirped CSC of fermionic ^{171}Yb atoms in a deep 2D horizontal lattice with depth $V_x = V_y \simeq 300E_{\text{rec}}$ and Lamb-Dicke parameter $\eta_x = \eta_y \simeq 0.22$, where $E_{\text{rec}} = \hbar^2/(2m\lambda^2)$ is the recoil energy, $\eta_i = \sqrt{\hbar\pi/(m\omega_i\lambda_c^2)}$, ω_i is the harmonic trap frequency, $\hbar$ is Planck's constant, and m is the mass of Yb. CSC is applied along the two horizontal axes using a calibrated carrier Rabi frequency of $\Omega/(2\pi) = 3.7\text{ kHz}$. We emphasize that for ^{171}Yb much higher clock Rabi frequencies could be realized, but we employ this modest strength to facilitate direct comparison to cooling of bosonic ^{174}Yb , where a magnetic field is required to induce a coupling between the two states [30]. We find robust ground-state cooling for pulse durations of $500\text{ }\mu\text{s}$, which are interleaved with $250\text{ }\mu\text{s}$ -long repumping pulses. To address all atoms efficiently, we apply a linear ramp of the clock-laser detuning from -40 to -72 kHz . Each sweep consists of 20 alternating cooling and repumping pulses. To cool both axes, we further alternate between both directions. The combination of one sweep along each axis defines one complete “cooling cycle.”

After loading the laser-cooled atoms into the lattice, the average occupation of excited states is $\bar{n}_{x,y} \approx 6$ [inset of Fig. 2(b)], measured using sideband spectroscopy on the clock transition with carrier Rabi frequency $\Omega'/(2\pi) = 1.1\text{ kHz}$ and 20 ms pulse duration. Repeating this spectroscopy after 15 cooling cycles, we obtain a 2D motional ground-state fraction of $\mathcal{F}_{2D} = 0.970^{+5}_{-2}$ [Fig. 2(b)] with nearly identical cooling performance along both axes reaching excited state populations with $\bar{n} \simeq 0.015$, where $\mathcal{F}_{2D} \approx (1 + \bar{n}_x)^{-1}(1 + \bar{n}_y)^{-1}$.

A quantitative analysis of the high-resolution clock sideband spectra relies on accurate modeling of the trap frequency

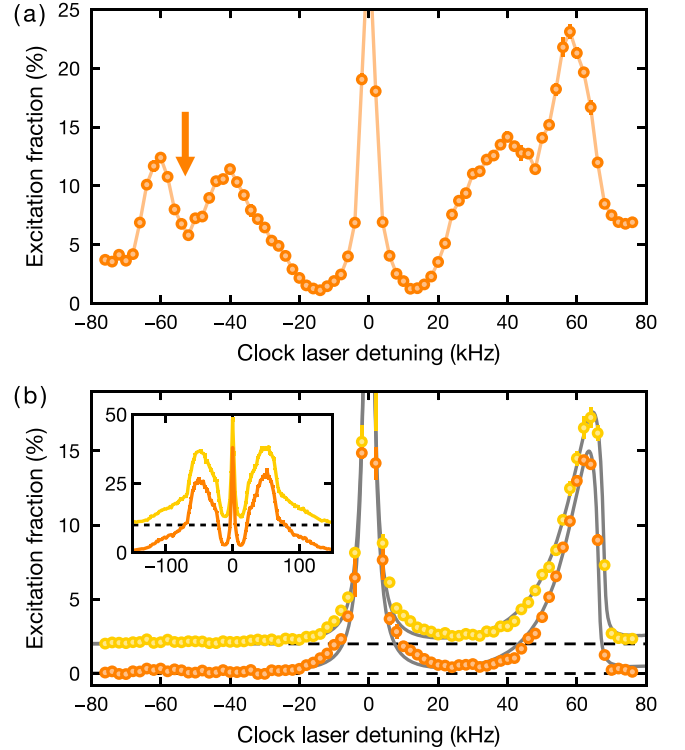


FIG. 2. Sideband cooling in a 2D lattice, illustrated for ^{171}Yb . (a) Inefficacy of cooling with constant clock-laser frequency. Spectroscopy along y reveals a nonthermal red sideband, showing a dip in the vicinity of the cooling frequency (indicated by the arrow). The solid line connects the data points and is a guide to the eye. In both panels, error bars represent the standard error over three repetitions and typically are smaller than the symbols [31]. (b) Sideband spectrum after chirped CSC. Spectra along x (yellow) and y (orange) are taken after 15 cooling cycles; the former is vertically offset (dashed lines indicate zero) for better visibility. The gray solid lines are fits with the model discussed in the main text, extracting $\bar{n}_x = 0.013^{+2}_{-4}$ and $\bar{n}_y = 0.018^{+2}_{-3}$; confidence intervals are evaluated with bootstrapping. Inset: Spectra of initial state before cooling.

inhomogeneities and thermal excitations. A rigorous mathematical derivation is presented in the Supplemental Material [31], which we briefly summarize here. For the coldest temperatures, the sideband spectrum $P(\tilde{\omega})$ consists of the carrier and the two first-order sidebands according to

$$P(\tilde{\omega}) = A_0 L_{\Gamma_0}(\tilde{\omega}) + A_1 L_{\Gamma_1}(\tilde{\omega}) * [\rho_{(0)}(\tilde{\omega}) + \rho_{(1)}(-\tilde{\omega} - \omega_{\text{rec}})], \quad (1)$$

where $A_{0,1}$ denote the amplitudes of the carrier and first-order sidebands, $\tilde{\omega}$ denotes the laser frequency detuning from the free-space clock resonance, $\hbar\omega_{\text{rec}} = E_{\text{rec}}$ is the lattice recoil energy and we explicitly introduce the kernel $\rho(\tilde{\omega})$, whose convolution with a Lorentzian L_Γ determines the shape of the sideband, where we allow the linewidth Γ to be different for the carrier (Γ_0) and the first-order sidebands (Γ_1); $\rho_{(n_0)}$ is a modified sideband kernel defined below, which accounts for the fact that the lowest n_0 motional states have no n_0 th order red sideband transitions.

We start by reviewing the result for 1D lattices, where atoms are strongly confined along x , but weakly confined

along y and z . Semiclassically, radial motion results in atoms sampling regions of the trapping potential where the longitudinal trap frequency ω_x is reduced. Hence, the sideband shape depends on the radial temperature T_r , resulting in a characteristic sideband given by [25,31]

$$\rho_{(n_0)}(\tilde{\omega}) = Z^{-1} \sum_{n=n_0} e^{-\frac{n\hbar\omega_x}{k_B T_r}} f_{1D}(\omega_x - \tilde{\omega} - \omega_{\text{rec}}(n+1)), \quad (2)$$

$$f_{1D}(s) = s e^{-\alpha s} \Theta(s), \quad (3)$$

where Z is the partition function, $\alpha = \hbar\omega_x/(\omega_{\text{rec}}k_B T_r)$, and $\Theta(s)$ is the Heaviside step function. Notably, ρ depends on the radial temperature through α but not the radial confinement or the waist of the lattice beam. The result is a sideband spectrum where the relative height of the red versus blue sidebands is determined by the longitudinal temperature T_x , while the width of the sideband encodes the radial temperature T_r .

In a 2D lattice, the atoms are confined in an array of 1D tubes with strong confinement along x and y , but weak confinement along z . Similar to 1D, the atoms sample regions of the weakly confined z axis, resulting in a dependence on T_z but not T_y , where the atoms are strongly confined. This leads to a modified sideband kernel with

$$f_{2D}(s) = e^{-\beta s} \Theta(s), \quad (4)$$

and $\beta = \hbar\omega_x(1 + \omega_y^2/\omega_x^2)/(\omega_{\text{rec}}k_B T_z)$. Note that the linear prefactor s , which accounted for the radial symmetry in 1D, disappeared, which results in a more sharply peaked sideband. This result holds for large homogeneous 2D lattices. However, if the trap frequency varies between tubes over the extent of the atomic cloud, this expression needs to be further averaged over spatial inhomogeneities and the shape of the sideband spectra explicitly depends on the relative size of the atomic cloud. In this work, the waist of the lattice laser beams is $w_0 \simeq 40 \mu\text{m}$ and the size of the atomic cloud is $\sigma \simeq 12 \mu\text{m}$ (defined as the Gaussian standard deviation); hence, inhomogeneous broadening of the sideband spectra is significant. While the relative height of the red and blue sideband still reveals information about the horizontal temperature T_x or T_y , the width of the sideband now depends on the vertical temperature T_z and the inhomogeneous broadening. This is in stark contrast to 1D lattices, where layer-to-layer variations are set by the Rayleigh range and can typically be safely ignored.

In a 3D lattice, atoms are strongly confined along all axes and the atoms cannot sample regions with lower trap frequency. The new kernel is now given by the simple Dirac δ function $f_{3D}(s) = \delta(s)$. In this case, the shape of the sideband is dominated by spatial inhomogeneities. Assuming an isotropic Gaussian population with standard deviation σ and radially symmetric lattice beams with waist w_0 , the site-averaged sideband kernel is given by Eq. (2) but with $f_{1D}(s)$ replaced by

$$\overline{f_{3D}}(s) = \frac{\gamma}{\omega_x} \left(1 - \frac{s}{\omega_x}\right)^{\gamma-1} \Theta(\omega_x - s) \Theta(s), \quad (5)$$

where $\gamma = w_0^2/(2\sigma^2)$. Thus, the sideband now acquires a polynomially peaked shape, where the width encodes information about the spatial distribution.

Given the expressions in Eqs. (1), (2), and (4), we extract temperatures from the measured sideband spectra [Fig. 2(b)],

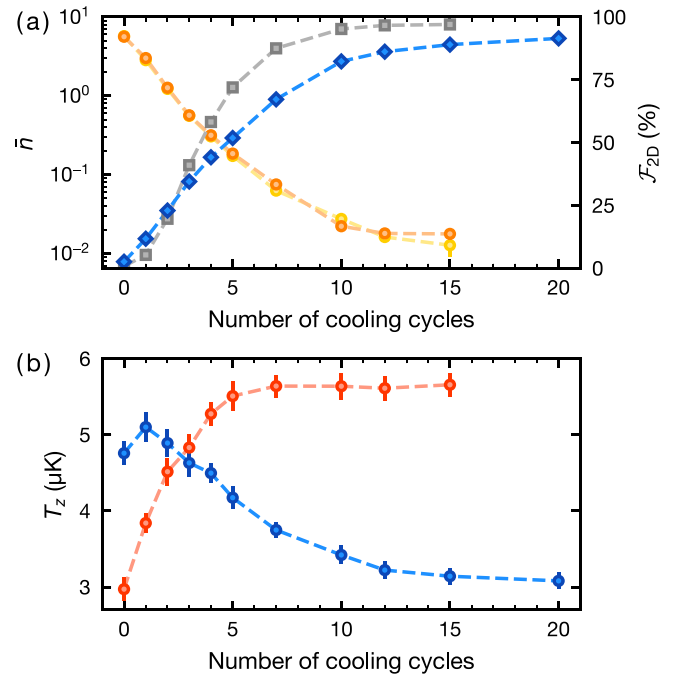


FIG. 3. Comparison of cooling performance of 2D CSC for ^{171}Yb and ^{174}Yb . (a) Mean motional occupation number $\bar{n}$ (left axis) vs number of cooling cycles for ^{171}Yb , measured with sideband spectroscopy along x (yellow) and y (orange). The reduction of $\bar{n}$ coincides with an increase of the 2D motional ground-state fraction $\mathcal{F}_{2D}$ (right axis), reaching 0.970^{+5}_{-5} after 15 cooling cycles for ^{171}Yb (gray squares) and $\mathcal{F}_{2D} = 0.915^{+5}_{-5}$ after 20 cooling cycles for ^{174}Yb (blue diamonds). Error bars from bootstrapping are all smaller than the data points. (b) Time-of-flight thermometry of the out-of-plane, vertical temperature for ^{171}Yb (red) and ^{174}Yb (blue). Error bars indicate the uncertainty in fitting the time-of-flight expansion.

where the lattice depth and amplitudes $A_{0,1}$ are additional free fit parameters. We monitor the cooling performance as a function of applied cooling cycles along both axes [Fig. 3(a)]. Note that after direct lattice loading, atoms approximately equally populate all $\simeq 11$ bands of the lattice—an extreme regime not accurately captured by our model, which otherwise matches the measured spectra well once the temperature is lower.

Since CSC does not require any internal structure, it is applicable to all isotopes. To demonstrate this, we implement chirped CSC of bosonic ^{174}Yb in a 2D lattice with equal depth and identical cooling sequence. For ^{174}Yb , the clock transition is magnetically induced using a 400 G field [30] resulting in the same clock Rabi frequencies for cooling and spectroscopy as for ^{171}Yb . Nonetheless, we find that cooling proceeds slower and 20 cooling cycles are needed to reach similar temperatures [Fig. 3(a)] with a ground-state fraction of $\mathcal{F}_{2D} = 0.915^{+5}_{-5}$ ($\bar{n}_x = 0.044^{+4}_{-2}$ and $\bar{n}_y = 0.047^{+4}_{-5}$). We attribute the observed difference in the cooling performance to the different scattering properties of the two isotopes: ^{171}Yb is essentially noninteracting, while bosonic ^{174}Yb has a scattering length of $105 a_0$ [32], where a_0 is the Bohr radius. This leads to significant redistribution of thermal energy between the vertical and horizontal modes, counteracting cooling along the lattice axes. This is further confirmed by a reduction of the vertical temperature, as observed via

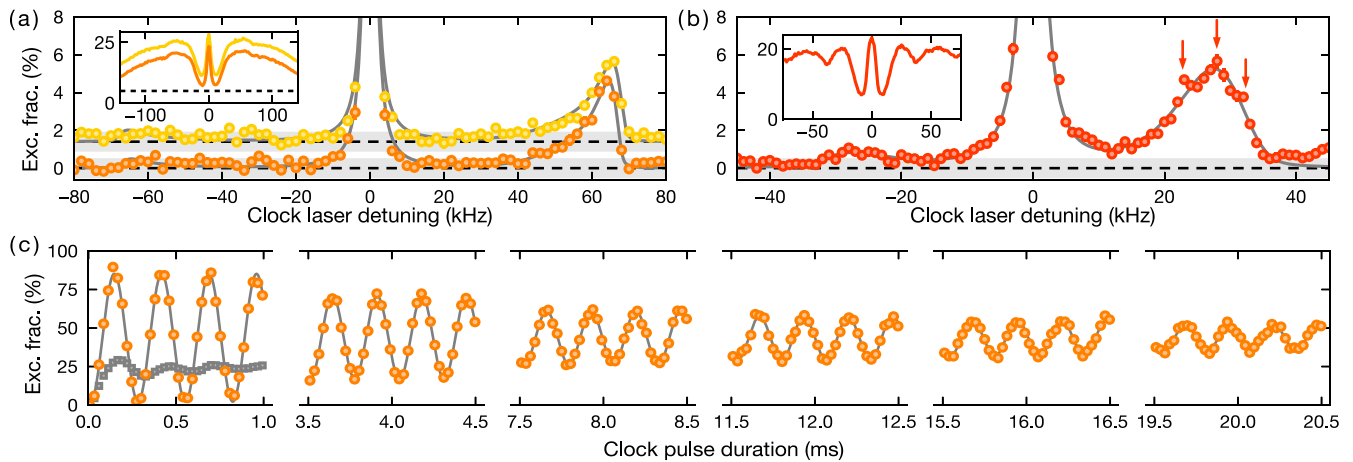


FIG. 4. 3D clock cooling of ^{171}Yb . Sideband spectra of the horizontal directions (a) and vertical direction (b), after 3D cooling. Insets show spectra prior to cooling. Gray shaded area indicates standard deviation of background noise present in imaging without any atoms present. The solid line is a fit where the sideband has a generic asymmetric lineshape, see the text for details. From the sideband asymmetry, we extract $(\bar{n}_x, \bar{n}_y, \bar{n}_z) \simeq (0.17, 0.12, 0.16)$, corresponding to a 3D ground-state fraction of 66%. Data are averaged over ten repetitions [three for panel (c)], their standard error is typically smaller than the point. (b) The vertical spectrum shows resolvable peaks in the blue sideband, indicated by arrows, corresponding to the different layers. (c) Rabi oscillations prior to cooling (gray squares) vs after 3D cooling (orange circles), driven by one of the horizontal beams. The former rapidly dephases due to the thermal mixture of Rabi frequencies, the latter shows persistent oscillation. The solid gray line is a separate fit for each segment, the contrast decays approximately exponentially with $1/e$ time of 11.4(2) ms.

time-of-flight measurements—an effect that is absent for the fermionic isotope [Fig. 3(b)]. We further observe nonthermal sideband spectra at intermediate temperatures in the case of ^{171}Yb , due to the absence of rethermalization [31]. Conversely, rethermalization offers an alternative route for cooling ^{174}Yb : While CSC directly cools only one axis, scattering mediates indirect cooling of the others. We demonstrate this technique in Ref. [31], but note that its duration is comparable to conventional evaporative cooling.

The efficiency of our chirped CSC is mainly limited by repumping via the $^3\text{D}_1$ state, which induces heating due to nonmagic trapping conditions and atom loss via leakage to the antitrapped $^3\text{P}_2$ state [Fig. 1(a)]. Both can be mitigated in the future through a coherent two-photon repumping scheme that couples $^3\text{P}_0$ and $^3\text{P}_1$. This avoids population in $^3\text{P}_2$ and spontaneous decay from $^3\text{P}_1$ to $^1\text{S}_0$ can be made near-magic in the 759 nm lattice. We characterize recoil heating to $\simeq 0.08$ motional quanta per repumping cycle and measure total atom loss of about 30% for the coldest 2D sideband spectra presented above. The latter is consistent with an independent characterization that also accounts for loss due to inelastic collisions [31]. We further observe technical heating induced by the lattices of $\lesssim 0.1$ quanta/s.

Cooling in 3D is demonstrated with ^{171}Yb as it does not require large magnetic fields [30]. However, we expect similar cooling performance for both isotopes, since rethermalization plays only a minor role in 3D due to low site occupations. To implement 3D CSC, we add a $\simeq 2800E_{\text{rec}}$ deep vertical lattice (Lamb-Dicke parameter $\eta_z \simeq 0.31$) to the $300E_{\text{rec}}$ deep horizontal lattices and interleave vertical cooling sweeps. The horizontal chirped CSC remains unchanged and the carrier Rabi frequency for the vertical direction is $\Omega/(2\pi) = 4.6$ kHz for cooling and $\Omega'/(2\pi) = 1.3$ kHz for spectroscopy. Specifically, each cycle now consists of four frequency sweeps: one for each horizontal axis and two for the vertical direction. The

latter contains 30 cooling pulses, each 150 μs in duration. The cooling frequency is swept from -15 to -33 kHz.

We record sideband spectra for each direction after 15 cooling cycles (Fig. 4). In the horizontal directions, we find that the shape of the sideband differs from the 2D case (Fig. 2). Accurately capturing this shape theoretically requires precise knowledge of the relative populations of the vertical-lattice layers, which we cannot measure independently. Instead, we employ an asymmetric Voigt profile, which captures the blue sideband shape well. Quantitative analysis of the red sideband is further complicated by reduced signal-to-noise and a potentially nonthermal population distribution. We extract $\bar{n}$ from the sideband asymmetry and find $\bar{n}_x \simeq 0.17$ and $\bar{n}_y \simeq 0.12$, higher than in 2D. We attribute this to a hotter initial ensemble [insets of Figs. 4(a) and 4(b)] and the additional recoil heating from cooling along the vertical direction.

The vertical cooling also effectively removes motional excitations along z [Fig. 4(b)]. The cold sideband spectrum reveals an additional structure, which we ascribe to the individual vertical layers. Due to tightly focused beams, the vertical lattice consists of only five trapped layers and their trap frequencies are sufficiently distinct that multiple separate peaks can be observed within the blue sideband (indicated by arrows). We note that this effect necessitates chirped CSC even in a 1D geometry. While we find moderate success in modeling this sideband structure during 1D spectroscopy (Fig. S7 in the Supplemental Material [31]), here we extract $\bar{n}_z \simeq 0.16$ using the same procedure described above for simplicity. This yields a 3D ground-state fraction of $\mathcal{F}_{3\text{D}} \approx 66\%$, which is remarkable considering the high initial temperature. Atom losses during cooling are severe ($\simeq 90\%$), but can be mitigated as discussed above or by preparing lower initial-state temperatures. Nonetheless, comparing different number of cooling cycles suggests that continued cooling beyond 15 cycles would further increase $\mathcal{F}_{3\text{D}}$. We anticipate that

removing the vertical trap frequency inhomogeneity, either by populating only a single layer or utilizing a retroreflected lattice, would result in 3D CSC performance equivalent to that in 2D.

We illustrate the effect of 3D cooling for quantum applications by comparing Rabi oscillations on the clock transition (after optical pumping) before and after cooling [Fig. 4(c)]. While contrast is rapidly lost due to thermal dephasing for the hot ensemble, the CSC-cooled atoms show long-lived Rabi oscillations with a fitted $1/e$ contrast decay time of 11.4(2) ms. This is limited by spatial inhomogeneity of the Rabi frequency across the cloud due to the finite size of the clock beam. For the lowest $\bar{n}$ of 0.013 achieved here, thermal dephasing results in a calculated clock π -pulse infidelity of 8×10^{-5} . Sensitivity to spatial inhomogeneity of the Rabi frequency is strongly reduced in 1D, where we find coherence times up to $\simeq 30$ ms after rethermalization cooling of ^{174}Yb [31].

In conclusion, we have demonstrated high-fidelity clock-sideband cooling applicable to all AELA. The ground-state fraction is on par with other methods [18,33,34] and can be further improved as outlined above. This offers a realistic route for fast all-optical cooling without evaporation [35–39], which is particularly exciting for bosonic AELA, where conventional subrecoil laser cooling methods fail. Fast assembly and ground-state initialization is crucial for quantum technologies. Reducing the dead time between sequential interrogations suppresses limitations in optical clock performance and increased data rates enhance measurement precision for analog quantum simulation. While the first fast-assembly techniques have been developed for ^{88}Sr atoms [15], CSC extends their applicability to a much broader range of AELA. Moreover, the ultralow mean motional excitations reported in this work promise high-fidelity quantum simulation of itinerant particles, analog quantum simulation of XY mod-

els with Rydberg atom arrays [40] and quantum computing protocols based on optical clock transitions [7,12,13]. Further, our work greatly reduces state-preparation complexity for double-isotope experiments, which are promising for quantum computing [41], metrology [42], atom interferometers [43,44], and high-precision spectroscopy for searches of new physics [45,46].

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Data availability. The data that support the findings of this article are openly available [47].

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