Quantum metrology by one-minute interrogation of a coherent atomic spatial superposition

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Abstract: In quantum metrology and quantum information processing, a coherent nonclassical state must be manipulated before unwanted interactions with the environment lead to decoherence. In atom interferometry, the nonclassical state is a spatial superposition, where each atom coexists in multiple locations at once as a collection of phase-coherent partial wavepackets. These states enable precise measurements in fundamental physics and inertial sensing. However, atom interferometers usually use atomic fountains, where the available free-fall time sets a hard time limit on the interrogation of the quantum state. Here, we realize atom interferometry with a spatial superposition state held by an optical lattice for as long as 1 minute, which is more than 25 times longer than any atomic fountain interferometer. We additionally present a theoretical and experimental toolbox to explore limits in coherence due to collective dephasing of the atomic ensemble. These gains in coherence may enable gravimetry measurements, searches for fifth forces, or fundamental probes into the non-classical nature of gravity.

One-Sentence Summary: Atomic matter-waves with enhanced coherence can now exist in two places at once for as long as one minute.

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Nonclassical states whose coherence can be maintained for tens of seconds or even minutes are at the forefront of quantum science. For example, optical lattice clocks with atoms trapped for 15 seconds have enabled 2-3 orders of magnitude sensitivity gains (1, 2) relative to atomic fountain clocks. In atom interferometry, achieving minute-scale coherence times would be instrumental for portable and vibration insensitive gravimetry (3–5) and many applications that are currently out of reach, such as testing the quantum nature of gravity (6, 7), or increasingly precise searches of dark energy candidates (8, 9). However, atomic fountains have been limited to 2.3 seconds by the free-fall times available in 10-meter fountains (10). Since the height required scales quadratically with time, experiments with fountains measuring hundreds of meters (11–14), sounding rockets (15, 16), zero-gravity planes (17), drop towers (18), and in microgravity on the International Space Station (19, 20) aim for several seconds of interrogation time, but none are currently proposed to achieve minute-scale coherence.

Initial attempts to trap atoms in an optical lattice have suffered from dephasing in the trap, limiting coherence to 1 second (21–23). Recently, we used the mode of a Fabry-Perot cavity to strongly reduce optical lattice imperfections, extending measurement time to 20 seconds (24). However, the exact fundamental or technical limits remain unexplored, limiting achieved coherence.

Here, we elucidate these limits, achieving a coherence time of 60 seconds, the longest-lasting spatial superposition of any massive particles, 26 times longer than possible with atoms in free-fall (10). Compared to atomic fountains, the mm-scale trajectories in our experiment facilitate maintaining homogeneity of electric, magnetic, and gravitational fields at levels required for precision measurement (25). We experimentally investigate the sources of decoherence, identify key influences, and develop a framework to describe decoherence in the optical lattice.

A coherent quantum spatial superposition state held by an optical lattice for 1 minute

The experiment sequence starts by preparing a sample of cold Cesium (Cs-133) atoms (Figure 1A) in the magnetically insensitive \( m_F = 0 \) state of the ground hyperfine manifold of the Cesium atom (see Supplementary Materials). The atoms are launched upwards by a moving optical lattice (Figure 1B) and their axial temperature is further reduced by a Fourier-limited Raman \( \pi \)-pulse to 80 nK. In free fall, counterpropagating laser pulses at 852 nm wavelength stimulate two-photon Raman transitions between the \( F = 3 \) and \( F = 4 \) hyperfine ground states (26). These pulses’ intensities and durations are tuned to transfer atoms with a 50% probability (\( \pi/2 \) pulses). This leads to a coherent beam splitter that separates the atomic matter-wave into two partial wavepackets that move with a differential velocity of \( 2v_c = \hbar k_{\text{eff}}/m_{\text{Cs}} = 7 \) mm/s given by the momentum of the 852 nm photons, where \( k_{\text{eff}} \) is the laser field wavevector and \( m_{\text{Cs}} \) is the Cs atom mass.
Applying a pair of $\pi/2$ pulses, separated by a time $T$, splits the matter-waves four-fold. We select two wavepackets that are moving at a constant separation $\Delta z = 2vT$, while sharing the same internal quantum state and external momentum. When they reach the apex, they are loaded into the high-intensity regions of a far-detuned optical lattice with a spatial periodicity of $\lambda_{\text{latt}}/2$, where $\lambda_{\text{latt}} = 943 \text{ nm}$ is the wavelength of the lattice laser. After a hold time $\tau$, they are adiabatically unloaded and recombined using a final pair of $\pi/2$ pulses.

Due to the resulting interference, the phase difference $\Delta \phi = \phi_t - \phi_b$ accumulated between the top and bottom wavepackets determines the probabilities $P_{3,4} = [1 \pm C \cos(\Delta \phi)]/2$ of detecting an atom in the output ports corresponding to $F=3$ and $F=4$, where $C$ is the fringe contrast. The maximum contrast is $C = 0.5$ because only two of the four interferometer outputs interfere. The atom numbers ($N_{3,4}$) in each port, which are proportional to $P_{3,4}$, are measured through fluorescence imaging on an electron-multiplied charge-coupled devices (EMCCD) camera. We extract the interferometer phase, $\Delta \phi$, from the measured population asymmetry, $A = \frac{N_3-N_4}{N_3+N_4} = C \cos(\Delta \phi)$. The primary contribution to interferometer phase is the propagation phase $\Delta \phi_{\text{grav}}$ (see Supplementary Materials for other contributions), which accumulates due to the gravitational potential difference $\Delta U_{\text{grav}} = m_{\text{Cs}}g\Delta z$ between the top and bottom interferometer arms during the lattice hold and is obtained by integrating the Lagrangian $\mathcal{L}$ over the classical trajectory (27),

$$\Delta \phi_{\text{grav}}^{\text{prop}} = \frac{1}{\hbar} \left( \int_{t=0}^{T} \mathcal{L}^t \, dt - \int_{t=0}^{T} \mathcal{L}^b \, dt \right) = \frac{1}{\hbar} \int_{t=0}^{T} \Delta U \, dt = \frac{m_{\text{Cs}}g\Delta z}{\hbar} \tau. \quad (1)$$
The experimental apparatus contains several upgrades that increase its performance over our previous result (24). Improved sample preparation and a more efficient moving-lattice launch cumulatively increased atom number 3-fold. Lower atomic sample temperature provided 1.4-fold higher contrast. A further detuned optical lattice laser (943 nm instead of 866 nm) reduced decoherence from single photon-scattering and allowed operation at smaller wavepacket separations, which more closely match the lattice structure. Improved stabilization of the intra-cavity lattice laser intensity increased the atomic lifetime to 14 seconds from 7 seconds. Imaging efficiency was improved through reduction of stray light using blackened radiation shields and the use of a higher gain and higher quantum efficiency EMCCD camera. Laser phase noise has also been reduced by using more stable oscillators, such that interferometer precision is within a factor of two from the standard quantum limit.

As a result of these improvements, we now observe up to 1 minute of coherent phase accumulation across the atomic spatial superposition state (Figure 2). This interferometer used a pulse separation $T = 0.267$ ms ($\Delta z = 1.9$ $\mu$m) and a peak trap depth of $U_0 = 7 E_r$, where $E_r = \frac{mCs^2}{2} = \hbar \cdot 2\pi \cdot 2.0663$ kHz is the Cs atom recoil energy.

![Figure 2. Interference fringes with up to one minute coherence. Oscillations in the asymmetry are shown as the interferometer phase varies proportionally to the hold time $\tau$. Each datapoint corresponds to the average of a few experiment cycles. The error bars correspond to 1σ standard error. Fringe offsets are removed.](image)

**Measured lattice decoherence**

We quantify interferometer coherence by extracting the fringe contrast, $C$, from a least-squares fit of the interferometer fringes with contrast, phase and fringe offset as free parameters. For hold times $\tau < 20$ s, contrast decays exponentially with the hold time, $\tau$: $C = C_0 \exp(-\tau/\tau_C)$ (Figure 3A), where $C_0$ is the interferometer contrast with no hold time ($C_0 = 0.5$ typically). At long hold times $\tau > 20$ s, however, we observe the contrast to be slightly larger than predicted from this exponential decay, consistent with our understanding of the experiment (see Supplementary Materials).

The decay time constant $\tau_C$ is measured to be inversely proportional to the atomic wavepacket separation, $\Delta z$, and the trap depth, $U_0$ (Figure 3B)

$$\frac{1}{\tau_C} = U_0 \Delta z / k.$$  (2)
Here, $\kappa = 110 \mu m \cdot s \cdot E_r$ is the measured global contrast decay constant. While this relation suggests that higher contrast can be achieved by decreasing the trap depth, holding the atoms against Earth’s gravitational field requires $U_0 > 4 E_r$ (experimentally measured) for trap lifetimes exceeding 10 s. We used a trap depth of $7 E_r$ above (Figure 2), sufficiently high to trap and detect a few hundred atoms per 60 second experiment cycle. The gravity limit could be overcome in microgravity (19), where the trap depth only needs to be larger than the atom sample kinetic energy to avoid atom loss.

Figure 3. Decoherence during optical lattice hold. (A) Contrast decays exponentially vs hold time $\tau$ with time constant $\tau_C$, $C = C_0 \exp[-\tau/\tau_C]$. (B) $\tau_C$ is inversely proportional to wavepacket separation, $\Delta z$, and trap depth, $U_0$: $1/\tau_C = U_0 \Delta z \kappa$. (C) The global contrast decay constant $\kappa$ increases when using atomic ensembles that are colder transversally. The dashed line shows $\kappa (T_\perp) = \kappa_0 * T_\perp^0 / T_\perp$. (D) Decrease of the contrast decay constant $\kappa$ with magnitude of applied tilt $\theta_{app}$. The line is a fit to equation $\kappa (\theta_{app}) = \kappa_0 / \sqrt{1 + (\theta_{app}/\theta_0)^2}$. All data points are shown with error bars corresponding to 1$\sigma$ standard error. The color bands correspond to 1$\sigma$ (68%) Gaussian confidence bands determined by the statistical uncertainty of a numerical simulation that estimates atomic ensemble dephasing in the presence of residual atomic motion and lattice tilt noise.

Improving the performance on Earth, however, requires understanding the physical mechanisms that limit the dephasing parameter, $\kappa$. Many factors were observed to not affect $\kappa$. For example, using higher-quality cavity mirrors (surface rms roughness < 1 Å) to further reduce holding potential distortions and locating the cavity waist near the atoms, so that the expansion of the laser beam does not change the lattice potential between the two interferometer arms, lattice laser imperfections (frequency noise, broadband emission, background scatter, imperfect cavity coupling), alignment of the lattice with gravity, atom density and axial temperature (which is much lower than the transversal temperature due to axial velocity selection), properties of the lattice laser...
beam (polarization, wavelength), symmetry of interferometry pulses and magnetic fields (see Supplementary Materials for details), did not change \( \kappa \). It thus initially appeared that the exponential contrast loss was very robust against experimental changes. It was much harder to identify parameters that do modify \( \kappa \).

First, \( \kappa \) is improved up to 3-fold when using higher order Laguerre-Gaussian (LG) modes for the optical lattice hold (Figure 3C). The radially symmetric LG10 and LG20 have full width at half maxima of the central intensity peak that are narrower than the fundamental LG00 Gaussian mode, 56\% and 43\% respectively. The low intensity “rings” of the higher-order modes are too weak to trap atoms and have poor overlap with the atom sample, so atoms only get trapped in the central peaks.

One possible explanation is that loading into higher-order cavity modes selects a subset of atoms with a lower temperature, and this might be responsible for the increased coherence. The selection occurs when the thinner lattice beam captures only atoms near the center of the atom cloud. After cooling, these atoms are measured with time-of-flight (TOF) spectroscopy to be coldest, likely due to variations in the intensity of cavity-derived Raman Sideband Cooling beams across the atom sample. In addition, in the time between the conclusion of laser cooling and lattice loading (38 ms), the atom sample expands, with the most energetic members moving away the fastest.

To determine whether the longer coherence is due to the thinner trap potential or lower transverse temperature, we have used the LG10 mode to hold the atomic sample only during state preparation. A TOF measurement after this lattice hold confirms that the LG10 mode selects an atom sample that is 1.8 times colder. The atoms are still confined in the same LG00 Gaussian mode during the interferometer sequence, so that there is no change to the interferometry trap potential. We observe an 1.8-fold increase in the contrast decay constant (Fig. Figure 3C).

We further confirm that coherence depends on sample temperature by “boiling off” the most energetic atoms. The lattice trap depth was set to \( U_0 = 14 E_r \), corresponding to axial trap frequency \( \omega = 2\pi \cdot 14 \text{ kHz} \). We amplitude-modulate the optical lattice during the initial 500 ms of hold with an amplitude of 10\% at a frequency that is twice the peak trap frequency, \( 2\omega = 2\pi \cdot 28 \text{ kHz} \). This leaves behind a sample with 0.7 times lower temperature, as measured through TOF. We observe that this reduces the number of remaining atoms 3-fold and leads to an increase in contrast (Figure 3C). These measurements suggest that the decoherence rate \( 1/\kappa \) is proportional to the residual radial motion of the atoms in the trap, quantified by sample temperature \( T_\perp \).

Finally, we observe that \( \kappa \) depends on oscillatory tilts with respect to the vertical \( \theta(t) \). We modulate the experiment tilt (which is floating on minus-K vibration isolators) along the \(-\hat{x}\) axis using a voice coil sinusoidally driven (typically at \( 2\pi \cdot 600 \text{ Hz} \)). The resulting tilt amplitude \( \theta_{\text{app}} \) was quantified by measuring the position of the cavity transmitted laser beam on a quadrant photodetector. Fringes were measured for varying amplitudes of applied tilt (Figure 3D). The resulting \( \kappa \) was fitted to a model \( \kappa(\theta_{\text{app}}) = \kappa_0 / \sqrt{1 + (\theta_{\text{app}}/\theta_0)^2} \), where \( \theta_{\text{app}} \) is the applied tilt and the fitted \( \theta_0 = 120 \mu\text{rad} \) is the residual environmental tilt.

We independently quantify the environmental tilt spectrum in our experiment \( \theta_0 \). The spectrum consists of multiple peaks, with the largest components in the few hundred hertz band, with a total rms tilt of \( 200 \pm 150 \mu\text{rad} \), consistent with that obtained from the fit above.
Understanding decoherence due to atomic ensemble dephasing

The above observations are compatible with a model that connects the global contrast decay constant \( \kappa \) with time-dependent tilts and residual atomic motion. This framework can quantify decoherence due to many other experimental imperfections.

In addition to the gravitational phase difference \( \Delta \phi_{\text{grav}}^{\text{prop}} \) (Eq. 1), each arm of the interferometer accumulates phase due to the lattice lightshift (AC Stark shift) from the optical potential \( U_{\text{latt},t} \). \( U_{\text{latt}} \) has a Gaussian profile in the transverse \( xy \)-plane and depends sinusoidally on \( z \): \( U_{\text{latt}} = U_0 \exp \left( -\frac{x^2+y^2}{w^2} \right) \sin \left( \frac{2\pi z}{\Delta l_{\text{latt}}} \right) \), where \( w_0 \approx 760 \mu \text{m} \) is the radius of the cavity mode. For an atom at rest at the center of a lattice with \( U_0 = 7 \ E_r \), \( \phi_{\text{latt}}^{\text{prop}} = 5.5 \ \text{Mrad} \) after \( \tau = 60 \) seconds.

Ideally, the trapping potentials for the top and bottom interferometer arms are identical, so that \( \Delta \phi_{\text{latt}}^{\text{prop}} = \phi_{\text{latt}}^t - \phi_{\text{latt}}^b \approx 0 \). However, any differential imperfections in the optical potential between the top and bottom arms, \( \Delta U_{\text{latt}} = U^t - U^b \), will lead to a differential phase shift \( \Delta \phi_{\text{latt}}^{\text{prop}} \propto \Delta U_{\text{latt}} \neq 0 \). In addition, \( \Delta U_{\text{latt}} \) modifies the trajectories of the top and bottom partial wavepackets so that they do not overlap exactly at the end of the interferometer, leading to a separation phase term, \( \Delta \phi_{\text{latt}}^{\text{sep}} = \sum_{i=\{x,y\}} (i^t - i^b) (v_i^t + v_i^b) m_c s / (2 \hbar) \) (28). The lattice phase shift is thus given by \( \Delta \phi_{\text{latt}} = \Delta \phi_{\text{latt}}^{\text{prop}} + \Delta \phi_{\text{latt}}^{\text{sep}} \).

Despite taking great care to minimize experimental imperfections, as described above, sources of differential phase shift remain. The top and bottom trapping potentials can vary as the cavity axis moves differentially with respect to the atom cloud. Time-dependent tilts due to vibrations cause the lattice sites corresponding to the top and bottom partial wavepackets to oscillate transversally with a differential amplitude proportional to \( \Delta z \): \( a_{\text{latt}}(t) = \theta(t) \cdot \Delta z \). This motion causes a differential potential between the top and bottom arms, \( \Delta U_{\text{latt}}(t) \propto \Delta z \cdot \theta(t) \cdot U_{\text{latt}}^0 \). To first order, the equations above give a linear phase shift as a function of tilt amplitude, trap depth, separation and hold time

\[
\Delta \phi_{\text{latt}}^{\text{latt}} \propto \Delta z \ast \theta(t) \ast U_{\text{latt}}^0 \tau.
\]  

(3)

The lattice phase shift also depends on the distribution of atomic trajectories in the ensemble, which motivates the transverse temperature dependence observed above. We focus here on motion in the transverse \( xy \)-plane, where the atoms follow orbital motion around the center of the optical trap. These trajectories can be treated semi-classically since the optical trap radius \( w = 760 \ \mu \text{m} \) is much larger than the atomic deBroglie wavelength of 0.3 \( \mu \text{m} \). Representative atomic motion timescales for a \( U_0 = 7 \ E_r \) trap depth are given by the harmonic trap frequency \( \omega_{\perp} = 2\pi \cdot 2.8 \ \text{Hz} \) in the transverse \( xy \) plane, much slower than the measured cavity tilts which typically occur at frequencies \( > 2\pi \cdot 100 \ \text{Hz} \). However, the trajectories have appreciable non-harmonic components, because of the long tails of the Gaussian potential. The transverse atomic sample temperature of 1.2 \( \mu \text{K} \) and the optical lattice potential determine the atom sample energy distribution. The spread in initial velocities and positions cause the lattice phase to accumulate at different rates for different velocity classes. This means that a hotter atom cloud with a larger energy spread leads to more phase dispersion

\[
\delta(\Delta \phi_{\text{latt}}) \propto \Delta z \ast \theta(t) \ast U_{\text{latt}}^0 \tau T_{\perp}.
\]  

(4)

We simulate these optical lattice atomic trajectories numerically to estimate the model proportionality factors (see Supplementary Materials). The simulations result in a Lorentzian
phase distribution across the sample, \( P(\Delta \phi) = \frac{1}{\pi} \frac{\delta(\Delta \phi_{\text{latt}})}{\Delta \phi^2 + [\delta(\Delta \phi_{\text{latt}})]^2} \), with a width \( \delta(\Delta \phi_{\text{latt}}) \) that scales like Eq. (4).

We use a density matrix formalism to show that the Lorentzian distribution results in an exponential decay of the ensemble contrast (29). Initially, the atoms are in a coherent superposition state of the top and bottom arms: \( |\psi\rangle_i = (|t\rangle + |b\rangle)/\sqrt{2} \). This corresponds to a pure state density matrix: \( \rho_i = |\psi\rangle_i\langle\psi|_i = \frac{1}{2}\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \). While in the optical lattice, the lower lattice site accumulates phase \( \Delta \phi_{\text{latt}} \) (Eq. (3)), and the state evolves as: \( |\psi\rangle_f = (|t\rangle + e^{i\Delta \phi_{\text{latt}}}|b\rangle)/\sqrt{2} \), corresponding to evolution operator \( \mathcal{E}(\Delta \phi_{\text{latt}}) = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\Delta \phi_{\text{latt}}} \end{pmatrix} \). The final density matrix of the two-level system is given by \( \rho_f = \int_{-\infty}^{\infty} \mathcal{E}(\phi)\rho_i\mathcal{E}^\dagger(\phi)P(\phi)\,d\phi \), which evaluates to

\[
\rho_f = \frac{1}{2}\begin{pmatrix} 1 & \text{Exp}[\delta(\Delta \phi_{\text{latt}})] \\ \text{Exp}[\delta(\Delta \phi_{\text{latt}})] & 1 \end{pmatrix}
\]

(5)

This represents a mixed state where the off-diagonal terms describe the coherence of the system. The contrast thus tends to zero for a large phase spread

\[
C = C_0\text{Exp}[-\delta(\Delta \phi_{\text{latt}})].
\]

(6)

This physical model combines differential phase shift due to tilts (Eq. (3)), phase dispersion due to residual atomic motion in the optical lattice (Eq. (4)) and ensemble collective dephasing due to the phase dispersion (Eq. (6)) to provide a complete description of decoherence

\[
C = C_0\text{Exp}[-\Delta z \ast U_{\text{latt}}^0\tau/\kappa],
\]

where \( \kappa \propto (\theta(t) T_\perp)^{-1} \).

The results of our physical model are quantified through numerical simulation of lattice trajectories within the atomic ensemble and are in quantitative agreement to the experimental data (Figure 3).

**Conclusion**

In conclusion, we have demonstrated the longest lasting spatial superposition state of a massive particle to date by measuring interference of atomic Cesium wavepackets after 60 seconds of hold time in an optical lattice, 26 times longer than previously achieved with atomic fountains (10). We describe a physical framework that explains the measured decoherence as resulting from residual atomic motion causing the spatial superposition state to differentially sample optical trap imperfections due to tilt.

Our models and experimental tests suggest further improvement in atom numbers and readout noise, reduction of atom sample temperature and reduction of oscillatory tilts may lead to spatial superposition states with ultra-long coherence, exceeding minutes. These increases in coherence are landmark results towards applications such as gravimetry (3–5), searches for fifth forces (8, 9), or fundamental probes into the non-classical nature of gravity (6, 7).

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Quantum metrology by one-minute interrogation of
a coherent atomic spatial superposition

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Materials and Methods

Atom sample preparation and detection

To describe the experiment in detail, we define a coordinate system in which \( \hat{z} \) points upwards and is aligned to Earth’s gravity. The optical cavity axis is approximately aligned with \( \hat{z} \). We define \( \hat{x} \) to lie in the horizontal plane, aligned with the direction of the MOT magnetic field coils, such that \( \hat{y} = \hat{z} \times \hat{x} \) is approximately along the direction of the camera (Fig. 1A).

Initial trapping of the atoms in a 2-dimensional MOT (2D MOT) takes place in a glass vacuum chamber (not shown in Fig. 1) which contains Cs vapor at room temperature. Four laser beams, 12.8 MHz red-detuned from the F=4 to F’=5 line in the Cs D2 manifold and the magnetic field generated by four coils create a 2D MOT. The 2D MOT axis is aligned with a differential pumping aperture tube that connects to the primary experimental chamber (octagon in Fig. 1). The primary chamber is evacuated with ion pumps and titanium sublimation pumps to a pressure of \( 6 \times 10^{-11} \) torr. The Cs atoms are loaded (loading time 700 ms) into a 3D MOT formed by 6 independent laser beams (wavelength 852 nm, 12.8 MHz red detuned from the F=4 to F’=5 line) with a beam diameter of \( \sim 3 \) cm and a magnetic quadrupole field. Three additional Helmholtz coils are used to zero the environmental magnetic field along the \( \hat{x} \), \( \hat{y} \) and \( \hat{z} \) directions. The MOT atoms load at the spatial location where net environmental plus applied magnetic field is 0.

After the 3D MOT phase, the magnetic quadrupole field is turned off and the atoms are laser cooled by optical molasses to 10 \( \mu \)K. The atoms are then Raman Sideband Cooled (RSC) in a 3D optical lattice (trap depth \( \sim 50 E_r \), wavelength 852 nm, \( \sim 50 \) GHz red-detuned from D2), where two of the laser beams are derived from the TEM00 cavity mode and the other two are provided through the side window. The atomic sample is similar in size to the radius of the vertical 3D optical lattice beam (760 \( \mu \)m), which means that the trap depth varies significantly across the atom sample. This limits the achieved RSC temperature to 1.2 \( \mu \)K.

The atoms are then transferred into a far off resonant 1D lattice formed by the TEM00 mode of the optical cavity (trap depth \( \sim 70 E_r \), wavelength 943 nm). RSC leaves atoms in the \( F = 3, m_F = 3 \) stretched state ([31]). The atoms are then transferred using microwave rapid adiabatic passage (9 ms ramp) followed by a microwave \( \pi \)-pulse to the magnetically insensitive \( F = 3, m_F = 0 \) state.

To launch the atoms vertically upwards, the intensity of the lattice is reduced (trap depth \( \sim 30 E_r \)), and the laser frequency is swept to launch \( \sim 10\% \) of the atoms upwards into free fall. The launch velocity is typically set to 196 mm/s, such that the atoms reach the apex of their trajectory after 20 ms of free-fall time, corresponding to a launch height of 1.96 mm. A Doppler sensitive Raman \( \pi \)-pulse along \( \hat{z} \) (Gaussian time profile with \( 1\sigma = 20 \) \( \mu \)s) restricts the longitudinal atomic velocity to \( v_{||} = 0.6 v_r \) (Gaussian 1\( \sigma \)), corresponding to a temperature of 80 nK and 2\( \pi \cdot 8 \) kHz (Gaussian 1\( \sigma \)) Doppler shift.

To obtain a pure sample, atoms that did not take part in the population transfer need to be removed. This is accomplished by a laser beam resonant with the D2 line (either \( F = 4 \) to \( F’ = 5 \) or \( F = 3 \) to \( F’ = 2 \)) which travels approximately along the \( -\hat{x} + \hat{z} \) direction and is used to push atoms with internal state that is either \( F = 4 \) or \( F = 3 \), respectively. It is also used at the beginning of the interferometer to push away two of the interferometer arms that are transferred in the unwanted momentum and hyperfine state (Fig. 1B).

For detection after the interferometer sequence, this same laser is used to push the atoms in \( F = 4 \) over a distance of \( \sim 1 \) mm relative to the \( F = 3 \) atoms, so that the two populations can be separately detected by fluorescence within one camera image. Fluorescence is excited using the MOT laser beams, blocking the ones along the \( \hat{x} \) direction to reduce stray light. The detection
light is typically 5.6 MHz red-detuned from the $F = 4$ to $F' = 5$ line and the atoms are imaged for 4-10 ms before imperfections in the laser light intensity profile or power imbalance push away the atom sample. This scheme measures both interferometer outputs simultaneously on the same image, minimizing detection noise due to fluctuations in the intensity or detuning of the detection light or variations in background stay light.

The camera is placed at a 45° angle with respect to the horizontal, along the $\hat{z} + \hat{x}$ direction and is pointed towards the atomic cloud. A high-NA objective (f/0.95 aperture, Navitar MVL50HS) is used to collect and image the fluorescence on the surface of the EMCCD sensor. The EMCCD gain is typically set to 0, except for long hold time measurements ($\tau > 20$ s), where the EMCCD gain is set to values up to 300x to image lower numbers of atoms ($N < 1000$).

**Optical cavity and lattice imperfections**

The optical Fabry-Perot cavity is formed by two curved mirrors (20 m radii of curvature) that are separated by $L = 37.5$ cm. This results in a cavity waist size of $w = 760 \mu$m and a Rayleigh length of $z_R = 1.92$ m at the lattice wavelength $\lambda_{\text{latt}} = 943$ nm. The cavity waist is located near the center of the atom cloud, which ensures that the diameter of the lattice at the top and bottom interferometer arms is as similar as possible. This minimizes dephasing due to variations in the transverse diameter of the trap potential between the top and bottom interferometer arms. Numerical simulations suggest that contrast decay due to the remaining small potential difference is now at least three orders of magnitude lower, therefore negligible at current sensitivity.

The mirror substrates are 1 inch diameter and superpolished to a root-mean square (rms) surface roughness of <1 Å. They are dielectric coated for 97.0 % reflectivity at $\lambda_{\text{Raman}} = 852$ nm, 98.3% at $\lambda_{\text{latt}} = 943$ nm and 93.5 % at $\lambda_{\text{tracer}} = 780$ nm. The linewidth of the cavity is 2.2 MHz at 943 nm, providing ~59 times power enhancement of the coupled light. The transverse mode spacing is 20 MHz, sufficiently large compared to the cavity linewidth so that most of the incoming light is coupled into a single transverse cavity optical mode.

**Laser frequency stabilization scheme**

A reference laser is frequency-stabilized to the Cs D2 line in a vapor cell (32). All the other frequency stabilization schemes described below use Pound-Drever-Hall (PDH), where the sidebands are provided by an electro-optical modulator (EOM - typical modulation frequency ~20 MHz). The length of a transfer cavity is stabilized with a piezo to the reference laser. The Raman laser ($\lambda_{\text{Raman}} = 852$ nm) and tracer laser ($\lambda_{\text{tracer}} = 780$ nm) are referenced to this transfer cavity. Both lasers enter the experiment science cavity from the bottom (along $+\hat{z}$), where a set of dichroic mirrors allow their reflection and transmission to be separately monitored by photodetectors. The length of the experiment science cavity described above is stabilized to the tracer laser against vibrations and slow drift due to mechanical expansion of the vacuum chamber.

Light from the lattice laser ($\lambda_{\text{latt}} = 943$ nm) is split into two paths. A small fraction (100 $\mu$W) enters the “science” cavity through the top mirror (along $-\hat{z}$) and is used to stabilize the lattice laser to the length of the “science” cavity. The remaining light is amplified by a tapered amplifier and enters the cavity from the bottom mirror (along $+\hat{z}$). The intra-cavity power is monitored by a photodetector placed at the transmission port and is used to stabilize the intra-cavity intensity by adjusting the RF voltage amplitude driving an acousto-optic modulator (AOM). The trap depths quoted throughout the paper are calculated by scaling the measured power of this photodetector.
Lattice properties and loading

The lattice laser used in these experiments is $\lambda_{\text{latt}} = 943$ nm, 49 nm red-detuned from the D1 transition and 91 nm red-detuned from the D2 transition. Compared to our previous work, where $\lambda_{\text{latt}} = 866$ nm with single photon scattering lifetime of $\frac{2\pi}{\Gamma_{\text{sp}}} = 2\pi \cdot 11$ s, this larger detuning reduces decoherence to $\frac{2\pi}{\Gamma_{\text{sp}}} = 2\pi \cdot 120$ s for $U_{\text{latt}}^0 = 5 E_r$. This level is negligible for all measurements described here.

Near the apex of the atoms’ free-fall trajectories, the optical lattice is turned on or off using a smooth exponential curve with time constant of 400 $\mu$s. This is fast compared to the transverse motion of the atoms (characteristic harmonic frequency $\omega_{\perp} = 2\pi \cdot 2.4$ Hz for $U_{\text{latt}}^0 = 5 E_{\text{rec}}$), but slow compared to the axial motion (characteristic harmonic frequency $\omega_{\parallel} = 2\pi \cdot 8.2$ kHz for $U_{\text{latt}}^0 = 5 E_{\text{rec}}$). This means that the atoms adiabatically load axially into the high-intensity regions of the optical lattice, which enforces quantization of the atomic wavepacket positions during the hold.

To probe this structure, we measure interferometer fringes when finely changing the initial interferometer arm separation by varying $T$: $\Delta z = v_r T$. We then perform a Fourier decomposition of the measured fringes to determine the primary frequency components. We observe frequency components from gravitational potential differences that necessarily correspond to integer multiples of lattice sites: $\Delta z = n \cdot \lambda_{\text{latt}}/2$, where $n$ is an integer number (Fig. S1).

Fig. S1. Atoms load into integer multiples of the lattice period. Fourier spectral decomposition components of the measured fringes as a function of separation. Yellow represents a higher power density at the specific fringe frequency. Inset. Raw data and fit for such a fringe, when the initial wavepacket separation equals 7.5 lattice sites. We observe that the optical lattice enacts a second beam splitter, where the partial atomic wavepacket loads evenly into adjacent lattice sites with 7 and 8 lattice site separations.
**Interferometer phase and contrast**

The interferometer phase is the sum of two terms: $\Delta \phi = \Delta \phi_L + \Delta \phi_{\text{prop}}$, where $\Delta \phi_L$ results from the interaction of atomic wavepacket with the Raman laser \((33)\) and $\Delta \phi_{\text{prop}}$ is the propagation phase. Each of the four applied laser pulses adds a term $\phi_i$ to this phase that is proportional to the atom’s position. In our interferometer,

$$\Delta \phi_L = \phi^L_t - \phi^L_b = (\phi_1 - \phi_2) - (\phi_3 - \phi_4) = k_{\text{eff}} g T (T + t_{\text{apex}}),$$  \((1)\)

where $g$ is the local gravitational acceleration and indexes $\phi^L_{t,b}$ denote the phase corresponding to the top and bottom arms, respectively. The total interferometer phase due to Earth’s gravitational acceleration $g$ amounts to

$$\Delta \phi = \Delta \phi_{\text{prop}} + \Delta \phi_L = \frac{m_{\text{Cs}} g \Delta z}{\hbar} \tau + k_{\text{eff}} g T (T + t_{\text{apex}}),$$  \((2)\)

To scan interferometer fringes, we can vary either \(a\) the hold time, $\tau$, or \(b\) the rate at which the Raman laser frequency is ramped so that is remains on-resonance with the atoms during free-fall, $\alpha = g * k_{\text{eff}} = 2\pi \cdot 23$ kHz/ms for the D2-line of cesium. Varying $\tau$ results in a fringe frequency that is given by

$$\omega_{\text{prop}} = \frac{\partial (\Delta \phi)}{\partial \tau} = m_{\text{Cs}} g \Delta z / \hbar.$$  \((3)\)

As shown in Fig. S2A, the adiabatic loading in the optical lattice forces the wavepacket separation to be an integer number of lattice sites, $\Delta z = n \cdot \frac{\lambda_{\text{latt}}}{2}$, where $n$ is an integer. When $\alpha$ is varied, the fringe frequency is

$$\omega_L = \frac{\partial (\Delta \phi)}{\partial \alpha} = k_{\text{eff}} T (T + t_{\text{apex}}).$$  \((4)\)

There is no quantization of scanned parameters in this case (Fig. S2B).

The loss in fringe contrast as a function of separation is shown in Figure S2C for a hold time of $\tau \approx 1$ s and is independent of whether $\alpha$ or $\tau$ are scanned. In addition to the slowly decaying exponential envelope discussed in detail in the main text, we also observe variation in the contrast at shorter separation length scales. The contrast varies as a function of $T$ with a fast sinusoidal component given by lattice spacing, $\frac{\lambda_{\text{latt}}}{2v_r}$. In addition, the contrast decay curve exhibits a smaller amplitude \((4\% \text{ typically})\) sinusoidal component with periodicity given by the least common multiple of the lattice laser and tracer laser wavelengths, $\lambda_{\text{latt}}$ and $\lambda_{\text{tracer}}$. This variation is due to dephasing from the interference of the lattice and tracer lasers. The separations used in Fig. 3 are chosen to minimize these additional dephasing mechanisms and only probe the slow exponential decay of contrast described in the main text. We note that this data was taken before replacing the lattice laser, so $\lambda_{\text{latt}}=866$ nm for data shown in Fig. S2 only.
**Fig. S2.** Measured interferometer fringe frequency when (A) the hold time $\tau$ is scanned and (B) the laser ramp rate $\alpha$ is scanned. Blue datapoints show fitted fringe frequency as a function of separation. Error bars correspond to $1\sigma$ (68%) Gaussian confidence intervals. Red lines correspond to the expected analytical fringe frequency as shown by Eqs. 2 and 3. (C) Contrast loss as a function of separation time, $T$. The fitted interferometer contrast varies as a function of $T$ with a fast sinusoidal component given by lattice spacing, $\lambda_{\text{latt}}/2 \cdot v_{\text{rec}}$, a slowly decaying exponential envelope and a lower frequency variation due to interference of the “lattice” and “tracer” lasers. The red line is a fit to the data using free parameters for the amplitudes of the exponential decay, amplitude of the higher frequency sinusoidal function and the amplitude of the lower frequency variation.

**Contrast at long hold times**

When $\tau > 20$ s, we observe a second, slower contrast decay term, $C_1 \exp(-\tau/\tau_{C1})$ ($\tau_{C1} \sim 1000$ s) (Fig. S3). Similar behavior is observed for the numerical simulations carried out in this regime. For low contrast values, noise (such as due to shot noise or imaging noise) will lead to a small bias in the contrast value extracted from the least-squares fit. We estimate this bias by fitting simulated fringes with similar levels of noise, as shown in Fig. S3. The observed slowing of the contrast decay is significantly nonzero, even when considering this small bias.

The decoherence model described in the paper suggests a slowing in the decoherence rate of our interferometer due to high energy atoms tunneling out of the interferometry trap (trap lifetime 14 s). The remaining atoms are lower energy and only sample the harmonic region of the potential, experiencing reduced decoherence. Since the $C_1$ term is significantly nonzero for long hold times, $\tau > 20$ s, only, we focus our analysis on the dominant contrast decay term, $\tau_C$. 
Fig. S3. Contrast loss at long hold times. Slowing down in the decoherence rate compared to an exponential decay (dashed line) when $\tau > 20$ s. This interferometer used a pulse separation $T = 0.267$ ms ($\Delta z = 1.9 \, \mu m$) and a peak trap depth of $U_0 = 7E_r$.

Investigating contrast loss

To find the source of decoherence, we have varied around 20 experimental parameters, looking for a dependence of the contrast decay constant $\kappa$. Most of these parameters were varied in a range that is large (factor of 2 to 1000) compared to the typical residual value in the experiment. A typical procedure involved measuring experiment fringes both under typical running conditions and when the experimental parameter was greatly exaggerated. Two fringes were taken in each configuration: one that corresponds to low $\Delta z$, $U_{\text{latt}}^0$ and $\tau$, where the contrast approximately equals $C_0$, and one where $\Delta z$, $U_{\text{latt}}^0$ and $\tau$ are set such that $C = C_0/2$, on the slope of the exponentially decaying contrast, $C = C_0 \exp \left[-\Delta z \frac{U_{\text{latt}}^0 \tau}{\kappa}\right]$. This makes the measurement maximally sensitive to variations in $\kappa$. Taking the ratio of the contrast values of the two fringes gives an accurate estimate of $\kappa$. The list of parameters that were investigated and found to have no influence on contrast decay is given in Table S1.

Table S1. Investigating the cause of contrast decay. Experimental parameters that were varied and found to have no influence on contrast decay at a level of 2%.

| Parameter Varied           | Experimental Test Performed                                                                 | Observed Outcome |
|----------------------------|-------------------------------------------------------------------------------------------|------------------|
| Radial lattice uniformity  | Installed new superpolished cavity mirrors (surface rms <1 Å)                              | Same $\kappa$    |
| Axial lattice uniformity   | Replaced planar- concave cavity with symmetric concave-concave cavity (mirrors have equal radii of curvature) | Same $\kappa$    |
| Parameter                        | Effect                                                                 | Expected Outcome                                    |
|---------------------------------|------------------------------------------------------------------------|------------------------------------------------------|
| Vacuum pressure                 | New pumps, reduced outgassing                                          | Same $\kappa$, slower decay of atom number          |
| Lattice laser frequency noise   | 2x higher with tuning PID lock                                        | Same $\kappa$                                        |
|                                 | Narrower laser linewidth by locking to a high-finesse (F=20,000) cavity|                                                      |
| Raman beamsplitter symmetry     | Symmetric beamsplitters using microwave $\frac{\pi}{2}$ pulse followed by optical $\pi$ pulse (32) | Same $\kappa$                                        |
| Laser lattice broadband emission| Suppressed >10x with filter cavity                                    | Same $\kappa$                                        |
| Lattice intensity noise         | 10x reduced by intensity stabilization using transmitted light as a monitor | Same $\kappa$, slower decay of atom number          |
| Background scatter              | Increased 20x by shining mode-mismatched light at cavity mirror and/or experiment vacuum window | Same $\kappa$                                        |
| Acoustic noise                  | Phone speaker, tapping the optical table                              | Same $\kappa$, vibrations primarily caused setup translation |
| Alignment with gravity          | Tilted optical table by 1.5 mrad                                      | Same $\kappa$, observed expected phase shift due to modified projection of local gravity along cavity axis |
| Changing atom number and density| 2x reduction by lowering state selection efficiency                   | Same $\kappa$, low contrast at very low atom numbers due to increased imaging noise |
| Axial atom temperature selection| Reduced 3x by increasing the length of velocity selection pulse       | Same $\kappa$, as expected since we only expect dependence on radial temperature |
| Misaligned lattice laser, coupling light to high order cavity modes | Reduced cavity coupling efficiency 2x by misaligning and changing beam diameter | Same $\kappa$                                        |
| Lattice laser detuning          | Replaced lattice laser with 866 nm ECDL (14 nm det.) and 1064 nm fiber laser (212 nm det.) | Same $\kappa$, except change in contrast due to single photon scattering, as expected |
| Environmental field gradients   | Varied the vertical atom position by up to 1.5 cm                    | Same $\kappa$                                        |
| Magnetic field gradients        | Increased 1000x by turning on MOT coils during interferometer         | Same $\kappa$, observed expected phase shift due to quadratic Zeeman shift |
| Position within the atomic sample | Analyzed horizontal and vertical slices of fluorescence image        | Same $\kappa$                                        |
Loading atoms into higher order modes

Movie S1 displays a sequence of fluorescence images showing the atom cloud being loaded into the horizontally asymmetric Hermite-Gauss TEM01 mode of the optical cavity.

To produce data shown in Fig. 3 of the main text, we use higher order cylindrically symmetric Laguerre-Gauss modes (LG10, LG20), which have increasingly narrower mode diameters of the central peak. Lattice laser light is coupled into these higher order modes by increasing the diameter of the incoming laser beam such that the incoming Gaussian beam has good overlap with the LG modes (typically 20-30%). An AOM is used to sweep the lattice laser frequency (sweep time 1 ms) over the optical cavity transverse mode spacing, switching between coupling the lattice laser to the LG00 and either LG10 (20 MHz sweep) or LG20 (40 MHz sweep range).

Movie S1. Sequence of fluorescence images showing dynamics of the spherically symmetric atom cloud loading into a TEM01 mode of the optical cavity. The yellow and red colors represent regions of space with high atom density. The atoms that have good overlap with the cavity get loaded and initially oscillate (period 150 ms) before eventually (after 300-400 ms) filling the available cavity mode trap volume.

Numerical simulation

As mentioned in the main text, we use a simulation with parameters that match our knowledge of the experiment to estimate the effect of lattice imperfections on interferometer decoherence. The simulation starts with a sample of 500-1000 atoms generated with 2D positions and velocities (in the $xy$ plane) that randomly drawn from Gaussian distributions with diameters of 540 $\mu$m and 26 mm/s, respectively. Each atom’s trajectory parameters $\{x(t), y(t), v_x(t), v_y(t)\}$ are calculated by integrating the equations of motion in each $x$, $y$ spatial direction

$$\frac{dx(t)}{dt} = v_x(t)$$

(5)
\[
\frac{dy(t)}{dt} = v_y(t) \\
\frac{dx(t)}{dt} = \frac{dU_{\text{latt}}(x(t), y(t), t)}{dx} \frac{1}{m_{\text{Cs}}} \\
\frac{dy(t)}{dt} = \frac{dU_{\text{latt}}(x(t), y(t), t)}{dy} \frac{1}{m_{\text{Cs}}}
\]

where \( U_{\text{latt}}(x(t), y(t), t) = 0 \) for the first 38 ms, corresponding to free-propagation and then \( U_{\text{latt}}(x(t), y(t), t) = U_0 \exp\left(-\frac{(x-x_0)^2+(y-y_0)^2}{2w^2}\right) \) during the lattice hold, where \( x_0 = y_0 = 0 \) for the unperturbed potential. In addition to trajectory parameters, probabilities for the atoms to leave the trap \( p(t) \) are calculated from the Landau-Zener criterion through \( \frac{dp}{dt} = \ln[1 - \exp(-\frac{\pi a_{\text{Cs}} U_{\text{latt}}(x(t), y(t), t)}{E_R})] \), where \( a_{\text{Cs}} = \frac{2 \pi h}{m_{\text{Cs}} g \lambda_{\text{latt}}/2} \). An atom that tunneled is assumed to have left the experiment and does not contribute to the interferometer output. The integration uses a Runge-Kutta routine, where the timestep (typically 100 \( \mu \)s) is much shorter than the timescales of the motion (10s of Hz). We verify that simulation results are independent of timestep size choice within an order of magnitude.

The interferometer propagation phase is calculated from \( \phi_{\text{latt}}^{\text{prop}}(t) = \int L \, dt \), where \( L = \frac{1}{2} m_{\text{Cs}} \left( v_x(t)^2 + v_y(t)^2 \right) - U_{\text{latt}}(x(t), y(t), t) \). The trajectory parameters, \( p(t) \) and \( \phi_{\text{latt}}^{\text{prop}}(t) \) are each calculated for two separate configurations: (a) one interferometer arm in an unperturbed Gaussian potential and (b) one interferometer arm perturbed by imperfections of the optical lattice, such as tilts. The effect of tilts is modeled by moving the center of the lattice potential to a time-dependent position \( x_0(t) = a_{\text{tilt}} \sin(\omega_{\text{tilt}} \, t) \), where \( a_{\text{tilt}} = \theta \, \Delta z \) is the tilt-induced lattice amplitude change. At the end of the integration, the separation phase is calculated from the final positions and velocities as \( \phi_{\text{latt}}^{\text{sep}}(t) = [(x^t - x^b)(v_x^t + v_x^b) + (y^t - y^b)(v_y^t + v_y^b)] m_{\text{Cs}}/(2h) \). The total phase is then \( \phi_{\text{latt}}(t) = \phi_{\text{latt}}^{\text{prop}}(t) + \phi_{\text{latt}}^{\text{sep}}(t) \).

The differential phase \( \Delta \phi_{\text{latt}} \) between the top and bottom arms, is calculated by subtracting the two phases. The average ensemble phase shift \( (\Delta \phi_{\text{latt}}) \) and phase spread, \( \delta(\Delta \phi_{\text{latt}}) \) are calculated by performing a sum over all atomic trajectories. The effect of the phase spread \( \delta(\Delta \phi_{\text{latt}}) \) on the fringe contrast \( C \) is quantified by computing an average of fringes with phases given by the ensemble phase distribution, each weighted by their individual Landau-Zener survival probabilities, \( p(t) \). A third contribution to fringe contrast loss due to poor overlap of the atomic wavepackets at the end of the interferometer is found to be negligible compared to the dephasing described above. The contrast decay time constant \( \tau_C \) is extracted from a decaying exponential fit (where \( \tau_C \) is the only free parameter) of the fringe contrast sampled for \( t = 0 \) to \( t = 20 \, \text{s} \) in steps of 0.2 s. The simulation time was extended to 60 s for generating Figure S3. We find good agreement between the simulations and experimental data (Figure 3).

We verify the performance of the trajectory simulation by measuring the lattice loading fraction under different laboratory conditions and comparing the resulting atom numbers with the simulation, as a fraction of the initially available atoms. We find good agreement between the atom numbers loaded and remaining in the lattice after a 1 second hold, when the experiment and simulation tilt is varied (Fig. S4(A)) and when the trap depth if varied (Fig. S4(B)).
Fig. S4. Loading fractions vs (A) global tilt angle and (B) trap depth, $U_{\text{latt}}^0$. Experimental data showing fractions of atoms remaining after loading and 1 second of hold time as a function of initial number. Experimental data is shown by blue dots with error bars corresponding to $1\sigma$ (68% confidence) Gaussian intervals, and simulation results are in green.

Lattice trajectories and contributions to lattice phase shift

The diagram shown in Figure S5 is a pictorial representation of the atomic trajectories inside the optical lattice and resulting differential phase shifts between the top and bottom interferometer wavepackets due to oscillatory tilts. It complements the description of decoherence due to such effects in the main text.
Figure S5. Phase shifts due to differential motion between the atomic wavepacket in the top (unperturbed) and bottom (perturbed) lattice sites. The atomic wavepacket (wavy line on top of grey disk) is split into an equal superposition of two partial wavepackets (wavy lines on top of green and red disks). The partial wavepackets are loaded into lattice sites (blue ovals) that are spatially separated by a distance of $\Delta z$. Solid lines show representative atom trajectories in the two lattice sites, which are both initially loaded at position $\{x, y\}_i$. Survival probabilities due to Landau-Zener tunneling are shown by the trajectories color gradients and range from 1 (green) to 0 (red). Time-dependent tilts with amplitude $a_{\text{tilt}}$ cause the position of the lower lattice site to oscillate in the transverse plane, while the top lattice site is unperturbed, leading to a displaced trajectory of the bottom atom partial wavepacket with final position $\{x, y\}_f \neq \{x, y\}_i$ and propagation phase difference $\phi_f^t \neq \phi_f^b$. The rightmost panels show the two main dephasing mechanisms, due to differential free-evolution phase, $\Delta \phi_{\text{latt}}^{\text{prop}}$, and separation phase, $\Delta \phi_{\text{latt}}^{\text{sep}}$. 