

Fast coherent splitting of Bose-Einstein condensates

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Preparation of nontrivial quantum states without introducing unwanted excitations or decoherence remains a central challenge in utilizing ultracold atomic systems for quantum simulation. We employ optimal control methods to realize fast, coherent splitting of a one-dimensional Bose-Einstein condensate, achieving negligible classical excitations while preserving quantum correlations. Furthermore, we explore two-step protocols in which controlled classical motion is first induced and subsequently suppressed via tailored control sequences. Our experiments highlight the potential of optimal control for quantum state engineering and dynamical control in many-body quantum systems.

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I. INTRODUCTION

Ultracold atomic systems provide a versatile platform for the implementation of quantum simulators [1,2], enabling the investigation of complex quantum many-body dynamics with unprecedented control and tunability. In many applications, it is essential to steer the system into nontrivial quantum states. In the presence of interactions, it may be hard to manually design control sequences, especially when high speed is required or certain other boundary conditions have to be met.

The use of optimal control (OC) has emerged as a powerful methodology for this purpose, offering fast, time-efficient, and robust pathways for quantum state engineering [3,4]. OC requires good knowledge of the system under study and an accurate mathematical model of its dynamical processes, which can be challenging to obtain. Quantum optimal control not only facilitates fast state preparation [5] but also accelerates transport tasks [6] and can suppress undesired excitations [7] and decoherence, which are otherwise limiting factors in quantum technology applications.

In this article, we demonstrate fast, coherent splitting of a one-dimensional Bose-Einstein condensate using OC. We introduce an effective model used for the OC protocols and discuss an efficient calibration method. Our results demonstrate that we are able to reduce classical excitations to a level comparable to a very slow adiabatic ramp for a wide range of splitting speeds. We achieve strikingly fast splitting,

approaching the system's theoretical speed limit, while preserving quantum correlations, offering a pathway for manipulating the quantum properties of the two condensates.

II. COHERENT SPLITTING FOR QUANTUM STATE PREPARATION

It has been demonstrated that the splitting of Bose-Einstein condensates (BECs) [8,9] into double-well potentials enables quantum state preparation protocols [10]. Interferometric and metrological applications have particularly benefited from squeezed and entangled states generated in split BECs [11], enabling enhanced sensitivity beyond the standard quantum limit (SQL). The quality of such processes depends critically on the suppression of motional excitations and the preservation of coherence and quantum correlations. Theoretical and experimental studies have shown that fast, coherent manipulations of ultracold atoms in state-dependent potentials or anharmonic traps are possible via optimal control [12,13].

We implement our experiments with a one-dimensional BEC of ⁸⁷Rb in a magnetic trap on an atom chip [14,15]. Radio frequency (RF) dressing [16–18] enables continuous and reproducible tuning of the trapping potential from a single-well configuration to a double-well geometry using a single parameter: the amplitude $\mathcal{A}$ of the RF current. Detection is performed by acquiring a fluorescence image after a time of flight (TOF) of 43.5 ms [19]. In earlier work, it has been demonstrated that this type of control and readout allows us to detect number squeezing and entanglement [20,21], but tunability of quantum properties was not possible.

III. OC MODEL

Precise feed-forward control relies on mathematical models that accurately captures the dynamics of the physical system while remaining simple enough to enable reliable

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calibration and tuning. To design optimizable and experimentally implementable control protocols for BEC splitting, we seek reduced models that describe the essential dynamics under time-dependent control. In our case, this requires not only an accurate representation of the trapping potential but also a framework for modeling the real-time evolution of the system.

For the latter, we focus on the evolution in the transverse (splitting) direction; the longitudinal direction remains approximately static during typical experimental time scales. The dynamical evolution of the classical nonlinear motion is modeled by a reduced Gross-Pitaevskii equation (GPE):

$$i\hbar \frac{\partial \Psi}{\partial t} = \left(-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} + V(x, \mathcal{A}(t)) + g_{\perp} |\Psi|^2 \right) \Psi,$$

where the time-dependent effective potential $V(x, \mathcal{A}(t))$ and the effective transverse interaction strength $g_{\perp}$ are open parameters. Accurate calibration of these parameters is essential for reproducing the experimental dynamics and ensuring the success of optimal control protocols.

For the effective potential $V(x, \mathcal{A})$, we employ the most simple double-well model [17,18],

$$V(x, \mathcal{A}) = a_2(\mathcal{A})x^2 + a_4(\mathcal{A})x^4,$$

where the coefficients are parameterized to reflect the curvature and separation of the wells as a function of the control parameter $\mathcal{A}$. Strikingly, this reduced model captures all relevant physical features of the system with sufficient accuracy for optimal control purposes.

The parameters of the effective model are calibrated from experimental observations. This is achieved by comparing the dynamical evolution predicted by the model with experimental observations and adjusting the model parameters to ensure agreement [see Fig. 1(b)]. A more detailed outline of the calibration procedure can be found in Appendixes C–E, and is discussed in full detail in Ref. [22].

In Fig. 1(c), we present a representative comparison of the performance of linear and OC splitting protocols. The figure shows the respective control ramps, the evolution of the interference fringe patterns during the ramp, and subsequent hold time, as well as the corresponding time-dependent shape of the double-well potential throughout the splitting process. The superior performance of the OC protocol is evident already from the fringe evolution, as the fringe pattern remains static after the end of the OC ramp.

IV. SHORTCUT TO ADIABATIC SPLITTING

Performing splitting via nonadiabatic, e.g., fast linear ramps, excites classical collective modes. The most prominent of these are oscillations of the interwell distance d , referred to as sloshing, and oscillations of the transverse width of the condensates $\tilde{\sigma}$, known as breathing [23]. We study resulting post-TOF interference patterns, from which we extract the fringe spatial frequency (fringe spacing) k_0 and the transverse width σ [cf. Fig. 1(a)], which relate, respectively, to the interwell separation and the *in situ* spatial extent of the individual condensates (see Appendix A).

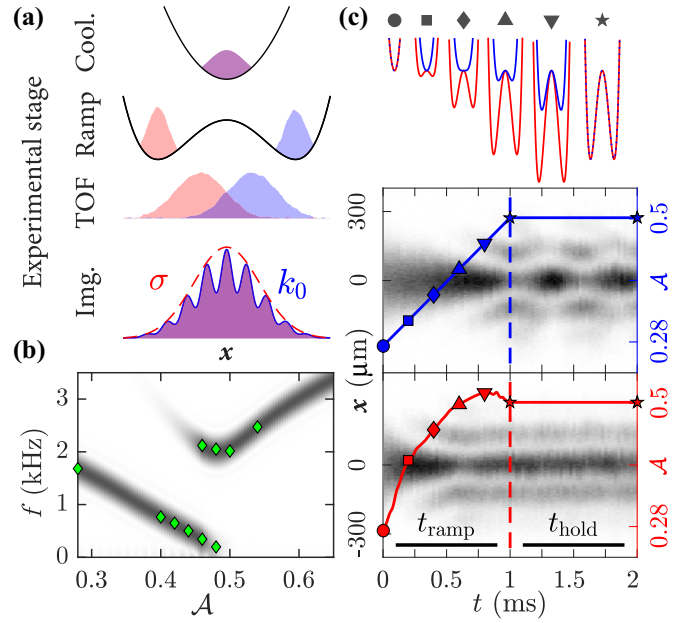


FIG. 1. Experimental scheme: (a) A BEC is prepared in a single-well harmonic trap. It is split into a double-well during t_{ramp} using RF-dressing amplitude; to probe the resulting state, it is held for t_{hold} , released from trap, and imaged after a TOF of 43.5 ms. Fluorescence imaging captures interference fringes, from which the transverse cloud size σ and fringe spatial frequency k_0 are extracted. (b) Trap frequencies (green diamonds) as a function of RF-dressing amplitude $\mathcal{A}$ determined from oscillatory motion of the displaced BEC are compared with frequencies extracted from simulations using the calibrated reduced model. (c) Comparison of linear (blue) and optimal-control (red) ramps. The evolution of the interference pattern during ramp and hold times is shown alongside the simulated potential at selected times. Linear ramps induce strong excitations, whereas OC ramps achieve splitting with negligible excitation.

As an example, Fig. 2(a) shows the evolution of the fringe pattern over a 1 ms hold time for both linear (top) and OC (bottom) ramps. In Fig. 2(b), we present the extracted fringe spatial frequency (fringe spacing) k_0 and the transverse width σ , displaying individual experimental realizations along with their mean values. The data demonstrate clear suppression of excitations in postramp dynamical evolution for the OC ramp. For quantitative analysis of the amplitude of these excitations without assuming a single dominant frequency, we evaluate two observables over the hold time: the variance of k_0 and the variance of σ (see Appendix B).

In Fig. 2(c), we show the performance of the OC splittings for two different scenarios: (I) varying the final splitting amplitude $\mathcal{A}_{\text{final}}$ while fixing the ramp duration t_{ramp} [first column in Fig. 2(c)] and (II) varying the ramp duration t_{ramp} while fixing the final amplitude $\mathcal{A}_{\text{final}}$ [second column in Fig. 2(c)]. For comparison, we show the results obtained using a linear ramp with identical parameters. Notably, due to the fact that properties of the double well depends nonlinearly on $\mathcal{A}$, the linear ramp exhibits nontrivial behavior, revealing a resonancelike structure in the excitation amplitude (see Appendix F for more details). Strikingly, the OC outperforms the linear ramps for almost all scenarios. For larger final dressing amplitudes, the performance is limited by the simplicity of

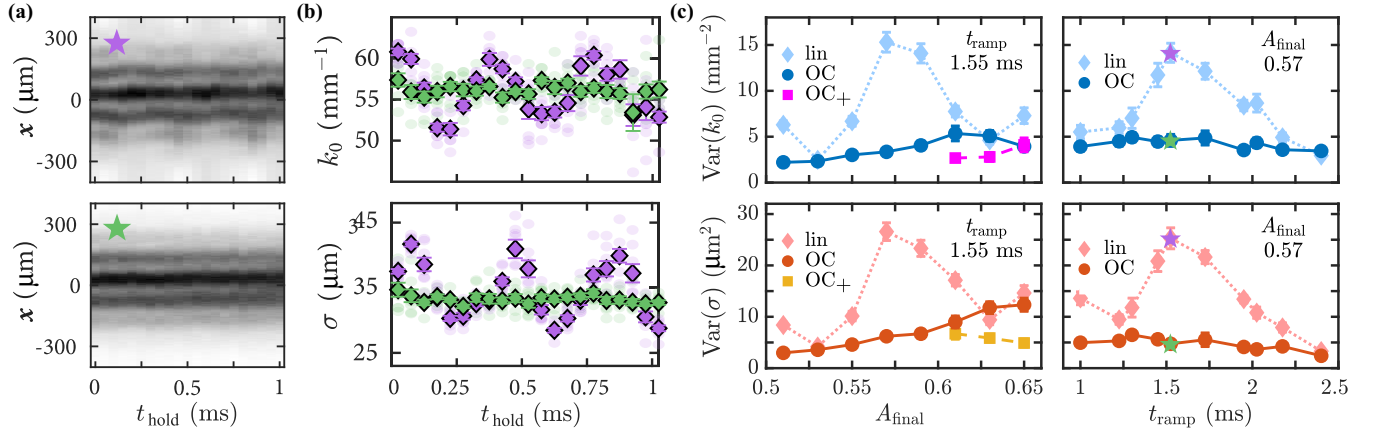


FIG. 2. OC minimization of splitting-induced excitations. (a) The fringe profiles (averaged over many realizations) as a function of hold time after the splitting ramp. (b) Displayed are the extracted fringe spacing k_0 and transversal width σ for both linear (magenta) and OC (green) ramps [cf. panel (a)]. Diamonds represent mean values, while transparent circles are single shots. This analysis highlights the suppression of sloshing dynamics achieved with OC protocols compared to linear ramps. (c) Top row: variance of the fringe spacing k_0 during t_{hold} after splitting (sloshing). (c) Bottom row: variance of the transverse width σ (breathing). (c) Left column: fixed ramp duration t_{ramp} , varying final splitting strength A_{final} . (c) Right column: fixed final splitting A_{final} , varying ramp duration. Two points marked with stars refer to panel (a). Linear ramps (diamonds) show strong excitations with nontrivial dependence on both ramp duration and final splitting. Optimal control ramps (circles) consistently suppress excitations across a wide parameter range. At larger A_{final} , the performance of OC deteriorates due to increased sensitivity to modeling inaccuracies. We introduce a modified control scheme, OC₊ (squares), employing rescaled ramp durations by a few percent, which restores performance and further suppresses excitations.

the model. However, with a simple linear time rescaling of the trajectory from $\mathcal{A}(t)$ to $\mathcal{A}((1 - \gamma)t)$ (labeled by OC₊), with $\gamma \ll 1$, we achieve superior performance.

The presented OC scheme allows us to perform splitting procedures for a broad range of timescales without exciting classical motion. In particular, the OC approach allows access to significantly shorter timescales compared to linear ramps (which typically require durations of 10 ms or longer to avoid excitations), thereby opening the door to splitting times that are comparable or even faster than interaction time scales.

V. OC ENGINEERING

So far, we have demonstrated control protocols capable of mitigating motion induced during the splitting process. However, residual sloshing can modulate key parameters such as the tunnel coupling, thereby affecting the properties of the final state [21,24,25]. Hence, achieving control over the motional degrees of freedom is crucial for creating engineered excitations to manipulate the resulting quantum state.

In Fig. 3, we present experiments demonstrating that an initially excited motion can be suppressed by applying a secondary control ramp. The two-step protocol is motivated by recent works on optimizing squeezing with nonequilibrium protocols [21,26,27]. We deliberately generate strong motion by a quick linear ramp to a strongly coupled trap $\mathcal{A} = 0.5$. After a 1 ms hold time, we apply one of two OC sequences: either to end up again in the coupled double-well with $\mathcal{A} = 0.5$ or to ramp up to a decoupled double-well with $\mathcal{A} = 0.6$ with the goal of suppressing the created excitations. The OC ramps for those scenarios are calculated by simulating the full dynamical evolution of the protocol. Due to small model

errors, we had to adjust the hold time before applying the OC ramp to match the simulation and experiment evolution [22].

As shown in Fig. 3, both OC protocols begin with excitations introduced by the initial linear ramp (indicated in red) and subsequently suppress these excitations effectively. The resulting final states exhibit excitation levels comparable to those achieved by a single OC splitting ramp directly targeting the final trap configuration (indicated in green). This indicates that our OC approach in the nonequilibrium scenario, where additional motion is excited, features the same level of control as in the shortcut-to-adiabaticity case.

VI. SPLITTING-SPEED LIMIT

Naturally, the system imposes constraints on the minimum duration over which the splitting can be performed, as instantaneous splitting is physically unattainable. We estimate this lower bound in our setup from numerical simulations. Starting from a single-well harmonic potential, we instantaneously switch to an inverted parabolic potential and evaluate the time required for the atomic density to reach the positions corresponding to the final well locations (without requiring atoms to come to rest there). These simulations give us an estimate of $t_{\text{lim}} \sim 200$ μs for the case of a final coupled trap characterized by $\mathcal{A}_{\text{final}} = 0.5$, with a corresponding trap frequency of 2 kHz.

Experimentally, we find that linear ramps with durations shorter than 1 ms fail to produce well-defined interference fringes; at the end of such ramps, the BECs are not yet localized in the two wells. In contrast, our OC protocol enables clean and controlled splitting within ramp durations as short as 350 μs. Therefore, with OC for a wide range of splitting speeds, we can suppress classical excitations to the lowest level we can achieve only with slow adiabatic splitting or direct double-well cooling (see Appendix G).

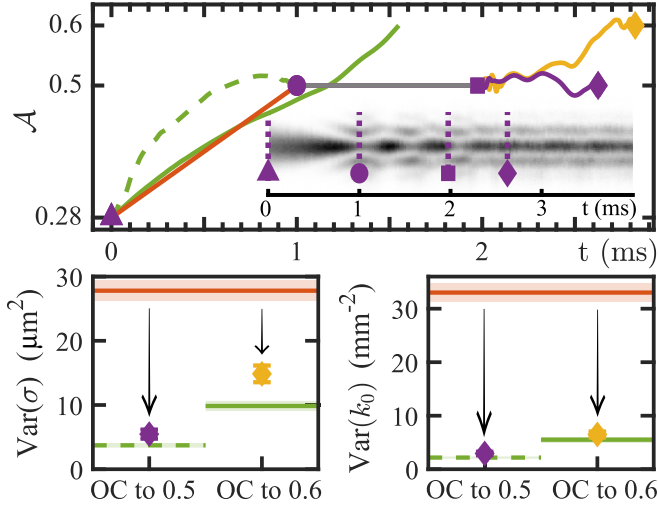


FIG. 3. Optimal control engineering. Dressing amplitude A as a function of time for different engineering scenarios. We first perform a fast linear splitting (red line) into a coupled double-well trap, introducing strong motional excitations. After a hold time of 1 ms (gray segment), we apply an OC sequence to either (I) further split into a more decoupled trap (orange trajectory) or (II) remove excitations while staying in the same coupled configuration (purple trajectory). Inset shows TOF interference fringe images with annotated markers: start of initial splitting (triangle), end of linear ramp (circle), start of OC sequence (square), end of OC sequence (diamond). The bottom panels show the variance of transverse cloud width σ and fringe spacing k_0 , comparing trajectories with standard singular linear (red line) and OC (green lines) ramps. Results demonstrate that excitation-minimizing OC sequences can reach near-optimal performance even when starting from highly nonadiabatic initial conditions.

VII. TUNING QUANTUM PROPERTIES

During splitting, quantum correlations are created in the relative degrees of freedom of the double well. In the ground state, the interplay of repulsive interactions and tunneling leads to relative atom number squeezing. While the OC protocol provides shortcuts to adiabaticity for the motional degrees of freedom within one well, the different splitting speeds change the impact of interactions. For the limiting case of an infinitely fast ramp, interactions can be neglected, and the splitting could be modeled as a noninteracting beam splitter. Thus, together with the adiabatic preparation of classical motion, tunable splitting times should allow modification of quantum properties.

We now explore whether quantum features are preserved under OC splitting protocols. For this, we extract the relative atom number $N_- = N_L - N_R$, where $N_{L/R}$ denotes the atom numbers in the two wells. From our experimental data, we infer the number-squeezing factor $\xi_{N_-}^2 = \Delta^2 N_- / N$, where Δ^2 denotes the statistical variance, and $N = N_L + N_R$ is the total atom number. Number squeezing is signaled by $\xi_{N_-}^2 < 1$, which indicates suppressed number fluctuations below the SQL; together with phase coherence, it allows for witnessing entanglement [11,28].

In Fig. 4, we investigate how the use of OC ramps enables systematic exploration of the fast splitting regime, where linear ramps fail. By tuning the ramp duration, we study the

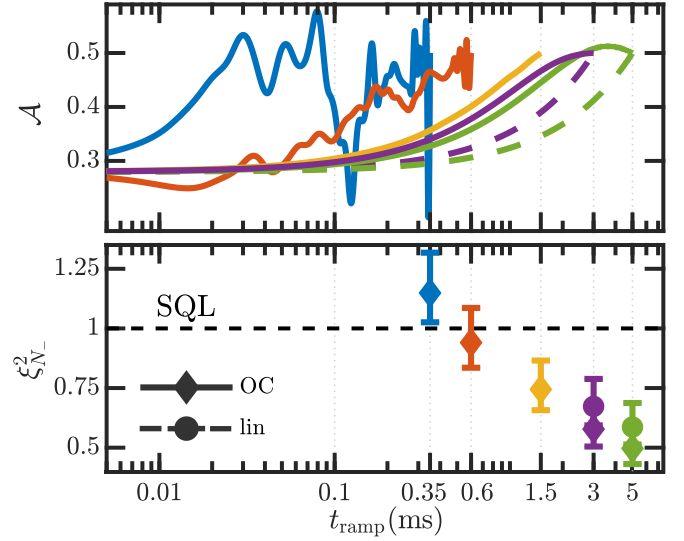


FIG. 4. Squeezing for fast OC ramps. We perform fast OC ramps to $A = 0.5$, trap with different ramp times (solid lines, upper panel); for comparison, we use linear ramps (dashed lines). In the lower panel, we show the inferred number-squeezing factor. Notably, decreasing the ramp duration reduces the squeezing toward the SQL, which is expected since interactions become negligible simply because the evolution time is too short for them to take effect. Even for the fastest ramps, quantum properties are preserved, i.e., the relative phase is well defined.

resulting evolution of the squeezing factor as a function of ramp time. While squeezing remains below the SQL for fast ramps, its magnitude decreases as the ramp duration gets shorter, and for the slower ramps, it matches the squeezing achieved with linear ramps of the same duration. This behavior is consistent with reduced correlation buildup time in the strongly nonadiabatic regime.

In our system, the detection of coherent state fluctuations is so far hampered by detection noise and technical fluctuations. However, it is important to note that the phase-squeezing factor ξ_{ϕ}^2 is decreased for shorter ramp times. This further indicates that quantum coherence persists despite rapid manipulations.

VIII. CONCLUSION AND OUTLOOK

In this work, we have demonstrated the application of optimal control engineering to the splitting of a 1D BEC into a double-well potential. Using a calibrated model for the experimental trapping potential, we generated energy-optimal control ramps that significantly suppress excitations such as sloshing and breathing.

We showed that the OC approach not only outperforms simple linear ramps across a broad parameter space but also remains effective at timescales where linear ramps cannot even localize atoms in two wells. While linear splitting protocols can suppress excitations only at long durations or at very specific splitting speeds and final amplitudes, and fast linear ramps inevitably generate strong motion, OC uniquely enables excitation-free dynamics independent of the ramp speed. Furthermore, we demonstrated the flexibility of OC by

applying it to complex scenarios, where it was used to remove excitations induced by prior manipulations. This provides a toolbox of building blocks for controlling quantum properties.

We provide a strategy for optimal control engineering as a powerful tool for quantum state preparation in cold atom systems. Our method is directly applicable to other experimental systems, especially also with two-dimensional condensates [29]. The demonstrated preservation of quantum correlations during fast, optimal-control-based splitting provides a tunable approach to initializing low-entropy entangled states, which are essential for quantum-enhanced metrology and form a building block for many-body quantum simulation platforms.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: RELATIVE PHASE AND ATOM NUMBER IMBALANCE

The measurement performed in the experiment is a fluorescence image acquired after 43.5 ms of ballistic expansion of the condensate, following its release from the trap [19].

This image reveals an interference pattern formed by the two overlapping condensates. From the fringe structure, we extract key parameters, including the transverse width, relative phase, and fringe spacing; the fringe spacing is related to the interwell distance. Being deep in the 1D regime, the interference fringes are fit using a Gaussian envelope modulated by a cosine function

$$f(x) \propto \exp\left(-\frac{(x-x_0)^2}{2\sigma^2}\right)[1 + C \cos(k_0 x + \phi)],$$

where x_0 is the center of the envelope, σ is the envelope width in the time-of-flight image, C is the fringe visibility (contrast), ϕ is the fringe phase, and k_0 is the spatial frequency, with its corresponding fringe spacing $\lambda = 2\pi/k_0$.

For measuring atom number imbalance, a nearly instantaneous momentum kick is applied just before release, resulting in spatial separation of the two clouds. The counts in the two resulting clouds are integrated to obtain the global atom number in the two wells.

APPENDIX B: MEASURES FOR MOTIONAL EXCITATIONS

To quantify the amount of breathing and sloshing, we calculate the variances of the transversal width of the cloud σ and

the spatial frequency k_0 , respectively. Explicitly, we compute the population variances using

$$\text{Var}(y_\eta) = \frac{1}{N_\eta - 1} \sum_{i=1}^{N_\eta} (y_{\eta,i} - \bar{y}_\eta)^2,$$

where $y_\eta \in \{\sigma, k_0\}$ denotes transversal width or fringe spatial frequency, $y_{\eta,i}$ are the individual data points, and N_η is the total number of points in the corresponding dataset. The sample means are given by

$$\bar{y}_\eta = \frac{1}{N_\eta} \sum_{i=1}^{N_\eta} y_{\eta,i}.$$

To estimate the statistical uncertainty of the variances, jackknife resampling is used [30].

APPENDIX C: THE MODEL

The model contains five free parameters:

- (1) $\mathcal{A}_s$: the splitting point of the double-well, marking the transition from a single-well to a double-well configuration;
- (2) c : a scaling factor for the position of the trap minima as a function of $\mathcal{A}$, described by

$$x_m(\mathcal{A}) = c \text{Re}[\sqrt{\mathcal{A} - \mathcal{A}_s}];$$

- (3) κ_1, κ_2 : scaling factors for the trap curvature at the minima in the single- and double-well regimes, respectively. The effective curvature is given by

$$\frac{\partial^2 V}{\partial x^2}(x_m(\mathcal{A}), \mathcal{A}) = \begin{cases} \kappa_1(\mathcal{A} - \mathcal{A}_s), & \text{for } \mathcal{A} < \mathcal{A}_s, \\ \kappa_2(\mathcal{A} - \mathcal{A}_s), & \text{for } \mathcal{A} > \mathcal{A}_s, \end{cases}$$

- (4) $g_\perp$: the effective transverse interaction strength.

These parameters collectively define the effective one-dimensional potential $V(x, \mathcal{A})$ used in the reduced Gross-Pitaevskii model.

The model parameters are subject to certain constraints, which are supported by full numerical simulation of the trapping potentials for the realistic experimental system [17,18]. The quadratic coefficient is assumed to vary linearly with the splitting parameter, $a_2(\mathcal{A}) \propto \mathcal{A}$; the quartic term $a_4(\mathcal{A})$ is taken to be constant; and higher-order terms $a_6(\mathcal{A})$ and above are neglected.

The coefficients $a_2(\mathcal{A})$ and a_4 are chosen to reflect the double-well structure as the RF amplitude is ramped,

$$a_2(\mathcal{A}) = \begin{cases} \frac{\kappa_1(\mathcal{A} - \mathcal{A}_s)}{2}, & \mathcal{A} < \mathcal{A}_s, \\ -\frac{\kappa_2(\mathcal{A} - \mathcal{A}_s)}{4}, & \mathcal{A} > \mathcal{A}_s, \end{cases}, \quad a_4 = \frac{\kappa_2}{8c^2}.$$

This structure is derived in detail in Ref. [22] and guarantees a smooth transition from a harmonic trap to a double-well configuration for experimentally relevant parameter ranges.

APPENDIX D: MODEL CALIBRATION

We calibrate the model using dynamical measurements extracted from controlled excitations of the system. Specifically, we initialize the condensate in a single well, slowly ramp to the target RF amplitude $\mathcal{A}$, and then apply a short kick to excite sloshing modes. The resulting-time evolution allows us to

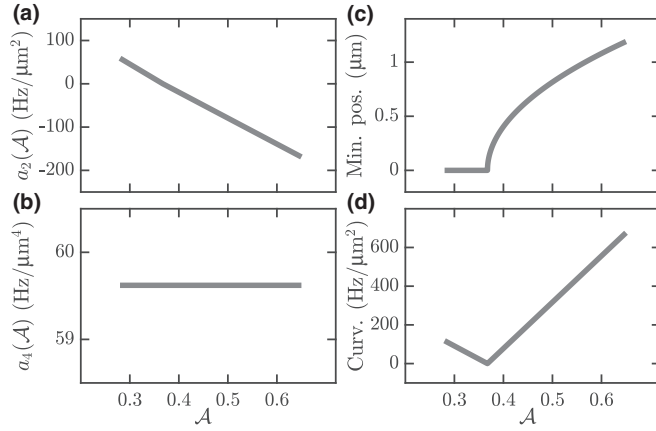


FIG. 5. Parameters of the trap model. This figure presents the behavior of the model used to reconstruct the trapping potential. (a) Coefficient $a_2(\mathcal{A})$ as a function of the splitting parameter $\mathcal{A}$. (b) Coefficient $a_4(\mathcal{A})$ characterizes the anharmonic contribution. (c) Position of the potential minima $x_m(\mathcal{A})$ as a function of $\mathcal{A}$. (d) Local curvature of the potential $\kappa_m(\mathcal{A})$ evaluated at the minima $x_m(\mathcal{A})$.

extract oscillation frequencies [green diamonds in Fig. 1(b)]. In regions with low barriers, both inner and outer trap frequencies can be resolved and included in the calibration. An additional set of data points comes from linear ramps and two consecutive linear ramps followed by hold times. Calibration proceeds by minimizing the two norm between measured and simulated trap frequencies, using the same experimental $\mathcal{A}(t)$ ramps, with an interior-point optimization algorithm.

With the calibrated model, we perform optimal control by solving a boundary value problem for the GPE using indirect methods [7,31]. The objective is to find a time-dependent ramp $\mathcal{A}(t)$ that transfers the initial ground state into the final double-well ground state while minimizing residual

excitations. This is formulated as an energy minimization problem over the control field, with the GPE as the dynamic constraint. The accuracy of this method is critically dependent on the fidelity of the model, reinforcing the importance of robust calibration.

In Fig. 5, we present the resulting dependencies: the behavior of the model coefficients as a function of $\mathcal{A}$, the position of the potential minima, and the curvature at the bottom of the wells, all for the case of a symmetric potential.

APPENDIX E: OC PROTOCOL STABILITY

The data presented in the main text is obtained for an average atom number of 3000. Robustness tests of the OC protocol with respect to atom number fluctuations demonstrate reliable performance across the range of 2000–6000 atoms. We observe a degradation at lower atom numbers, which highlights the importance of nonlinear interactions ($g_\perp$) in this regime, indicating that the model is trained and optimized for dynamics governed by strong nonlinearity. Our experimental observations qualitatively agree with numerical simulations.

APPENDIX F: RESONANCELIKE STRUCTURE FOR LINEAR SPLITTING

The amount of excitation after the linear ramp exhibits resonancelike structures. Contrary to intuition, the excitation does not decrease monotonically with time, nor does it grow monotonically with the final ramp amplitude. The experimental observations are corroborated by numerical simulations, which reproduce these nontrivial features quantitatively. This can be understood in the following way. The sudden termination of the ramp cancels the excitations generated at its onset. In systems with finite-velocity wave propagation, such cancellation is only possible at specific times, giving rise to the resonance-type behavior we observe. Below a certain

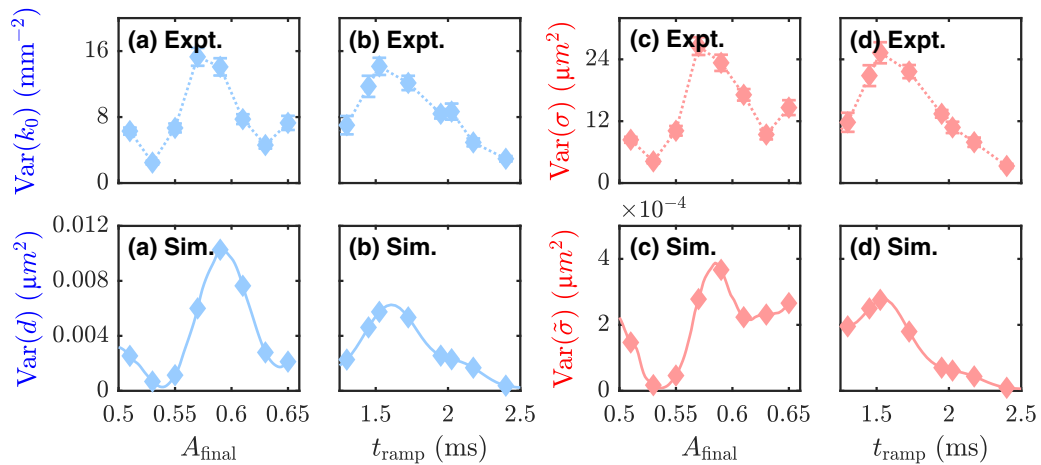


FIG. 6. Comparison between experiment and GPE simulation for excitations induced by linear splitting ramps [experimental data is the same as shown in Fig. 2(c)]. Top row: experimental data extracted in time of flight, displaying sloshing (a), (b) as variance of fringe spacing $\text{Var}(k_0)$ and breathing (c), (d) as variance of transverse width $\text{Var}(\sigma)$. Bottom row: corresponding numerical simulations *in situ*, where sloshing and breathing are quantified by the variances of cloud displacement $\text{Var}(d)$, and width $\text{Var}(\tilde{\sigma})$, respectively. In all cases, variance is calculated over 1 ms of hold time following the splitting procedure. Both experiment and simulation reveal the characteristic dependence of excitations on ramp duration t_{ramp} and final splitting strength $\mathcal{A}_{\text{final}}$, and qualitatively match with each other.

minimum transition time, this mechanism cannot occur because the excitations have not yet propagated across the system.

In Fig. 6, we compare the excitation dynamics obtained for linear splitting ramps with numerical simulations of the *in situ* cloud evolution. While the experiment probes excitations in time of flight, quantified by the variances of the fringe spacing k_0 (sloshing) and the transverse width σ (breathing), the simulations provide direct access to the corresponding *in situ* quantities, namely the displacement d and the width $\tilde{\sigma}$. This comparison enables a direct validation of the interpretation of the experimental signals, a consistency check between *in situ* and time-of-flight diagnostics, and an assessment of the accuracy of our model of the splitting process.

APPENDIX G: ACHIEVABLE LEVEL OF CLASSICAL EXCITATIONS

To define the achievable level of excitations in our system, we performed two complementary measurements. First, we employed a very slow, nearly adiabatic linear ramp of duration exceeding 10 ms and quantified the residual breathing and sloshing oscillations. Second, we cooled the condensate directly into the double-well configuration, where no oscillatory dynamics are present and the remaining fluctuations reflect only readout and experimental shot-to-shot noise. We find that the residual excitation level obtained with optimal control is comparable to that of the slowest feasible ramps.

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